Research Article

Anbarasu Krishnan, Kuppusamy Sathishkumar, Okram Ricky Devi, Smita Agrawal, Abhijit Debnath, Mariadhas Valan Arasu, Thanigaivel Sundaram, Kumaran Subramanian, and Rohini Karunakaran*

Metal oxides on the frontlines: Antimicrobial activity in plant-derived biometallic nanoparticles

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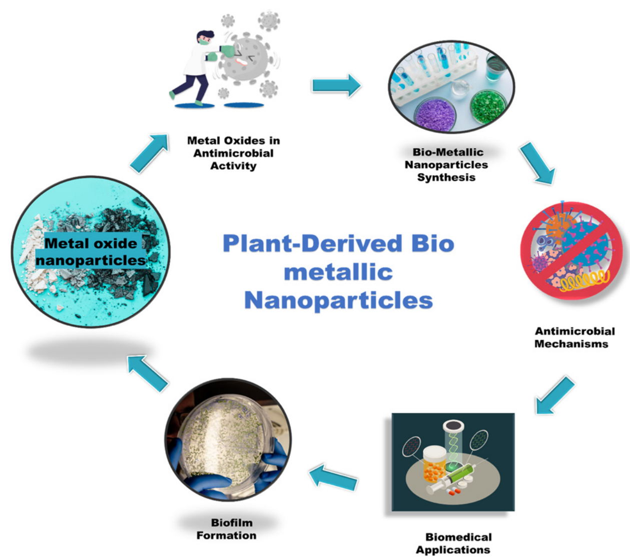
Abstract: The limitless possibilities of nanotechnology can be explained by the remarkable antimicrobial activity demonstrated by plant-derived biometallic nanoparticles, with a particular focus on their interactions with metal oxides. Plant-derived biomaterials and metal oxides work harmoniously to provide a new dimension in materials science that might lead to ground-breaking applications in environmental remediation and biomedicine. Using sophisticated analytical methods, including transmission electron microscopy, Fourier-transform infrared spectroscopy, and X-ray diffraction, this work consists of a systematic inquiry into the production and characterization of these biometallic nanoparticles. The results highlight the exact control over particle size, shape, and composition, highlighting how important these factors are in determining the resultant nanoparticles' ability to fight microbes. One of the main themes involves antioxidant activity, as the biometallic nanoparticles made from plants have the natural capacity to scavenge free radicals, which enhances their antimicrobial effectiveness. The work carefully evaluates the processes behind this dual function, providing insight into the complex interactions between metal oxides and chemicals originating from plants. This study delves into possible uses in biological remediation, where the produced nanoparticles show promise in reducing environmental pollutants. It emphasizes how environmentally benign the suggested biometallic nanoparticles are, imagining a long-term strategy to mitigate microbial dangers and concurrently clean up contaminants in various ecosystems. An in-depth understanding of the complex interactions between biometallic nanoparticles generated from plants and metal oxides, as well as the various roles that these



Graphical abstract

*** Corresponding author: Rohini Karunakaran,** Department of Computational Biology, Saveetha School of Engineering, Saveetha Institute of Medical and Technical Sciences (SIMATS), Saveetha University, Thandalam, Chennai, Tamil Nadu, 602105, India; Unit of Biochemistry and Medical Education, Faculty of Medicine, AIMST University, Semeling, Bedong, Malaysia, e-mail: rohini@aimst.edu.my
Anbarasu Krishnan: Department of Computational Biology, Saveetha School of Engineering, Saveetha Institute of Medical and Technical Sciences (SIMATS), Saveetha University, Thandalam, Chennai, Tamil Nadu, 602105, India
Kuppusamy Sathishkumar: Center for Global Health Research, Saveetha Medical College and Hospitals, Saveetha Institute of Medical and Technical Sciences (SIMATS), Saveetha University, Thandalam, Chennai, Tamil Nadu, 602105, India
Okram Ricky Devi: Department of Agronomy, Assam Agricultural University, Jorhat-785013, Assam, India
Smita Agrawal: Department of Horticulture, B.M. College of Agriculture Khandwa, Madhya Pradesh, India
Abhijit Debnath: Krishi Vigyan Kendra Dhalai, Tripura-799278, India
Mariadhas Valan Arasu: Department of Botany and Microbiology, College of Science, King Saud University, P.O. Box 2455, Riyadh, 11451, Saudi Arabia
Thanigaivel Sundaram: Department of Biotechnology, Faculty of Science and Humanities, SRM Institute of Science and Technology, Kattankulathur, Tamil Nadu, India
Kumaran Subramanian: P.G. Research Department of Microbiology, Sri Sankara Arts and Science College (Autonomous), Enathur, Kanchipuram, Tamil Nadu, India

materials play in biological remediation and antimicrobial activity, is obtained. Thus, our review offers a paradigm change in the design and use of materials, opening up opportunities for further developments in nanotechnology.

Keywords: anti-oxidant activity, antimicrobial activity, metal oxide nanoparticles, biometallic nanoparticles

1 Introduction

Green nanotechnology has been developed to study the initiation and usage of nanomaterials and nanotechnologies to benefit the environment. Consequently, it also aims to develop green approaches that can reduce the ecological footprint of various nanotechnology processes and products [1]. Some of them are the reduction of waste and energy consumption in production, the use of renewable resources, and the development of nontoxic and biodegradable nanomaterials. Applications include water purification to save energy as with solar cells, battery technologies, or air quality improvements. Green nanotechnology is the development of clean technologies to minimize potential environmental and human health risks associated with the manufacture and use of nanotechnology products and to encourage the replacement of existing products with new nano-products that are more environmentally friendly throughout their lifecycle [2]. The integration of biometallic nanoparticles established by plants signifies a revolutionary combination of nanotechnology and botanical extracts, wherein the intrinsic biological capabilities of plants combine with the specific engineering of metallic nanoparticles at the nanoscale [3]. Plant extracts rich in phytochemicals are used in this synthesis procedure to function as stabilizing and reducing agents when biometallic nanoparticles are formed. This novel strategy emphasizes sustainable nanoparticle synthesis using plant-mediated reduction processes, utilizing the natural, environmentally beneficial qualities of green chemistry principles [4]. The synthesis process carefully regulates the interactions between phytochemicals and metal precursors, resulting in the nucleation and development of nanoparticles with specific surface and morphological properties [5]. The resultant biometallic nanoparticles are very adaptable for a variety of applications since they show a unique blend of inorganic and plant characteristics. The precisely calibrated physicochemical characteristics of these nanoparticles impact critical elements, including biocompatibility, stability, and reactivity, opening up new avenues for use in biomedicine and catalysis [6]. Plant-derived biometallic nanoparticles are a viable contender for pushing scientific and technological boundaries because of their combination of botanical expertise with nanoscale engineering. Understanding antimicrobial activity in organisms generated from plants is a meeting point between biologically derived substances and cutting-edge nanotechnological approaches. With an emphasis on botanical sources, bioactive components having innate antibacterial qualities are extracted and used [7]. After these chemicals are included in nanoscale formulations using methods like green synthesis, more effective plant-derived antibacterial agents are produced. These plant-derived antimicrobial compounds work by complexly interacting on a nano-biolevel with a variety of microbiological organisms, including viruses, fungi, and bacteria. The specific physicochemical characteristics of the nanomaterials impact their mechanism of action, causing important cellular functions in the microorganisms to be disrupted [8]. This leads to oxidative stress induction, disruption of cellular signalling pathways, and membrane destabilization, all of which have strong antibacterial effects. Moreover, the use of antimicrobial compounds derived from plants has the potential to mitigate the growing problems associated with antibiotic resistance [9]. These multifunctional nanostructured botanical compositions are strong competitors in the continuing fight against infectious illnesses. The potential for incorporating plant-derived antimicrobial agents into a variety of applications, such as environmental remediation and medicine, is becoming more and more compelling as the scientific community continues to explore the intricacies of these antimicrobial mechanisms [10]. This represents a significant opportunity for groundbreaking discoveries at the connection of biology and nanotechnology.

Sophisticated advances in nanotechnology and advanced materials science are embodied in the tactical use of metal oxides on the front lines. This technological effort is focused on using the different physicochemical properties of metal oxides, especially when designed at the nanoscale, to tackle urgent problems in several fields [11]. Metal oxides' inherent characteristics, which include their electrical, optical, and catalytic capabilities, place them at the centre of innovative applications. In this field of science, the attention is directed to the complex domain of biometallic nanoparticles, in which the combined action of two different metal oxides amplifies their antibacterial efficacy [12]. Careful techniques, such as hydrothermal and green synthesis, are used in the synthesis of these nanostructures in order to create nanoparticles with perfect control over their size, shape, and surface properties. The environmentally friendly and sustainable green synthesis process uses the reducing and stabilizing properties of botanical extracts to direct the formation of biometallic nanoparticles [13]. As these biometallic nanoparticles become strong competitors in the fight against microbiological enemies, the scientific story begins to take shape. A thorough grasp of complex nano-bio interactions is necessary to comprehend the interactions that occur between various microbiological organisms, including bacteria and viruses and metal oxide nanostructures [14]. Given that metal oxides are at the forefront of antimicrobial tactics, the combination of technical expertise and cutting-edge materials highlights a possible path for revolutionary developments at the nexus of metal oxide nanotechnology and biological interfaces. The recent development of metal oxide formation through plant-derived biomimetic has been erased as potent nonconventional antimicrobial agents due to their eco-friendly and sustainable nature. This review, as opposed to conventional reviews, is special in the sense that it reveals synthesis and characterization along with antimicrobial improvement results using plant-based biometallic nanoparticles [15]. Our review article illustrates the plant extract-mediated synthesis of biocidal metal oxides by an innovative junction between nanotechnology and plant-based biochemistry. This new perspective highlights the most recent advances and novel opportunities for their implementation in agriculture, medicine or environment protection.

2 Synthesis and characterization techniques

A thorough investigation of synthesis and characterization methods must be done to understand material characteristics [16]. When it comes to nanomaterials, the synthesis technique is essential for personalizing certain properties. Green synthesis techniques, which use biomolecules as reducing agents and ecologically safe methods, are a leading instance of sustainable procedures that provide control over the content and form of nanoparticles [17]. Characterization methods include a variety of sophisticated approaches and are essential to understanding the complexities of nanomaterials. High-resolution imaging is made possible by transmission electron microscopy (TEM), which provides information on the size, shape, and distribution of nanoparticles. Crystallographic information is revealed by X-ray diffraction (XRD), which reveals the crystalline structure and phase composition of various materials. Molecular analysis is made possible by Fourier-transform infrared spectroscopy (FTIR), which illuminates chemical interactions and functions. Other methods, such as zeta potential measurements and dynamic light scattering (DLS), help to clarify surface charge and colloidal stability, which are important for a variety of applications. Mass spectrometry and nuclear magnetic resonance (NMR) spectroscopy provide comprehensive insights into the compositions and structures of molecules [18]. Combining these synthesis and characterization methods is essential for directing the precise engineering of materials for particular uses in a variety of scientific fields, such as biomedical and nanoelectronics.

2.1 Selection and preparation of plant materials

A thorough comprehension of technological procedures is necessary in the selection and processing of plant materials for scientific investigations. The selection of plant species is crucial when it comes to biologically produced substances, requiring thought to be given to the phytochemical composition, bioactive potential, and sustainability. By ensuring taxonomic accuracy using methods like DNA barcoding, botanical authenticity reduces variability in plant material [19]. Thorough extraction techniques are used throughout the preparation stage to separate bioactive substances. Utilizing technical solvents like ethanol, hexane, or supercritical fluids, solvent extraction maximizes the number of phytochemicals extracted while reducing contaminants. The stability and polarity of the drug will determine whether extraction method maceration, Soxhlet, or ultrasound-assisted extraction is used [20]. It is essential to carry out further purification procedures like chromatography or recrystallization in order to isolate certain bioactive components. The quantitative identification and quantification of chemicals is made possible by analytical methods such as gas chromatography-mass spectrometry and high-performance liquid chromatography, which guarantee the consistency and repeatability of plant materials that have been extracted. The botanical sciences and analytical techniques are closely related, as shown by the technological complexities in plant material processing and selection [21]. This meticulous processing of the material serves as a basis for further scientific research, especially in the areas of phytochemistry, pharmacology, and nanotechnology.

2.2 Techniques for biometallic nanoparticle synthesis

In order to achieve exact control over nanoparticle properties, a comprehensive convergence of multiple technological approaches has resulted in the production of biometallic nanoparticles [22]. Green synthesis is a well-known method that uses ecologically friendly processes and plant extracts as stabilizing and reducing agents. This environmentally friendly method enables the production of nanoparticles with specific morphological and compositional properties. Chemical techniques that allow for exact control over nanoparticle size and form include thermal decomposition and the reduction of metal salts in solution [23]. Through the hydrolysis and condensation of metal precursors, sol–gel techniques provide exact control over the characteristics of nanoparticles. Using droplets stabilized with a surfactant, microemulsion methods make it possible to create monodisperse nanoparticles. Using acoustic or electromagnetic radiation, advanced techniques such as sono chemical and microwave-assisted procedures provide efficient and quick synthesis [24]. Through electrodeposition, electrochemical methods provide exact control over the size of nanoparticles. Synthesis methods get a biocompatible dimension when bioreduction activities involving microbes or enzymes are used. In order to validate the effectiveness of synthesis procedures and customize nanoparticles for particular applications, characterization approaches such as FTIR spectroscopy, XRD, and TEM are essential [25]. The dynamic interaction between various technological approaches highlights the complex terrain of biometallic nanoparticle production, demonstrating the merging of sustainable practices, chemistry, and nanotechnology.

2.2.1 Green synthesis methods

Green synthesis techniques are an important paradigm in the production of sustainable and environmentally friendly nanomaterials. By using plant extracts as stabilizing and reducing agents, these techniques eliminate the need for harsh chemicals and lower their negative effects on the environment [26]. Selecting plant materials requires careful consideration of their phytochemical makeup in order to ensure that the bioactive components are suitable for the production of nanoparticles. The synthesis processes include a range of approaches, although hydrothermal methods are particularly notable for their effective nucleation and regulated reaction conditions [27]. By using electromagnetic radiation, microwave-assisted synthesis accelerates reaction kinetics and shortens the synthesis time. The quick and uniform production of nanoparticles is facilitated by ultrasound-assisted techniques that make use of acoustic cavitation. The fundamental principles of green synthesis include how plant components, such as flavonoids and polyphenols, have an innate ability to reduce and modify metal ion precursors in order to produce nanoparticles. In order to maintain colloidal stability and avoid agglomeration, stabilizing agents, typically proteins or polysaccharides from plant extracts, play a crucial role [28]. The effectiveness of green synthesis is confirmed by characterization methods such as DLS, XRD, and UV-Vis spectroscopy, which also clarify the characteristics of the nanoparticles. Phytochemicals like flavonoids, terpenoids, and phenolic acids assist in the green synthesis of nanoparticles by playing the role of reducing and capping agents. The presence of these compounds provides electrons to metal ions, which form metal nanoparticles [29]. At the same time, they enable the binding to the surface of the nanoparticles, which stabilizes it and prevents aggregation. This duality helps in the synthesis of nanoparticles and makes them stable. Our process is green because instead of chemicals, we synthesize the nanomaterials in a natural way by using nature-produced metabolites. Green synthesis techniques are characterized by their combination of technical accuracy, sustainability, and low environmental impact, which places them at the forefront of the developing field of nanomaterial development [30]. The natural formulation of nanoparticles is swayed by several pivotal considerations: pH, temperature, concentration, and reaction period, each playing a significant role in choosing the attributes and productivity of the synthesized nanoparticles [31].

pH: the pH of the reaction environment impacts the ionization condition of plant biomolecules and the reduction opportunity of metal ions. Ideal pH levels fluctuate depending on the specific plant extract and metal utilized [32]. A higher pH normally advances the decrease process, bringing about more uniform and steady nanoparticles, while extraordinary pH levels can cause precipitation or grouping.

Temperature: temperature is pivotal in controlling the kinetics of the nanoparticle amalgamation. Higher temperatures generally expand the response rate, advancing quicker nucleation and development of nanoparticles [33]. In any case, excessively high temperatures can bring about the arrangement of larger particles and potential disintegration. In contrast, decreasing temperatures may bring about slower responses, delivering less and, in some cases, larger nanoparticles with fluctuating morphologies.

Concentration: the focus of both the plant concentrates and metal precursors fundamentally affects the size, yield, and circulation of nanoparticles. Higher focuses on plant concentrates give more dynamic biomolecules for lessening and topping, normally bringing about smaller, more uniform nanoparticles [34]. In contrast, higher metal particle focuses can yield larger particle sizes and potential amalgamation if not adequately controlled.

Time: reaction time impacts the development and ripening of nanoparticles. Briefer response times may bring about incomplete lessening, delivering fewer or smaller nanoparticles. Prolonged reaction times, while beneficial for finish amalgamation, can sometimes cause particle agglomeration and changes in morphology [35]. Optimizing the reaction time is fundamental to accomplishing the required nanoparticle properties. By fastidiously controlling these elements, the green amalgamation strategy can be fine-tuned to create nanoparticles with explicit attributes, improving their usability in different fields, for example, medication, horticulture, and natural science.

Green synthesis of nanoparticles employs different biological entities acting as reducing as well as stabilizing agents. Besides, the phytochemical-rich content plant extracts have been identified as useful agents for nanoparticle formation and, therefore, are found to be used widely. A gold nanoparticle produced with a bacterial enzyme in the LA bacteria has a particular type of enzyme that is capable of producing stable and all surface functionalized nanoparticles [36]. Algae rapidly growing, high-biomass, and eco-friendly resources contribute as beneficial synthesis extracts for abundant and scalable nanoparticle production. Excellent synthesis capability with fungi extracellular enzymes leads to specific morphologies. Besides, several other biomaterials like yeasts and viruses are being exploited for nanoparticle synthesis. All biological sources provide different benefits to consider the diversity and sustainability of green nanotechnology.

2.2.2 Chemical reduction approaches

The production of nanoparticles relies heavily on chemical reduction techniques, which provide a flexible and regulated way to design materials at the nanoscale. This process depends on precisely reducing metal ions, which is usually accomplished by using reducing agents [37]. This causes the nucleation and subsequent development of nanoparticles. The kinetics and results of the reduction process are significantly affected by the choice of reducing agents, such as sodium borohydride or hydrazine. The reduction kinetics and nanoparticle shapes are further influenced by the choice of solvent systems, which often include the aqueous or organic media [38]. The latest tool in the chemical reduction toolbox is thermal reduction, which involves carefully regulated heating operations to create nanoparticles with precise sizes and crystallinities. Numerous kinds of metal ions may be used with the chemical reduction method to create a variety of metallic nanoparticles, each with unique characteristics and uses. The ultimate size distribution and form of the nanoparticles are influenced by the carefully regulated nucleation and growth phases [39]. Customizing the required nanoparticle properties necessitates the optimization of reaction parameters, such as pH, temperature, and concentration. Evaluation of the effectiveness and fineness of the chemical reduction synthesis process depends on characterization techniques like TEM, XRD, and spectroscopic approaches like UV-Vis and FTIR [40]. Chemical reduction techniques are positioned as essential instruments in the toolset for nanomaterial production because of their methodological accuracy and versatility, which are crucial for a wide range of scientific and technological applications.

2.3 Advanced analytical tools for characterization

In order to completely understand the complex characteristics and functions of nanomaterials, modern analytical methods must be used throughout the characterization process [41]. An essential tool in nanoscale imaging is TEM, which offers high-resolution information on the shape, size distribution, and crystallinity of the particles. The spatial distribution of component elements inside the nanoparticles may be determined using elemental mapping, which is made possible by the combination of TEM and energy-dispersive X-ray spectroscopy (EDS). Critical information on the phase composition and crystal structure of nanomaterials may be obtained through XRD. Crystallographic orientations and phase purity may be determined using this approach by examining the diffraction patterns that arise from X-ray interactions with the material's lattice [42]. By identifying chemical bonds and vibrational modes, spectroscopic methods like Raman spectroscopy and FTIR spectroscopy make molecular-level investigation easier. These tools are essential for clarifying chemical compositions, intermolecular interactions, and surface functionalization in nanomaterials [43]. Essential information on the particle size distribution, aggregation state, and surface charge is provided by DLS and zeta potential. This information is crucial for evaluating colloidal stability and possible interparticle interactions. Determining molecular structures and dynamics is possible by NMR spectroscopy, which is especially useful for nanomaterials functionalized with organic ligands or polymers. Through integrating these innovative analytical techniques, it is possible to obtain a thorough grasp of the properties of nanomaterials, which facilitates the customization of materials for particular use and the improvement of synthesis procedures [44]. When these methods are used wisely, they may guarantee accuracy and consistency in the characterization of nanomaterials in the rapidly developing field of nanotechnology, which leads to advances in many different kinds of scientific and

Table 1: Advanced analytical tools for characterization: unveiling insights through cutting-edge techniques

Analytical tool	Principle	Application	Limit of detection	Sensitivity	Ref.
Scanning electron microscopy (SEM)	Electron beam interaction	Surface morphology	~1 nm	High	[45]
TEM	Electron transmission	Internal structure analysis	~0.1 nm	Very high	[46]
XRD	X-ray scattering	Crystalline structure	~1% crystallinity	High	[47]
FTIR spectroscopy	Infrared absorption	Functional group identification	~0.01%	Moderate	[48]
Raman spectroscopy	Inelastic scattering of photons	Molecular composition	~1 μg/cm^2	High	[49]
DLS	Light scattering	Particle size distribution	~1 nm	High	[50]
Atomic force microscopy (AFM)	Cantilever deflection	Surface topology	~1 nm	High	[51]
Inductively coupled plasma mass spectrometry	Ionization and mass spectrometry	Elemental analysis	~ppt (parts per trillion)	Very high	[52]
UV-Vis spectroscopy	Absorption of ultraviolet-visible light	Concentration determination	~10^{-6} M	Moderate	[53]
NMR spectroscopy	Magnetic resonance	Molecular structure elucidation	~10^{-5} M	High	[54]

technical fields. Table 1 provides an overview of sophisticated analytical tools employed for precise characterization, encompassing various scientific disciplines. It details their specific applications, key features, and recent research advancements, showcasing the versatility and advancements in cutting-edge analytical techniques.

2.3.1 XRD

For evaluating a material's atomic and molecular structure and phase composition, XRD is a crucial analytical method [55]. Bragg's law, which suggests that the arriving X-rays interact with a crystalline lattice to produce diffracted beams that can be detected and analysed to determine structural information, is the foundation of this non-destructive approach. By making it easier to determine crystallographic properties, including lattice spacing, unit cell diameters, and crystallite size, XRD offers vital information about how atoms are arranged in a material. To determine certain phases and their relative abundance, the diffraction pattern results are examined. This pattern is indicative of the material's crystal structure [56]. The method is frequently employed in many scientific fields, such as chemistry, geology, and materials science. XRD plays a key role in nanomaterial research by evaluating the crystallinity of nanoparticles, evaluating phase transitions, and verifying the effectiveness of production procedures. Enhanced collecting information is made possible by sophisticated XRD devices, such as synchrotron X-ray sources, especially for materials exhibiting low crystallinity or complicated crystal structures [57]. A comprehensive understanding of nanomaterial characteristics may be achieved by combining XRD with complementing methods like spectroscopy and TEM. For structural characterization, XRD is a vital technique that helps researchers rationally design and optimize materials for a range of applications, including electronic devices and catalysis [58]. XRD is a valuable tool for improving our knowledge of nanomaterials and their customized functions because of its reliability and flexibility.

2.3.2 TEM

One of the most important analytical methods for characterizing nanomaterials is TEM, which offers unmatched insights into the composition, shape, and structure of materials at the nanoscale [59]. Based on the concepts of electron optics, TEM achieves sub-nanometres spatial resolution by passing a concentrated electron beam through a thin object. Superior imaging capabilities provided by TEM enable researchers to see individual nanoparticles in great contrast and detail. Knowledge of the physical properties of the nanomaterial requires a knowledge of the size, shape, and distribution of the particles, all of which are crucially revealed by the ensuing photographs [60]. Furthermore, using selected area electron diffraction, TEM makes it possible to clarify crystalline structures and identify crystallographic phases and orientations. When used in combination with TEM, EDS expands analytical capabilities by facilitating elemental analysis and mapping [61]. The chemical makeup and elemental distribution inside nanomaterials may be ascertained owing to this integration. Through challenging the limits of resolution, advanced TEM techniques such as aberration-corrected TEM and high-resolution TEM (HRTEM) allow for atomic-level imaging and improved visualization of nanomaterial edges and mistakes. TEM is commonly employed in many scientific fields, including biology and materials science, and it helps to accelerate advances in nanotechnology research [62]. When combined with other characterization techniques, such as XRD and spectroscopy, TEM becomes an invaluable tool in the search for customized materials with cutting-edge functions, providing a thorough knowledge of nanomaterials.

2.3.3 FTIR spectroscopy

For the purpose of characterizing nanomaterials, FTIR spectroscopy is an essential analytical method that makes it possible to examine molecular structures and functional groups in great detail. This non-destructive method works on the basis of infrared absorption, in which when infrared light interacts with a material, vibrational changes in the sample's molecular bonds are induced. FTIR spectroscopy offers a thorough fingerprint of the molecular makeup of a nanomaterial, illuminating details on its organic coatings, surface functionalities, and structural arrangements [63]. The resultant infrared spectrum, which is made up of absorption bands that fit certain molecular vibrations, makes it possible to determine and measure the different chemical moieties that are present in the nanomaterial. The method has several uses in nanotechnology and nanoscience, including important insights into the presence of organic ligands or polymers, intermolecular interactions, and surface modification of nanoparticles [64]. When used in tandem with complementing methods like TEM and XRD, FTIR spectroscopy advances our comprehensive knowledge of the characteristics of nanomaterials. Attenuated total reflection accessories for high-end FTIR spectroscopy instruments enhance sensitivity and enable the investigation of nanomaterials in powder, film, and suspension form. Moreover, FTIR spectroscopy combined with other spectroscopic techniques like NMR spectroscopy offers a complementary way for detailed structural elucidation [64]. With the goal of better understanding the chemical compositions, surface functions, and molecular interactions inside nanomaterials, FTIR spectroscopy is a vital technique for nanomaterial description.

2.3.4 UV-visible spectroscopy

A critical analytical method for characterizing nanomaterials is UV-visible spectroscopy, which uses the interaction of visible and ultraviolet light with matter to clarify the electronic transitions occurring in a sample [65]. This non-destructive technique offers important insights into the electrical structure, bandgap, and optical properties of nanomaterials, as well as their absorption and transmission characteristics. Using UV-visible spectroscopy, one may identify chromophores and determine the size and concentration of nanoparticles by identifying certain absorption bands that correspond to electronic transitions in the absorption spectrum [66]. The method is particularly beneficial for examining the plasmonic characteristics of the metallic nanoparticles and provides a quantitative explanation of surface plasmon resonance occurrences. UV-visible spectroscopy is widely used in nanotechnology to guide the evaluation of nanoparticle stability and the optimization of production procedures [67]. The method makes it easier to identify surface modifications, ligand interactions, and the impact of nanomaterial shape on optical characteristics due to its sensitivity to minute changes in the electronic structure. The calculation of the nanoparticle concentrations and their extinction coefficients is made possible by quantitative analysis, which uses the Beer–Lambert law. More sophisticated UV-visible instruments with integrated spheres or accessories for variable-angle specular reflection expand the use of this method to a wider variety of nanomaterial shapes and sizes. As an essential instrument for characterizing nanomaterials, UV-visible spectroscopy offers a quick and flexible way to reveal electrical and optical properties that are essential to the understanding and development of nanoscience and nanotechnology.

3 Antimicrobial mechanisms and efficacy

The antimicrobial activity displayed by biometallic nanoparticles synthesized using plant materials involves an array of actions that comprehensively undermine microbial virulence. Whether disrupting bacterial cell membranes, interfering with metabolic processes, or disabling infectious ability, these nanoparticles' diverse means of sabotaging pathogens surpass that of single-component variants. Derived through green chemistry practices respecting both planetary and human well-being, their multimodal defences against contagion merit expanded investigation [68].

(1) Generation of reactive oxygen species (ROS): ROS play a key role in microbial death. Superoxide anions, hydroxyl radicals, and hydrogen peroxide are generated as one of the primary mechanisms. These reactive molecules inflict oxidative stress upon microbial cells, creating havoc at a molecular level. Lipids, proteins, and DNA sustain collateral damage from the toxic oxygen derivatives. Such oxidative wreckage compromises the wholeness of the microbial membrane and its interior constitution. With structures in disarray, functioning grinds to a halt, marking the end of the cell [69].

(2) Disruption of cell membrane integrity: ROS play a key role in microbial demise. Superoxide anions, hydroxyl radicals, and hydrogen peroxide are generated as one of the primary mechanisms. These reactive molecules inflict oxidative stress upon microbial cells, creating havoc at a molecular level. Lipids, proteins, and DNA sustain collateral damage from the toxic oxygen derivatives. Such oxidative wreckage compromises the wholeness of the microbial membrane and its interior constitution. With structures in disarray, functioning grinds to a halt, marking the end of the cell [70].
(3) Interaction with DNA and proteins: these diminutive yet potent nanoparticles wreak havoc upon microbial cells through a plethora of perturbations. They infiltrate the membranous barriers to interact intimately with the genomic material, instigating mutations that mar replication and transcription [71]. Additionally, their binding disrupts the ribosomal subunits and various proteins crucial for synthesizing further constituents, crippling the cell's competency and fecundity.
(4) Biofilm inhibition: the biofilm, nature's protective shroud for microbial colonies, provides a scant sanctuary from these nanoparticles' attack. They penetrate the convoluted matrix and assail the embedded cells, pre-empting biofilm formation or dismantling established films [72]. This magnifies conventional antimicrobials' efficacy by permitting deeper dissemination and action of the nanoparticles within the deconstructed biofilms.

Efficacy: The efficacy of biometallic nanoparticles shows great potential due to their multi-pronged approach. By targeting microbes through different mechanisms, resistance is far less likely to evolve. Research has found that at lower doses, these particles eradicate more types of microbes than traditional drugs [73]. This wide spectrum of action, coupled with opportunities to alter surfaces to hone in on particular infectious agents, positions them as a promising solution across medical and environmental applications. Moving forward, focusing on refining nanoparticle mixtures and release methods could boost their antimicrobial strength even more while ensuring safety and compatibility with living tissues. The flexibility to adapt as microbes change promises to maintain their usefulness far into the future [74].

3.1 Interactions of biometallic nanoparticles with microorganisms

Biometallic nanoparticle–microorganism interactions are complex interactions at the nano–bio interface that include complex molecular dynamics and physical phenomena. The electrostatic interactions between the charged surface of nanoparticles and the membranes of microorganisms is one important aspect [75]. This interaction affects adhesion, which makes it easier for nanoparticles to come into direct contact with microorganisms and affects the integrity of the cellular membrane as a result. Furthermore, the biometallic nanoparticle's method of action is greatly influenced by its size, shape, and surface charge [76]. Certain-sized nanoparticles have the ability to enter microbial cells, rupturing their structure and releasing cytoplasm. Selective antibacterial actions are partly due to the surface charge, which affects the attraction for microbial cell surfaces. One important factor determining the effectiveness of antimicrobial agents is the release of metal ions from nanoparticles as a result of their interactions with microbes [77]. This process has the potential to cause oxidative stress, impair cellular processes, and damage microbial enzymatic pathways. Furthermore, when microbes internalize nanoparticles, it sets off intracellular reactions that impact cellular metabolism and function [36]. The microorganisms, fungi, viruses, or bacteria introduce variation in the interactions with biometallic nanoparticles. ROS cause nanoparticle-induced oxidative stress, which is a prevalent mechanism impacting a variety of microorganisms [4]. It takes spectroscopic techniques like FTIR spectroscopy and analytical procedures like TEM to fully understand these complex interactions [14]. The complicated connection between biometallic nanoparticles and microorganisms highlights the complex dynamics influencing antimicrobial efficacy and provides opportunities for customizing nanomaterials for specific and potent antimicrobial applications as researchers work to understand the nano–bio interactions. Table 2 comprehensively explores the intricate dynamics between bio-metallic nanoparticles and diverse microorganisms, unravelling interaction mechanisms, biological responses, and the potential applications across various scientific domains. It provides insights into the evolving landscape of nanobiotechnology and microbial interactions.

3.2 Impact of particle size and morphology

Particle shape and size play an essential role in determining the effectiveness and usefulness of nanomaterials in a variety of applications. The physicochemical characteristics and biological interactions of nanoparticles are significantly influenced by their size, which is a crucial factor in both nanoscience and nanotechnology. The surface area-to-volume ratios of smaller nanoparticles are higher, which affects colloidal stability, optical characteristics, and reactivity [85]. The penetration and interaction of biometallic nanoparticles with microbial cells are greatly influenced by

Table 2: Interactions of biometallic nanoparticles with microorganisms: Mechanisms and biological responses

Nanoparticle type	Microorganism species	Interaction mechanism	Biological response	Research applications	Ref.
Silver nanoparticles (Ag NPs)	*Escherichia coli* (E. coli)	Cell membrane disruption	Antimicrobial activity	Development of antibacterial agents	[77]
Gold nanoparticles (Au NPs)	*Saccharomyces cerevisiae* (yeast)	Intracellular uptake and localization	Inhibition of cellular functions	Biomedical imaging and drug delivery systems	[78]
Copper nanoparticles (Cu NPs)	*Pseudomonas aeruginosa* (bacteria)	ROS generation and oxidative stress	Modulation of microbial metabolism	Water treatment for microbial contamination control	[79]
Zinc oxide nanoparticles (ZnO NPs)	*Aspergillus niger* (fungus)	Cell wall disruption and enzyme inhibition	Inhibition of fungal growth	Antifungal agents in agriculture and medicine	[80]
Iron oxide nanoparticles (Fe_2O_3 NPs)	*Bacillus subtilis* (bacterium)	Magnetic field-enhanced antibacterial effect	Disruption of bacterial cell functions	Magnetic hyperthermia for cancer therapy	[4]
Titanium dioxide nanoparticles (TiO_2 NPs)	*Chlorella vulgaris* (algae)	Photocatalytic generation of ROS	Impairment of algal photosynthesis	Water purification and environmental remediation	[81]
Carbon nanotubes (CNTs)	*Staphylococcus aureus* (bacterium)	Penetration and disruption of cell membranes	Inhibition of bacterial growth	Drug delivery systems and biosensing applications	[82]
Manganese dioxide nanoparticles (MnO_2 NPs)	*Rhizobium legumin Sarum* (bacterium)	Redox reactions and electron transfer	Stimulation of microbial electron transport	Bioremediation of contaminated environments	[14]
Cobalt nanoparticles	*Fusarium oxysporum* (fungus)	Interference with fungal reproduction	Fungicidal effect on spore germination	Agricultural fungicides and crop protection	[83]
Graphene oxide nanoparticles	*Lactobacillus acidophilus* (bacterium)	Physical interaction with cell membranes	Modification of bacterial growth and metabolism	Probiotic delivery systems and gut microbiome studies	[84]

their particle size in antibacterial applications. Smaller-sized nanoparticles often show better cellular absorption, which results in stronger antibacterial effects. Because size-dependent features are changeable, nanoparticles may be designed to target specific microbes. Morphology, which includes surface characteristics and form, further modifies the behaviour of nanomaterials [86]. Anisotropic morphologies, including nanowires and nanorods, have distinct optical and electrical properties that affect sensing and catalysis applications. In addition to affecting cellular internalization and interactions with biological entities, the nanoparticle form also affects the biological destiny and therapeutic effectiveness of the particles [87]. The size distribution and shape of nanoparticles may be determined with great importance using quantitative analysis and characterization methods such as TEM, XRD, and DLS. By precisely controlling these characteristics, synthesis settings may be adjusted to customize nanomaterials to fulfil certain performance needs [88]. Beyond basic material qualities, particle size and shape influence a wide range of scientific fields [89]. By carefully adjusting these properties, scientists may create nanomaterials with specific functions that meet the complex requirements of a variety of applications, including medication delivery and catalysis.

3.3 Synergistic effects of metal oxides

The investigation of the synergistic effects resulting from the integration of metal oxides is a comprehensive examination within the discipline of nanotechnology that illustrates the convergence of many metallic components to provide improved characteristics and functions [90]. The complex interactions between the unique physicochemical characteristics of specific metal oxides often result in this synergism, which enhances performance in a variety of applications. An important area where synergistic effects can be observed is in antibacterial treatments [91]. When compared to their solo equivalents, combinations of various metal oxides, such as titanium dioxide (TiO_2), copper oxide (CuO), and zinc oxide (ZnO), have higher antibacterial activity. This coordinated activity is thought to have a cumulative effect on cellular structures, redox processes, and microbial membranes, erecting a strong barrier against the growth of bacteria. The synergistic effects of metal oxides are used in catalysis to enhance catalytic efficiency and optimize reaction pathways [91]. A catalytic system's overall performance may be improved by carefully combining metal oxides with different redox potentials to assist electron transfer activities. This synergism is often used in environmental remediation procedures, where the combined catalytic strength of many metal oxides aids in the removal of pollutants and pollutants. The characterization methods, FTIR spectroscopy and X-ray photoelectron spectroscopy (XPS) are essential for identifying the compositional and structural subtleties that underlie synergistic effects. These findings provide important new perspectives on the interfacial processes and electrical interactions between different metal oxides [92]. The investigation of synergistic effects in metal oxides is an area of the frontier where technical expertise combined with materials science results in multifunctional nanostructured materials that open up new avenues for technological breakthroughs across a range of applications. Figure 1 shows the synergistic interactions among metal oxides, revealing their combined effects that enhance catalytic and antibacterial properties. It illustrates the collaborative impact of these materials, paving the way for multifunctional applications in various fields.

3.4 Mechanistic insights into antimicrobial activity

Mechanistic information of the antibacterial activity of nanomaterials requires a thorough understanding of the complex chemical and cellular interactions that exist between nanoparticles and microorganisms [93]. The breaking down of microbial cell membranes is one important way. Because of their small size and large surface area, nanoparticles may make direct contact with other materials, which can destabilize membranes and jeopardize the integrity of microbial cells [94]. The cellular contents may leak as a consequence of this physical disturbance, which also causes permeability alterations. Nanomaterials' production of ROS is another essential antibacterial mechanism. Inducing cellular damage such as lipid peroxidation, protein oxidation, and DNA breakage is one way by which oxidative stress might contribute to the overall antimicrobial impact. Further enhancing their effectiveness, nanoparticles with intrinsic or induced catalytic activity contribute to the formation of ROS [95]. The antibacterial mechanisms of nanoparticles are further complicated by their surface functionalization. On the surface of nanoparticles, bioactive compounds or ligands may selectively engage with microbiological constituents, affecting cellular absorption and recognition. The antibacterial efficaciousness and specificity are improved by this focused strategy. Determining minimum inhibitory concentrations and evaluating the kinetics of microbial growth are key components of the quantitative investigation of antibiotic effectiveness [96]. Methods that provide dynamic insights into the kinetics of nanomaterial-mediated microbial suppression include live/dead staining and time-kill examinations. Mechanistic

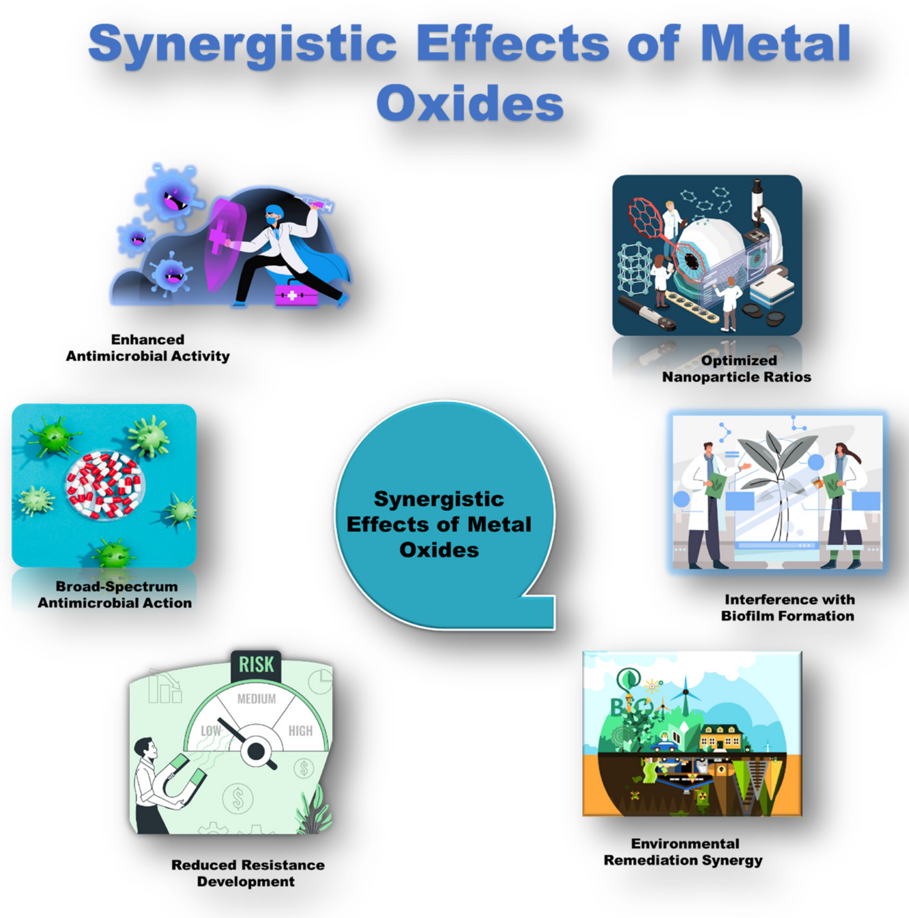


Figure 1: Synergistic effects of metal oxides: enhancing catalytic and antibacterial properties.

insights into antimicrobial action are essential for customizing nanomaterials to particular microbial targets as researchers explore the molecular details. The integration of materials science, microbiology, and analytical techniques such as spectroscopic approaches and TEM allows for a comprehensive comprehension of the nano–bio interactions that determine antimicrobial results.

4 Antioxidant activity of plant-derived biometallic nanoparticles

Determining the antioxidant activity of biometallic nanoparticles generated from plants entails a thorough investigation of their ability to mitigate oxidative stress and scavenge ROS. Green chemistry concepts are used in the synthesis of these nanoparticles, which capitalize on the intrinsic antioxidant capacity of plant extracts that are rich in flavonoids and polyphenolic chemical substances [7]. The bioactive moieties found in the plant-mediated synthesis are principally responsible for the antioxidative effectiveness; they function as stabilizing and reducing agents during the production of nanoparticles [97]. These nanoparticles' biometallic makeup increases their antioxidant activity by fostering synergistic interactions between different metallic constituents, providing a strong barrier against oxidative damage. Assays like the ferric reducing antioxidant power (FRAP) test and the 2,2-diphenyl-1-picrylhydrazyl (DPPH) radical scavenging assay are used to quantify antioxidant activity [98]. These tests assess the nanoparticles' capacity to decrease metal ions and neutralize free radicals, respectively. Advanced spectroscopic methods such as FTIR and UV-Vis spectroscopy help to decipher the chemical processes behind the antioxidant action. Through these investigations, the interactions, surface functions, and chemical composition of the nanoparticle matrix are determined. Understanding the antioxidant characteristics of biometallic nanoparticles generated from plants is essential for both biomedical uses and optimizing their potential in food preservation and cosmetics

[99]. The complex interactions between metallic nanoparticles and plant substances highlight the diverse range of antioxidant defences, making these materials attractive options for treating diseases caused by oxidative stress.

4.1 Role of plant compounds in antioxidant properties

The complex interaction of phytochemicals, reducing agents, and stabilizing agents plays a role in the antioxidant capabilities that plants provide to biometallic nanoparticles, hence enhancing the multifarious antioxidant potential of these nanostructures [100]. Plant-derived chemicals, including flavonoids and polyphenols, are essential components in the environmentally friendly production of biometallic nanoparticles. These phytochemicals, which are widely distributed in different plant extracts, function as strong reducing agents and help transform metal precursors into nanoparticles. The capacity of plant chemicals to donate electrons or hydrogen atoms, neutralizing free radicals and ROS, is thought to be the source of their antioxidant potential [101]. By severing the chains that free radicals start, this electron-donating ability is essential in averting oxidative damage. These plant chemicals act as stabilizing agents during the production of nanoparticles, avoiding nanoparticle aggregation and guaranteeing colloidal stability [102]. They also promote the reduction process. Functional groups like hydroxyl and carbonyl groups that are present in plant chemicals improve their antioxidant properties and make it easier for them to interact with metallic nanoparticles. The moment spectroscopic methods, such as FTIR spectroscopy, allow certain functional groups implicated in antioxidant interactions to be clarified. Moreover, UV-Vis spectroscopy sheds light on the absorbance traits and electronic transitions suggestive of the antioxidant capacity of biometallic nanoparticles generated from plants. Plant chemicals combine synergistically to synthesize nanoparticles, which reveal a sophisticated network of antioxidant defences and make these nanoparticles attractive options for use in biotechnology, medicine, and environmental cleanup [103]. The complex chemical processes at work highlight how important it is to understand how plant-based molecules function to customize antioxidant qualities in the developing area of green nanotechnology. Figure 2 shows the intricate role of plant compounds in antioxidant properties, showcasing nature's intricate defence mechanisms. It highlights the diverse compounds contributing to the antioxidant capacity of plants and their implications for human health.

4.2 Free radical scavenging mechanisms

Free radical scavenging methods are an essential component of antioxidant protection mechanisms that include complex chemical interactions intended to counteract and lessen the deleterious effects of free radicals and ROS. The

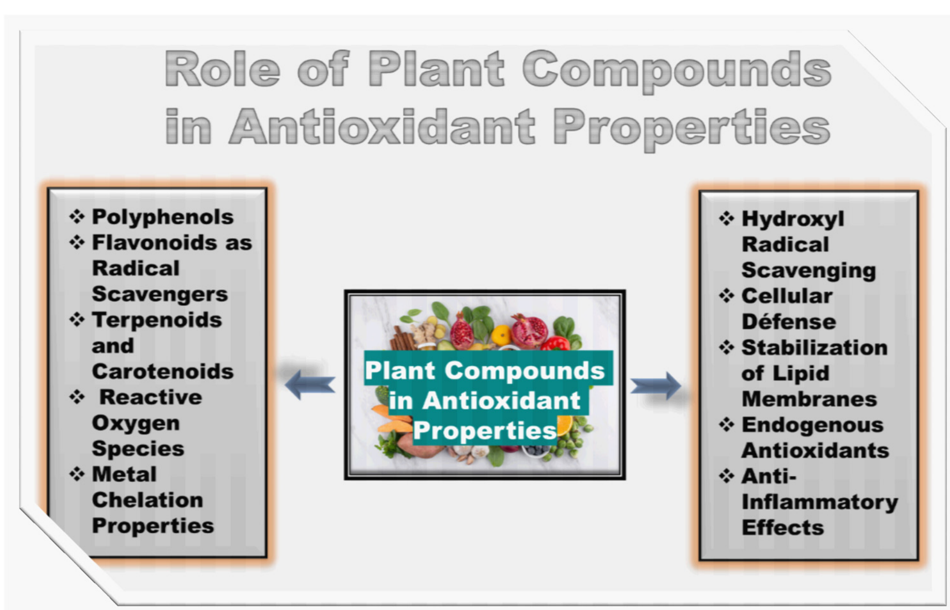


Figure 2: Role of plant compounds in antioxidant properties: unveiling nature's defence mechanisms.

intrinsic antioxidant characteristics of phytochemicals are responsible for these processes in the context of biometallic nanoparticles derived from plant components [104]. Plant extracts are rich in polyphenols and flavonoids, which operate as electron-donating agents and actively contribute to the reduction of free radicals. By donating electrons or hydrogen atoms to stabilize and neutralize these very reactive species, scavenging ROS helps stop oxidative damage to biomolecules. The metallic constituents of biometallic nanoparticles work in concert to scavenge free radicals. Metals like copper, zinc, or silver increase catalytic activity, which makes it easier for reactive species to form and function as secondary scavengers. The nanoparticles' total antioxidant efficaciousness is increased by this synergism [105]. Through surface adsorption and electron transfer mechanisms, biometallic nanoparticles and free radicals directly interact. High surface area nanoparticles with certain surface functions show a stronger affinity for ROS and facilitate efficient scavenging. Tests like 2,2-diphenyl-1-picrylhydrazyl (DPPH) and 2,2′-azino-bis(3-ethylbenzothiazoline-6-sulphonic acid) (ABTS) radical scavenging tests are used to quantify the effectiveness of free radical scavenging [106]. These tests evaluate the capacity of nanoparticles to squelch and neutralize free radicals, offering quantifiable insights into their potential as antioxidants. Comprehending the processes involved in scavenging free radicals at the nano–bio interface is essential in customizing biometallic nanoparticles with improved antioxidant capabilities, hence creating opportunities for use in environmental remediation, biomedicine, and other disciplines [107]. Table 3 provides a detailed exploration of free radical scavenging mechanisms exhibited by diverse antioxidant compounds. It elucidates their sources, biological significance, and potential applications, offering a comprehensive understanding of their roles in health, nutrition, and industry.

4.3 Influence of metal oxides on antioxidant potential

Metal oxides' effect on antioxidant potential is a result of a dynamic interaction at the nano–bio interface, where metal oxides' inherent characteristics work in concert to alter and augment the antioxidant capacities of nanomaterials [118]. Zinc oxide (ZnO), titanium dioxide (TiO_2), and copper oxide (CuO) are examples of metal oxides that have unique physicochemical properties that significantly influence the antioxidant behaviour of nanocomposites [119]. Because metal oxides are semiconductors, they have special electrical characteristics that enable the production of charge carriers when exposed to light [120]. By encouraging electron donation and squelching ROS, this photo-induced electron transfer might increase the antioxidant potential. Metal oxides' surface functionalization and modification further customize how they interact with antioxidant species [121]. The adsorption and stabilization of bioactive chemicals are influenced by the unique surface chemistry and electronic states of metal oxides, which enhances their antioxidant ability. Modulating antioxidant pathways is also significantly influenced by the redox activity of metal oxides [122]. Reversible redox reactions are facilitated by several metal oxides, which help antioxidant species regenerate and remain effective for longer. Assays like the FRAP test and the oxygen radical absorbance capacity assay are used in the quantitative evaluation of antioxidant potential [123]. These experiments shed light on the metal oxide nanocomposites' overall antioxidant efficiency by reducing metal ions and scavenging free radicals. Understanding the complex impact of metal oxides on antioxidant potential is crucial for optimizing nanomaterials in a variety of applications, such as environmental remediation and biomedical devices, where improved antioxidant properties are critical for preventing oxidative stress and enhancing cellular health.

5 Biomedical applications

Metal oxide nanoparticles have an extensive number of uses in biomedicine, making use of their special physicochemical characteristics to provide therapeutic, imaging, and diagnostic capabilities [124]. Metal oxide nanoparticles are useful agents for computed tomography (CT) and magnetic resonance imaging (MRI) in the field of diagnostics because they naturally enhance contrast. The exact imaging and localization of biological structures are made possible by their adjustable optical and magnetic characteristics [125]. Because metal oxide nanoparticles may encapsulate and release therapeutic substances in a regulated way, they are used as drug delivery vehicles in medicine [126]. Targeting ligands or biocompatible polymers may be used to modify the surface to improve specificity and bioavailability, which guarantees accurate drug delivery to the intended locations [127]. Metal oxide nanoparticles, especially iron oxide nanoparticles, are used in hyperthermia therapy as part of cancer treatment. When exposed to an external magnetic field, their magnetic qualities allow for the production of localized hyperthermia, which damages cancer cells alone while preserving healthy tissues untouched. Furthermore, certain metal oxide nanoparticles, including copper and zinc oxide, have antibacterial qualities that make them useful for treating infections and covering medical equipment

Table 3: Free radical scavenging mechanisms: a comprehensive overview

Antioxidant compound	Free radical scavenging mechanism	Source or origin	Biological significance	Applications	Ref.
Ascorbic acid (vitamin C)	Donation of electrons to neutralize radicals	Fruits and vegetables	Protection against oxidative stress	Food preservation and cosmetic formulations	[108]
Alpha-tocopherol (vitamin E)	Breaking free radical chain reactions	Nuts, seeds, and oils	Cell membrane protection	Pharmaceuticals and skincare products	[109]
Glutathione	Conjugation and detoxification of radicals	Synthesized in cells	Detoxification in liver cells	Antioxidant supplements and health products	[110]
Polyphenols (flavonoids)	Metal chelation and ROS scavenging	Found in plants	Cardioprotective and anti-inflammatory effects	Functional foods and nutraceuticals	[111]
Carotenoids (beta-carotene)	Quenching singlet oxygen and neutralizing radicals	Coloured vegetables and fruits	Promotion of healthy vision	Dietary supplements and natural colourants	[112]
Melatonin	Direct radical scavenging and indirect antioxidant activation	Produced in the pineal gland	Regulation of circadian rhythms and sleep	Sleep aid supplements and neuroprotective applications	[113]
Coenzyme Q10 (ubiquinone)	Electron transfer in the mitochondrial respiration chain	Synthesized in cells	Energy production and cellular protection	Anti-aging and cardiovascular health supplements	[114]
Selenium	Incorporation into selenoproteins for antioxidant enzyme activity	Found in nuts and seeds	Reduction of DNA damage and cellular protection	Dietary supplements and anticancer research	[115]
Lipoic acid	Regeneration of other antioxidants and metal chelation	Synthesized in cells	Enhanced antioxidant capacity	Diabetes management and neurological health supplements	[116]
Quercetin	ROS scavenging and modulation of cellular signalling pathways	Present in fruits and vegetables	Anti-inflammatory and anticancer effects	Nutraceuticals and functional food additive	[117]

surfaces [128]. Metal oxide nanoparticles are useful in tissue engineering and regenerative medicine because they improve scaffold characteristics and encourage cell adhesion, proliferation, and differentiation. Their usefulness in the creation of biomimetic materials stems from their biocompatibility and capacity to alter biological reactions. TEM, XPS, and DLS are characterization methods that are essential for evaluating the stability and physicochemical characteristics of metal oxide nanoparticles for use in biomedical applications [129]. These nanoparticles' diverse contributions highlight their promise as adaptable instruments in improving medical treatments, diagnostics, and regenerative techniques.

5.1 Drug delivery systems

Metal oxide nanoparticle-based drug delivery systems have become modern platforms that are transforming the pharmaceutical industry with their targeted distribution, improved bioavailability, and customized release kinetics [130]. Metal oxide nanoparticles have special physicochemical characteristics that make them excellent options for drug encapsulation and release, including a large surface area, variable surface charge, and variable size [131]. Mesoporous silica, iron oxide, and zinc oxide are a few examples of metal oxide nanoparticles that provide a flexible matrix for drug delivery. These nanoparticles' mesoporous shape allows for substantial drug loading capacities, while surface modifications with ligands or polymers improve stability and biocompatibility. Numerous processes, including diffusion, degradation, and stimuli-responsive release prompted by environmental variables like pH, temperature, or particular biomolecules, may be used to accomplish controlled drug release [132]. This release kinetic accuracy minimizes negative effects and guarantees maximum therapeutic effectiveness. By functionalizing metal oxide nanoparticles with ligands that recognize certain receptors on target cells, targeted medication administration is accomplished [133]. By improving medication accumulation in targeted areas, this active targeting strategy lowers systemic toxicity and undesirable side effects. In order to understand the structure, content, and morphology of drug-loaded metal oxide nanoparticles, characterization methods, including NMR, SEM, and (FTIR spectroscopy are essential [134]. Metal oxide nanoparticles' adaptability is leveraged by the combination of nanotechnology with pharmaceuticals in drug delivery systems, offering a customized and advanced treatment strategy. The combination of biological compatibility and technological accuracy puts metal oxide-based drug delivery systems at the forefront of pharmaceutical research advancement and patient care.

5.2 Implant coatings and biocompatibility

Implant coatings are essential for improving the biocompatibility and functionality of medical implants by reducing problems with implant integration and host reaction. Metal oxide coatings, such as hydroxyapatite (HA) and titanium oxide (TiO_2), have remarkable osteoconductive and biocompatibility, which encourage osseointegration and lower implant rejection risk [135]. Metal oxide coatings are meticulously developed to modify their surface qualities in order to regulate their interactions with surrounding biological tissues. Improved cell adhesion, proliferation, and differentiation are made possible by nanoscale surface roughness, regulated porosity, and customized surface charge [136]. This promotes the development of a stable interface between the implant and host tissues. Metal oxide coatings may be enhanced with bioactive capabilities, such as growth factors or peptides, which accelerate tissue regeneration and enhance cellular responses. By creating a customized microenvironment that supports certain cellular behaviours, these biofunctionalized coatings improve tissue integration. Electrochemical methods, chemical vapour deposition, and plasma spraying are examples of advanced deposition techniques that are used to guarantee the accurate and consistent application of metal oxide coatings on implant surfaces [137]. The shape, content, and adherence of the coating are evaluated by characterization methods such as AFM, SEM, and XPS. Evaluations of biocompatibility include both *in vitro* and *in vivo* research that examine immunological responses, tissue integration, and cellular responses [138]. The capacity of metal oxide coatings to regulate inflammatory reactions and cultivate an environment conducive to tissue regeneration highlights its pivotal function in augmenting the durability and efficacy of medical implants. The ongoing improvement of metal oxide coating techniques is a leading edge in implant technology advancement for improved patient outcomes.

5.3 Wound healing and tissue regeneration

Due to their ability to orchestrate complex biological responses *via* their unique physicochemical features, metal oxide nanoparticles have become highly promising agents in the field of wound healing and tissue regeneration [139]. It has been shown that adding metal oxide nanoparticles, including titanium dioxide (TiO_2) or zinc oxide (ZnO), to scaffolds and wound dressings may promote the most effective potential wound healing results. Certain metal oxide nanoparticles have antibacterial qualities that aid in infection management by halting bacterial colonization and fostering a sterile wound environment. These nanoparticles also have anti-inflammatory properties, which work by regulating immune responses to minimize excessive inflammation and create an environment that is favourable for tissue healing. Angiogenesis, the process of creating new blood vessels that are essential for delivering nutrition and oxygen to healing tissues, is greatly aided by metal oxide nanoparticles [140]. Improved blood vessel creation is a result of their capacity to upregulate endothelial cell proliferation and increase the production of vascular endothelial growth factor. Further enhancing tissue regeneration is the controlled release of growth hormones, medicines, or bioactive compounds from metal oxide-based wound dressings. The precise administration of therapeutic drugs, which encourage cell migration, proliferation, and extracellular matrix formation, is made possible by nanoparticles with variable release kinetics [141]. Molecular biology experiments, TEM, SEM, and other characterization methods provide light on the structural integrity of scaffolds loaded with nanoparticles and how they affect cellular activity. Assessments of biocompatibility, such as *in vivo* wound healing models and *in vitro* cell viability experiments, confirm the safety and effectiveness of metal oxide nanoparticles in tissue regeneration applications. Metal oxide nanoparticles are essential to the advancement of wound healing and tissue regeneration because of the synergistic interaction between nanotechnology and regenerative medicine.

6 Environmental remediation potential

Metal oxide nanoparticles exhibit tremendous potential for environmental remediation; they are useful instruments for dealing with a wide range of toxins and pollutants. Metal oxides, such as iron oxide (Fe_2O_3), zinc oxide (ZnO), and titanium dioxide (TiO_2), have unique physicochemical characteristics that make them useful in a number of remediation techniques [142]. Using metal oxide nanoparticles' photocatalytic activity in the presence of UV or visible light, photocatalytic degradation is a popular method for eliminating organic contaminants from water and air. TiO_2's photocatalytic effectiveness makes it easier for organic molecules to break down into safe byproducts [143]. By means of ion exchange and adsorption processes, metal oxide nanoparticles play a crucial role in heavy metal cleanup. Metal oxides' large surface area and unique surface functions increase their affinity for binding heavy metal ions, which helps remove pollution from aqueous solutions. Certain metal oxide nanoparticles, like ZnO, have antibacterial qualities that are used in water treatment to disinfect. The toxicity of the nanoparticles towards microorganisms helps to manage watery illnesses. Moreover, by immobilizing or changing pollutants, metal oxide nanoparticles aid in the rehabilitation of soil [144]. Fe_2O_3 nanoparticles, for example, may take part in adsorption, precipitation, or redox reactions in order to clean up polluted soils. Advanced analytical methods such as electron microscopy, XPS, and X-ray absorption spectroscopy are used to fully characterize metal oxide nanoparticles and how they interact with contaminants. The main variables in determining the effectiveness of metal oxide nanoparticles for environmental cleanup are their regulated production and surface modification [145]. The many properties of metal oxide nanoparticles make them adaptable and viable tools for reducing pollution and developing environmentally friendly remediation solutions, even in the face of continuing environmental concerns.

6.1 Nanoparticles in environmental cleanup

Nanoparticles have the potential to substantially transform methods for cleaning up the environment by offering novel approaches to reducing pollution and restoring polluted areas [146]. There are several different ways that nanoparticles are used in environmental remediation, including metal oxides, carbon-based nanomaterials, and nanocomposites [147]. Metal oxide nanoparticles, such as iron oxide (Fe_2O_3) and titanium dioxide (TiO_2), have photocatalytic qualities that may be used to break down organic contaminants in water and air. Because these nanoparticles are semiconductors, photocatalysis, which breaks down pollutants into less hazardous chemicals when exposed to light, is made possible. Graphene and CNTs are two examples of carbon-based nanomaterials that help clean up the environment because of their remarkable adsorption abilities. These nanoparticles have the ability to target and extract heavy metals and organic compounds from water and air matrices [148]. Through the combination of various nanoparticles or their integration with supporting matrices, nanocomposites improve the overall performance of environmental remediation solutions. For example, graphene oxide-based nanocomposites exhibit flexibility in cleaning applications since they may be engineered to adsorb and remove a broad spectrum of contaminants. The optimization of nanoparticle performance in environmental cleaning is contingent upon the implementation of functionalization and surface changes [149]. Nanoparticles may have their stability, reactivity, and selectivity for certain pollutants improved by customizing their surface attributes. To ensure that nanoparticles are efficient in environmental cleaning applications, characterization techniques, including XRD, TEM, and spectroscopic approaches, are essential for evaluating the structural and chemical characteristics of the particles. The incorporation of nanoparticles into cleaning methods is a viable path towards effective and long-lasting remediation solutions, even in light of the ongoing problem of environmental contamination [150]. The persistent progress in nanotechnology presents unparalleled prospects for tackling intricate environmental concerns and progressing towards a more robust and sustainable future.

6.2 Biological remediation strategies

Biological remediation techniques are advanced methods of cleaning up the environment that use the power of microorganisms and their metabolic processes. Because of their special characteristics for targeted distribution, increased microbial activity, and greater bioavailability of nutrients and pollutants, nanoparticles are essential for improving the effectiveness of biological remediation procedures [151]. As carriers of microbial consortia or bioactive substances, metal oxide nanoparticles such as zinc oxide (ZnO) and titanium dioxide (TiO_2) contribute to biological remediation. By enabling regulated release mechanisms, these nanoparticles guarantee long-term microbial activity and provide an ideal habitat for disposal [152]. Certain metal oxide nanoparticles have antibacterial qualities that help biological remediation efforts by limiting the growth of harmful microorganisms. This guarantees that the microbial consortia's integrity will not be compromised while the remediation process stays concentrated on the intended pollutants. Functionalized nanoparticles allow for tailored interactions with microbial populations by modifying their surface with certain biomolecules or ligands [153]. Encouraging the adhesion and growth of advantageous microorganisms in polluted settings improves the specificity and efficacy of biological remediation techniques. Nanoparticles

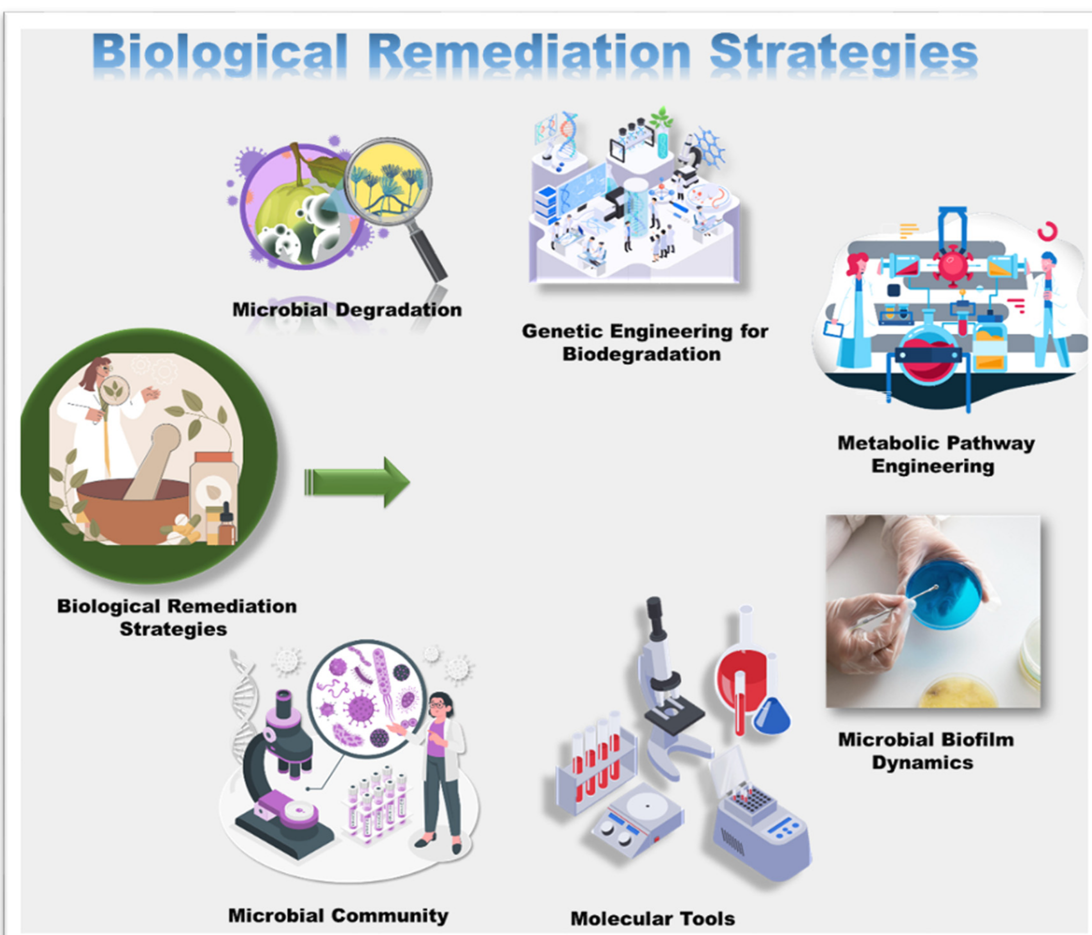


Figure 3: Biological remediation strategies: Harnessing nature's potential for environmental cleanup.

help to increase microbial survival and activity in *in situ* bioremediation, which applies microorganisms directly to the polluted site. Microbial inoculants are carried by nanoparticles, which shields them from unfavourable environmental conditions and allows them to continue working throughout the procedure of repair [154]. Metagenomics, molecular biology tools, and nanoscale imaging are a few examples of advanced analytical approaches that are essential for monitoring and assessing the dynamics of microbial communities interacting with nanoparticles in environmental matrices. A possible option for improving the effectiveness and accuracy of microbial-driven processes for the long-term regeneration of damaged ecosystems is the use of nanoparticles in biological remediation procedures. Figure 3 elucidates the diverse biological remediation strategies employed to harness nature's potential for effective environmental cleanup. It visualizes the intricate processes and organisms involved in bioremediation, showcasing sustainable solutions for addressing environmental contaminants.

6.3 Sustainability and eco-friendly approaches

The development and use of nanoparticles in multiple industries need careful consideration of sustainability and environmentally friendly techniques. Sustainable nanotechnology is based on the green production of nanoparticles using bio-derived reducing agents and environmentally secure processes [155]. This method reduces the amount of dangerous chemicals used, saves energy, and lessens the environmental impact of producing nanoparticles. By reducing long-term environmental effects, the use of biocompatible and biodegradable nanoparticles in environmental applications promotes sustainability [156]. Natural or biopolymer-based nanoparticles are examples of nanomaterials with intrinsically green properties that support environmental compatibility and conform to green chemistry concepts. Cleaner and renewable energy solutions may be developed more easily when nanoparticles are included in sustainable technology like solar cells and energy storage devices. Improved catalytic activity nanomaterials are also helpful in advancing sustainable energy conversion techniques. In the field of medicine, the creation of environmentally friendly drug delivery systems based on nanoparticles not only enhances therapeutic results but also reduces the environmental effect of conventional pharmaceutical formulations [157]. The total environmental friendliness of treatment delivery systems is enhanced by the use of biodegradable nanocarriers and biomaterials derived from sustainable sources. Lifecycle evaluations are essential for assessing the sustainability of applications based on nanoparticles since they include indicators like energy usage and carbon footprint [158]. Through the promotion of material recycling and the reduction of waste creation, the integration of nanotechnology with the concepts of the circular economy further promotes sustainability. In order to achieve sustainability in nanotechnology, multidisciplinary cooperation is required, combining the ideas of environmental engineering, materials science, and green chemistry. It is essential to use environmentally friendly methodologies in nanoparticle applications and research to maximize the promise of nanotechnology while reducing its negative effects on the environment.

7 Challenges and future directions

The rapid progress in investigating the nature of nanoparticles brings with it a variety of difficulties that need careful thought in order to achieve future goals and integrate nanotechnology sustainably into many sectors. Gaining a thorough knowledge of the possible toxicity and long-term environmental effects linked to the manufacture and use of nanoparticles is an important goal. In order to fully understand the complex processes behind nanoparticle interactions with biological systems and ecosystems, modern analytical approaches such as high-throughput omics analysis and *in vivo* imaging must be refined *via* multifaceted cooperation [3]. Large-scale industrial applications of laboratory-scale accomplishments are severely hindered by the scalability and repeatability of nanoparticle fabrication procedures. It is still very difficult to ensure that nanoparticles with the appropriate qualities are consistently produced while following the principles of green synthesis; this calls for creative technical solutions and strong quality control procedures. To advance safe and effective therapeutic applications, it is imperative in the biomedical domain to address the intricacies of nanoparticle interactions with biological entities, including off-target effects and immunogenic reactions. The customization of nanoparticles for distinct biomedical purposes necessitates accuracy in structure, functionalization of the surface, and regulated release rates [4]. This calls for novel techniques in nanomedicine and individualized treatment plans. Concerns about unexplained ecological repercussions and the fate and transport of nanoparticles in complex matrices pose hurdles to their use in environmental applications. It is essential to create prediction models that take into consideration the dynamic behaviour of nanoparticles in various environmental conditions in order to establish remediation solutions that are both ecologically acceptable and effective. The ethical and regulatory aspects related to nanotechnology need ongoing examination and improvement [6]. Ensuring the appropriate development and deployment of nanoparticle-based technologies requires the establishment of comprehensive regulatory frameworks, ethical principles, and risk assessment methods. Overcoming these challenges through working together in materials science, biology, engineering, and regulatory science are the future paths of nanoparticle research [7]. Technological developments in real-time monitoring, predictive modelling, and precise synthesis are essential for managing the challenges posed by nanoparticles. Nanotechnology will continue to advance towards safe, significant, and ecologically conscious uses in a variety of fields as long as ethical issues, sustainable methods, and multidisciplinary cooperation are emphasized.

8 Conclusion

In conclusion, biometallic nanoparticles prepared from both plant extracts and metal oxide have been reported to have broad antimicrobial activities and could thus be exploited for numerous applications. These nanoparticles harness the distinctive properties of metal oxides, including high surface area and the potential to generate ROS, to reveal potent antibacterial, antifungal, and antiviral activity while selectively sparing host mammalian cells. Treating plant extracts used in their fabrication process is a well-applicable, eco-friendly, sustainable strategy and thus increases their biocompatibility and efficacy due to the natural biological activities of phytochemicals. Plant-derived phytochemicals are also indispensable for the green synthesis of these nanoparticles as they are assumed to play a dual role in the synthesis, reducing the metal ions and capping the nanoparticle surface. This dual function promotes the formation of nanoparticles in a controlled manner with well-defined morphologies, a feature known to be crucial for their antimicrobial activity. The green synthesis of GNPs also significantly complies with the current prerequisite for the development of sustainable nanotechnological solutions. Antimicrobial action: Mechanisms of action are complex, comprising damage of microbial cell membranes, production of ROS, blocking microbial DNA replication, and protein synthesis. This combination of mechanisms provides multiple points of attack that potential pathogens cannot learn to fend off, an advantage over traditional antimicrobial agents. Biometallic nanoparticle flexibility allows them to be incorporated into a plethora of materials like medical devices, coatings, packaging materials, and more where the antimicrobial character is desired. This is a natural way to prevent microbial contamination and infection, making them highly useful in medical and environmental applications. Moving forward, more work is needed to optimize the synthesis parameters for directed characteristics of the particle's parameters for specificity-directed antimicrobial applications. Live animal studies and full toxicity testing will need to be conducted to verify safety and effectiveness and get it ready for use in the clinic and on the market. Finally, plant-synthesized biometallic nanoparticles with metal oxide nanoparticles are a significant class of biometallic nanoparticles for the development of antimicrobial technology. Hence, the green synthesis, highly efficient antimicrobial activity, and general applications of a various range indicate that the compounds are valuable in the face of current and resistance against the few novel infectious germs; they are expected to play a role in keeping pace with public health and environmental sustainability.

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