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Green Synthesis of Metal Oxide Nanoparticles Using Plant Extracts and Their Applications in Antimicrobial and Environmental Remediation: A Sustainable Approach

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ARTICLE INFO	ABSTRACT
Submission: July 09, 2026 Revised: July 24, 2026 Accepted: August 08, 2026 Available Online: August 22, 2026 Keywords: <i>Green synthesis, Metal oxide nanoparticles, Phytochemicals, Antimicrobial activity, Environmental remediation</i> Corresponding author: Moazam Ali Email: moazamalidarban123@gmail.com	With this emerging need for materials that are environmentally friendly, sustainable synthesis methods that reduce the use of harmful chemicals, energy use and environmental impact have gained considerable interest. Thus, the ability to synthesize metal oxide nanoparticles by plants seems to be a green technology alternative to the traditional physical and chemical methods, but evidence is still weak on the phytochemical mechanisms underlying the synthesis of nanoparticles and their synergistic applications in antimicrobial activity and environmental remediation (Jadoun et al., 2021; Iravani, 2011). To critically examine the status quo of knowledge, this study used systematic review of peer-reviewed literature and thematic synthesis and qualitative content analysis to identify trends, mechanistic insights, technological advances and gaps in literature. The findings are that various phytochemicals from plants such as polyphenols, flavonoids, terpenoids, alkaloids, proteins and reducing sugars act in a synergistic way as reducing, stabilizing and capping agents, which allow a controlled synthesis of metal oxide nanoparticles with desired physicochemical properties. The surveyed evidence also confirms that these nanoparticles possess a wide spectrum antimicrobial activity attributed to the induction of oxidative stress, disruption of membrane and biomolecular damage inside the cells, along with the high potential for environmental remediation via photocatalytic degradation of organic contaminants, heavy metal adsorption and wastewater treatment (Ahmed et al., 2016; Khan et al., 2022). Plant-mediated synthesis approaches consistently show greater sustainability than conventional approaches, through decreased use of toxic reagents, lower energy consumption, increased biocompatibility, and by adhering to the principles of circular bioeconomy. The study contributes to the theoretical understanding by embedding the concepts and principles of green chemistry and nanotechnology together within a unified conceptual framework and offers practical inputs for the design of an eco-friendly, scalable-approach to the production of nanoparticles. However, the variability in plant metabolites, lack of process standardization, and lack of validation in the industrial scale are still important limits. Standardized synthesis methods, mechanistic molecular studies, life cycle analysis and pilot scale commercialization should be analyzed in future studies to facilitate sustainable implementation in the industry. Overall, plant-mediated green synthesis is a scientifically sound and eco-friendly route to obtain multifunctional metal oxide nanoparticles which can simultaneously combat antimicrobial resistance, environmental pollution, and promote sustainable nanotechnology.

Introduction

Nanotechnology is one of the most encouraging and promising sciences of the 21st century, which can offer solutions to old problems in various fields, including medicine, agriculture, the environment, energy and materials engineering. By manipulating matter at the nanoscale, nanomaterials have been developed that have properties that are altered and can be quite distinct from the bulk. Of these, metal oxide nanoparticles have been the focus of a great amount of scientific and industrial interest due to their unique catalytic properties, high surface area to volume ratio, tunable optical and electronic properties, chemical stability, and multifunctional properties. Metal oxide nanoparticles such as zinc oxide, titanium dioxide, iron oxide, copper oxide, magnesium oxide, cerium oxide, and nickel oxide nanoparticles have shown great promise in various applications, including biomedical, antimicrobial coatings, wastewater treatment, environmental monitoring, photocatalytic applications, renewable energy, and other uses (Khan et al., 2022; Singh et al., 2023). As the problems around the world concerning the pollutions of the environment and antimicrobial resistance are constantly growing, there is an increasing need for environment friendly methods to synthesize nanoparticles.

The rise of the significance of metal oxide nanoparticles is closely related with these unique characteristics and functions. The combination of small size, high surface reactivity, quantum confinement effects and catalytic efficiency result in better performance at the nanoscale than conventional materials. These properties have led to significant advances in biomedical diagnostics, targeted drug delivery, biosensing, antimicrobial formulations, food packaging, and technologies to remove toxic materials from the environment. In particular, the broad spectrum of antimicrobial activity exhibited by certain metal oxide nanoparticles has generated considerable interest in its potential for application as an alternative strategy for countering multi antibiotic resistant microorganisms, a major public health threat in the world today. At the same time, the photocatalytic and adsorption properties make these nanomaterials highly prospective in the degradation of persistent organic pollutants, the adsorption of heavy metals, and wastewater purification, which contributes to the efforts of achieving environmental sustainability and sustainable use of resources around the world (Sharma et al., 2022; Rai et al., 2023). Consequently, the synthesis area of metal oxide nanoparticles has received a huge boost in recent years, and nanotechnology is an important field of sustainable scientific and technological development.

Even though these great strides have been made, the synthesis method used in the production of nanoparticles is crucial for the determination of their physicochemical properties, biological effects and environmental compatibility as well as their commercial ability. The synthesis of the metal oxide nanoparticles has been accomplished in the past using physical and chemical methods such as chemical reduction, hydrothermal process, sol-gel process, microwave-assisted process, laser ablation, chemical vapor deposition, precipitation and combustion process. The highly effective strategies have enabled researchers to develop nanoparticles of specific dimensions, forms, crystallinity and composition, thereby advancing the application of these nanoparticles to multiple industrial fields. The benefits of traditional synthesis approaches, however, are becoming increasingly marred by major environmental, economic and toxicological issues. Many chemical synthesis routes employ toxic reducing agents, environmentally hazardous by-products, energy intensive reaction conditions, and toxic stabilizers; all of which are costly to manufacturing. Physical methods are generally complicated, require expensive instrumentation, high temperatures, high pressure, and may require high energy consumption which is not sustainable and scalable for environmentally friendly manufacturing (Iravani, 2011; Jadoun et al., 2021).

The study of the environmental impact of the production of the traditional NP has become a significant focus for Green Chemistry and Sustainable Development. Industrial pollution, climate change and resource depletion have created a need to use manufacturing processes that minimise waste generation, hazardous use of chemicals and maximise the efficiency of material use in the material life cycle. Conventional production methods for nanoparticles do not achieve these goals, because toxic chemicals may end up in the final nanoparticles or be released into the environment during the production or use/disposal of the materials. This form of contamination is a genuine concern for ecological toxicity, occupational health risks and environmental persistence. Also, high production energy use increases the operating costs and the greenhouse gas emissions of the innovations based on nanotechnology, thus reducing their sustainability. As a result, it is now gaining increasing awareness that new nanomaterials development should not only emphasize functionality, but also comply with internationally agreed guidelines of green chemistry, sustainable manufacturing and stewardship of the environment (Anastas & Warner, 1998; Hussain et al., 2023).

The need to develop environmentally friendly synthesis routes with the ability to generate high-quality nanoparticles, with less environmental or human health impact, has fueled the search for more environmentally friendly synthesis routes. The biological

utilization of nanoparticles, where biological materials are employed for the production of nanoparticles, is one of the most promising alternatives that could contribute to replacing the use of dangerous chemicals, using naturally-occurring reducing agents and stabilizing agents. Biological synthesis methods are microorganisms, algae, fungi, bacteria, yeast, and plants. In this list, plant-mediated synthesis has received special attention, due to its simplicity, the quickness of the reaction process, economic feasibility, scalability, avoidance of complex cultivation processes of microbes. Microbial synthesis is time-consuming, demands sterile conditions and requires purification at the downstream, while plant extract-mediated synthesis is simple, can be done under ambient conditions using easily-available botanical resources, which is particularly appealing for sustainable, large-scale production (Ahmed et al., 2016; Singh et al., 2023).

Plant extracts are complex biochemical systems which contain various secondary metabolites, which can be directly involved in the formation of nanoparticles. These are natural compounds that eliminate the need for synthetic reducing agents, while providing surface functionalization, thus increasing the stability of the nanoparticles. Therefore, the plant mediated synthesis not only reduces the environmental pollution but may also increase the biological compatibility of the synthesized nanoparticles, which can further increase the applicability of these nanoparticles in biomedical and environmental applications. In addition, the diversity of plants offers access to a huge library of phytochemicals that have structural diversity, allowing the ability to fine-tune the morphology, crystallinity, surface chemistry, and biological activity of nanoparticles. This biochemical diversity has attracted in-depth research in the different interdisciplinary fields such as nanotechnology, green chemistry and green materials science, and thereby, the development of sustainable nanotechnology as an emerging research field (Jadoun et al., 2021; Khan et al., 2022).

The phytochemical richness of botanical extracts is also well grounded in the science of synthesis of nanoparticles using plants. Plants have the ability to produce vast array of primary and secondary metabolites with various physiological and ecological roles and they also have high reducing and antioxidant capacities. Involvement of polyphenols, flavonoids, phenolic acids, tannins, terpenoids, alkaloids, proteins, amino acids, carbohydrates, organic acids, vitamins and reducing sugars have been reported in the bioreduction of metal ions to nano-sized metal oxide structures. These biomolecules donate electrons in redox reaction to reduce the metal ion precursors to stable nanoparticles, can be used as capping agents, stabilize the nanoparticles, and prevent further aggregation of the nanoparticles. Phytochemicals adsorption on the surface of nanoparticles also impose a significant effect on the physicochemical properties and functional performances of the resulting nanomaterials, which in turn affect the nucleus formation, growth of crystals, morphology, stability of dispersion, and surface reactivity (Hussain et al., 2023; Ahmed et al., 2016).

Although the general principles of phytochemical mediated synthesis of nanoparticles has become more familiar the exact mechanism by which this occurs remains not fully understood since each plant has different geographical origin, cultivation, extraction procedure and metabolites contained in the extract, thus there could be great variations between different plants in the process of the synthesis. The diverse phytochemical composition has a significant impact on reaction kinetics, yields of nanoparticles, size distribution of the nanoparticles, crystallinity and biological activity, which makes it difficult to be reproducible and to standardize the process. Although plenty of studies are available on the synthesis of metal oxide nanoparticles using plants, the trend observed in the various studies is inconsistent and is not directly correlated with plant phytochemical composition, synthesis conditions, the properties of the resultant nanoparticles and the efficacy as a specific application. Important challenges include the need to integrate knowledge within the fields of phytochemistry, reaction mechanisms and nano-material engineering to develop trustworthy, reproducible, and scalable green synthesis routes to satisfy both scientific and industrial requirements. This knowledge base will be an ever-evolving resource to study the potential of improving the properties of plant derived metal oxide nanoparticles for more advanced uses, such as in antimicrobial and environmental uses, but also in the rising trend of sustainable nanotechnology.

In recent years, the potential application scope for plant-mediated metal oxide nanoparticles has been greatly broadened from these mechanistic understanding, as green nanotechnology has advanced. Improvements in extraction procedures, optimization of precursors, reaction parameters and physicochemical characterisation have led to the generation of nanoparticles with improved stability and tunable morphology and application-specific functionalities. Advanced analytical methods such as X-ray diffraction, Fourier transform infrared spectroscopy, ultraviolet-visible spectroscopy, and scanning and transmission electron microscopy, dynamic light scattering, and energy-dispersive X-ray spectroscopy, have yielded more understanding of the mechanism of nanoparticle formation, crystallinity, elemental composition and functionalization of the surfaces. Such developments have bolstered the scientific confidence in the synthesis of plants as a reliable and environmentally friendly method

and enabled comparative studies of different plant species/techniques and synthesis methods (Khan et al., 2022; Sharma et al., 2022). Despite all of this, there are still methodological variations between the experiments and experiments in the design, the choice of precursors, the method of extraction, and the method of characterization, making it difficult to draw conclusions from one experiment to another and requiring greater methodological standardization.

With the increasing threat of antimicrobial resistance in the world, the antimicrobial activity of green-synthesized metal oxide nanoparticles (MONs) has been given a special emphasis among the many applications that are benefiting from green-synthesized MONs. The global spread of MDR bacteria, fungi and other pathogenic bacteria has rendered the efficacy of traditional antimicrobials ineffective, so there is a great need for novel therapeutic and preventive approaches. The plant mediated metal oxide nanoparticles are found to have the wide spectrum antimicrobial effect against Gram positive and Gram negative bacteria and various fungal pathogens. These mechanisms of action are not single but multiple, making it difficult for the microbes to get resistant to these nanoparticles, as compared with that with conventional antimicrobial compounds which only target a single pathway (Rai et al., 2023).

Currently, it is thought that the most significant properties that influence antimicrobial activity are size, high surface reactivity and the production of reactive oxygen species (ROS) by metal oxide nanoparticles. These are the Reactive Oxygen Species (ROS) which bring oxidative stress and destroy the microbial cell by triggering lipid peroxidation, protein denaturation, enzyme inactivation, damage to nucleic acids and disruption of essential metabolic pathways. At the same time, direct contacts between nanoparticles and cell membranes cause cell membrane permeability, destroy cell membrane integrity and bring about leakage of intracellular contents, resulting cell death. Additionally, some nanoparticles have the ability to transport metals that interfere with breathing functions and intercellular communication of microbes. Importantly, phytochemicals that are bound to the surface of the nanoparticles could have a synergistic effect, which may increase the antimicrobial activity as compared to their chemically synthesized counterparts and thus improve the biological activity of the nanoparticles (Singh et al., 2023; Hussain et al., 2023). The multi-functionality properties of the metal oxide nanoparticles derived from plants are suitable for use in antimicrobial coatings, wound dressings, biomedical devices, food packaging materials, water disinfection technologies, and drug formulations.

In addition to biomedical applications, plant mediated metal oxide nanoparticles have also proved to be tremendous potential to address global environmental issues that have been in existence for years because of industrialization, urbanization and increasing population. With the accelerated economic development, the amount of synthetic dyes, pharmaceutical residues, pesticides, heavy metals and other persistent organic compounds (POPs) has increased considerably and these hazardous substances are now being released into the aquatic and terrestrial environments. In traditional treatment technologies, the efficiency is low, the operation cost is high, or secondary pollution is generated, so it is necessary to pay attention to the selection of more environmentally-friendly treatment technologies. The high surface area to volume ratio, tunable electronic properties, and high catalytic activity make metal oxide nanoparticles (MONs) prepared by the green synthesis method ideal candidates for pollutant treatment, pollutant adsorptive capacity, and cleaning waste water (Sharma et al., 2022; Rai et al., 2023).

Among the most widely studied applications of metal oxide nanoparticles in the environment are photocatalysis. The electron-hole pairs created by light treatment of these nanoparticles (such as titanium dioxide and zinc oxide) can result in the generation of highly reactive oxygen species that can oxidize the complex organic pollutants into less harmful products. Many studies have shown that industrially used dyes, pharmaceutical contaminants, pesticides and endocrine disrupting compounds can be degraded efficiently by photocatalytic processes based on green synthesized nanoparticles. In addition, iron oxide, magnesium oxide, and other metal oxide nanoparticles have demonstrated great adsorption capacity for toxic metals like lead, cadmium, chromium, mercury, and arsenic, which promotes water quality and reduces environmental toxicity. Furthermore, in certain cases their magnetic property allows for effective recovery and re-use, thus making the remediation processes resource efficient and in line with the circular economy principles (Khan et al., 2022).

A critical literature review of field subject, that is modern literature, however, reveals some scientific and technological issues that are yet to be resolved. Although metal oxide nanoparticles synthesis has been reported using various plant species, the reported synthesis procedures vary greatly regarding the sources of plant materials, metal salt concentrations, extraction methods, reaction conditions, purification process and characterization techniques. The methodological variety makes it challenging to duplicate research and to make comparisons. Moreover, many published articles deal with the successful synthesis of nanoparticles, preliminary biological activity assessment, and overlook the study of the reduction, stabilization and

functionalization mechanism of nanoparticles with phytochemicals. As a result, there is still a lack of general understanding of the mechanisms, although experiments have been rapidly increasing.

One other major drawback is the connection between the diversity of phytochemicals and the performance of nanoparticles. Metabolite composition of various plant extracts is highly variable among different plant species, their geographical origin, season, environmental condition, cultivation methods and extraction techniques. There are comparatively few studies that systematically compared such variables, or established a standardized predictive framework, that can directly impact the size, morphology, crystallinity, surface chemistry and biological activity of nanoparticles. Similarly, few efforts have been made to optimize the process, to make it scalable across the process, to make it stable for long periods of time, to provide storage characteristics, to make it reproducible from batch to batch, and to ensure it is costable. Although promising laboratory results have been achieved, there is relatively less evidence of the commercialization and large-scale production, which requires interdisciplinary collaboration and cooperation between materials scientists, chemists, environmental engineers, microbiologists and industrial partners (Jadoun et al., 2021; Hussain et al., 2023).

Further, a large number of studies have been performed on antimicrobial applications and environmental applications individually with very few studies that have investigated both lines of research in a critical way from a sustainability perspective. Current reviews tend to focus on specific types of nanoparticles, plant species, single biological activities, or specific environmental applications, leading to the lack of broad knowledge and insight into plant-mediated metal oxide nanoparticle systems. Secondly, these synthesis pathways have been studied so far more from the narrow point of view of 'green chemistry', 'sustainable manufacturing' or 'life cycle assessment' and the 'circular bioeconomy' view has been comparatively little studied so far. Therefore, it is very much required to have a comprehensive synthesis that will critically discuss the mechanism(s) of phytochemicals, synthetic pathways to nanoparticles, antimicrobial activity, environmental remediation of contaminants, sustainability and potential future technological challenges in a single umbrella.

Hence, the present qualitative study is aimed to find out the gaps in the literature and to review and synthesize the literature in a systematic and critical manner on production of metal oxide nanoparticles using plant extracts. The study brings scientific evidence into its scope that has already been published, using qualitative content analysis and thematic synthesis to explore the phytochemical processes involved in the formation of nanoparticles, review of latest developments in synthesis techniques and their application in antimicrobial activity and environmental remediation. Instead of just sharing the isolated experimental results, this review aims to provide an integrated viewpoint of the role that biological resources, nanotechnology and green chemistry play together in the context of developing sustainable materials.

This study aims primarily to review critically the scientific development, developmental trends, opportunities and challenges of synthesis of metal oxide nanoparticles utilizing plants. The study focuses in particular on the phytochemical aspects related to the formation of nanoparticles, in comparison to the sustainability of the green synthesis with the traditional physical and chemical processes, as well as on the analysis of the existing literature on their antimicrobial applications and applications for environmental remediation, highlighting the remaining methodologic, mechanistic and translation challenges and suggesting future research priorities that open the way to sustainable nanotechnology. So, the study research questions are: What are the roles of phytochemicals of plants in the synthesis and stabilization of Metal oxide Nanoparticles? What is the crucial advantage of the plant-mediated synthesis over the usual synthesis methods? (3) What is their performance as antimicrobial agent and environmental remediation materials when synthesized by green route and (4) what are the scientific, technological and industrial problems which need to be solved for their sustainable application in large scale?

This study has implications more than just compendiousness of literature review. It has an interdisciplinary approach that aims to synthesize the advances made by nanotechnology, green and phytochemistry sciences, environmental sciences and materials engineering in order to allow interdisciplinary research and future evidence-based technological innovation. The review also contributes to the theory and conceptual development, by consolidating and organizing the isolated mechanistic information in a coherent conceptual landscape, which provides a description of the mechanisms of plant phytochemicals and their relationship to the mechanism of nanoparticles. On the practical side, it offers researchers, industrial practitioners, and policy makers a critical assessment of sustainable synthesis strategies that can enable feasible production of nanomaterials that are not harmful to the environment, but are beneficial to medical, environmental, and sustainable manufacturing applications.

The rest of this article is structured in a systematic way to review the existing knowledge in a critical manner. The methodology outlines the approach and qualitative analysis adopted in the evidence synthesis. The critical discussion of the phytochemical mechanisms, green synthesis processes, antimicrobial applications, and environmental remediation technologies is also included, and the emerging challenges, future research directions and implications of sustainable nanotechnology are discussed. In general, the article has demonstrated that the route of the synthesis of metal oxide nanoparticles via plants is a proper and environmentally friendly path to the development of multifunctional nanomaterials with potential applications to address some of the most pressing biomedical and environmental challenges of the present day.

Literature Review

The progress of nanotechnology is so rapid that functional materials for medical, agricultural, environmental engineering, electronic and energy systems are being produced. The metal oxide nanoparticles are the engineered nanomaterials which have been attracting a continuous research interest since they possess peculiar physicochemical properties like high surface area/volume ratio, high catalytic activity, tunable optical properties and extraordinary chemical stability. The properties make the metal oxide nanoparticles suitable to antimicrobial formulations, biosensing, photocatalysis, wastewater treatment and environmental monitoring applications. Therefore, the focus is now shifting towards the more effective ways of improving the performance of nanoparticles, while simultaneously taking into account their environmental sustainability and cost effectiveness of their synthesis procedures (Khan et al., 2022; Singh et al., 2023). The transition is a general shift from the old nanotechnology towards green nanotechnology, which is the innovation of materials in the green and sustainable development perspective.

GREEN NANOTECHNOLOGY is based on the principles of green chemistry and sustainable engineering that is developing of materials and processes with minimal or no use of toxic chemicals, energy consumption and waste over the entire life of the product (Anastas & Warner, 1998). In the sense of green nanotechnology, the environmental issues are not a second consideration, but a part of the design of the materials from the design of the precursor materials to its disposal at the end of life. Functional properties are not the only properties that will determine the future competitiveness of nanotechnology; recent studies show that the sustainability of nanomaterials' manufacturing processes will also play a role (Jadoun et al., 2021). In this context, the purely environmental-friendly synthesis pathways become more and more relevant to guarantee the sustainability of nanotechnology in industrial and biomedical applications.

The traditional synthesis method for metal oxide nanoparticles has contributed greatly to the development of science by enabling scientists to manipulate the size, crystallinity and shape of the nanoparticles. They are still used as of this writing, many of them re-usable and have the advantages of being scalable such as sol-gel processing, hydrothermal synthesis, chemical reduction, precipitation, thermal decomposition and chemical vapor deposition. However, it is well established in the literature that there are important shortcomings of these approaches. The conventional methods of synthesis involve the use of dangerous reducing agents, toxic organic solvents, costly instrumentation, high temperature and/or high pressure, making the production process costly and environmentally harmful (Irvani, 2011). Furthermore, the generation of toxic chemicals and the consumption of a lot of energy are not compatible with sustainable manufacturing or green chemistry. Some studies have suggested that conventional techniques still provide better control of the characteristics of nanoparticles, but more and more scientists are saying that these benefits should be considered in addition to the environmental and human health impacts of the technology.

Hence, the green synthesis has been in demand because of the need to reconcile the production of nanoparticles with protecting the environment. In green synthesis, the biological resources are employed as a reducing and stabilizing agent, and are made from renewable resources, rather than synthetic chemicals. Though bacteria, fungi, algae, yeast and plant extracts have been tried for biological synthesis, the plant-mediated method is the most widely explored method due to its simplicity, rapid reaction rate, cost effectiveness and scalability (Ahmed et al., 2016). Compared to microbial synthesis, plant-based technologies are suitable for large-scale production, because they don't demand highly strict sterile conditions or long culture processes. Therefore, the synthesis using plant becomes more and more accepted as a sustainable industrial production alternative to innovation in the laboratory and has been investigated recently.

Although it is accepted that green synthesis is environmentally friendly, the nanoparticles' properties and characteristics that can be achieved by this method is still a topic of discussion. Depending on the differences observed among various plant species, extraction techniques, precursor concentration and reaction conditions, some studies reported excellent control of the morphology and stability of particles, whereas others reported that particle morphology and particle stability varies widely

(Jadoun et al., 2021; Hussain et al., 2023). This is a result of the fact that green synthesis is not a panacea for the generic synthetic methods, but is an emerging science, which requires more knowledge of the mechanistic aspects and more process standardization.

The diversity in phytochemicals present in plant extracts, which are extracted during the synthesis through the process of plant mediated synthesis, is one of the most important characteristics of plant mediated synthesis. In plants, there are many primary and secondary metabolites which actively take part in the process of the formation of nanoparticles in plants by reduction, stabilization and capping. Polyphenols, flavonoids, terpenoids, alkaloids, tannins, phenolic acids, proteins, amino acids, carbohydrates and reducing sugars are some of the most important components that have been identified as being responsible for the synthesis of nanoparticles (Ahmed et al., 2016). The functional groups present in these compounds can donate electrons to metal ions thereby starting reduction reactions and causing the formation of nuclei and then growth of nanoparticles. At the same time, many phytochemicals tend to attach to the surfaces of nanoparticles, to prevent excessive aggregation, and to enhance the colloidal stability and biological compatibility.

While most of the researchers have agreed that phytochemicals play role in the synthesis of nanoparticles, the route through which synthesis of nanoparticles is achieved in the presence of these phytochemicals is still partially unclear. Currently, it is known that multiple simultaneous biochemical reactions occur in the production of nanoparticles and not one single universal pathway. The importance of the individual phytochemicals will differ depending on the individual plant species, concentration of metabolites, extraction solvent, pH, temperature, precursor chemistry, reaction time. On this basis, the synthesis conditions are frequently different, leading to nanoparticles with very distinct physicochemical properties when different plant extracts are used. In light of this observation, there is a rising interest in exploring the linkage between the phytochemical composition and the performance of the nanoparticles, by employing advanced metabolomic and spectroscopic analysis (Khan et al., 2022). Existing work, however, focuses mainly on successful synthesis and not on systematic identification of the metabolites that lead to reduction and stabilization which are of interest in terms of mechanisms.

Another literature source suggests that the synthesis of nanoparticles can be better characterized as a dynamic process, consisting of four steps—nucleation, crystal growth, stabilization and surface functionalization. Phytochemicals are oxidized to form reactive intermediates that condense to form stable nuclei in the early stages. Controlled crystal growth takes place when the growth of the particles occurs by the addition of further reduced species on nuclei and when capping molecules prevent the uncontrolled aggregation of particles. The final surface chemistry of nanoparticles is thus not only determined by the metal precursor and the phytochemical composition of the extract in the surroundings of nanoparticles is also a factor. Beyond the synthetic benefit, phytochemical diversity could be an additional functional variable to consider when bound to the surface, as it may potentially impact catalytic activity, antimicrobial properties, dispersibility and interactions with the environment (Singh et al., 2023). Few comparative studies, however, have been performed to quantify the impact of each type of phytochemical on each of these processes in a wide variety of metal oxide systems.

Another common thread in the literature recently is that of factors that affect the properties of nanoparticles. The reaction conditions influence the particle size, shape, crystallinity, surface charge, stability and capability to be used as a catalyst. Various factors such as concentration of the precursors, concentration of the extracts, pH, reaction temperature, reaction time, mixing rate, and calcination conditions are known to influence the characteristics of the nanoparticles. For example, alkaline conditions may increase the reduction rate of the ions while high temperature may increase the nucleation rate of particles, which may also increase the aggregation rate of the particles. Similarly, high levels of the precursors may result in abnormal shapes and the low levels of the phytochemicals may result in lower synthesis efficiency. Although these relations are well known, the consistency of reporting of all trends is not necessarily observed in all studies because of the very great differences in the biochemical composition of plant extracts. Thus it would be unrealistic to apply optimization technique that has been used for specific plants to other species of plants, and a uniform experimental design is important.

Another area of variability is plant selection. All the above-mentioned parts of various plants have been used with great success to prepare metal oxide nanoparticles. Considering that medicinal plants contain high level of antioxidants, they can thus contain nanoparticles with high biological activity, as stated by many researchers. In contrast, the research on agricultural waste is concerned with the economic aspects and resource recovery of circular bioeconomy. Different opinions are given on the selection of plants, meaning that apart from the synthesis efficiency, the sustainability goals, resources and final use should also impact on

the selection of plants. Comparative studies, however, that compare several species directly by the same experimental techniques, are comparatively few and you don't know which plant species are best overall.

Fully comprehensive characterization of nanoparticles is also critical for the trustworthiness of green synthesis research. To confirm successful formation of nanoparticles and to define relationships between the synthesis condition and the properties of the material, the accurate characterization is important. X-ray diffraction is the most common analytical method used to identify the crystal structure and the purity of the crystal phase while Fourier transform infrared (FTIR) spectroscopy is used for identification of functional groups of the phytochemical capping agents. These images of the morphology and size distribution of the resultant nanoparticles are obtained by scanning electron microscopy (SEM) and transmission electron microscopy (TEM), respectively, with UV-visible spectroscopy providing a quick detection of nanoparticles (based on their characteristic absorption spectra). Dynamic light scattering and zeta potential measurement are used to evaluate particle dispersion and the colloidal stability of the particle dispersion, respectively, and EDXRF analysis is further verified by energy dispersive X-ray spectroscopy. Together, these methods yield complementary information to result in greater confidence that synthesis outcomes have been reported.

While the techniques of characterization have become more refined over the years, as pointed out in the more recent literature, the reporting of the characterization has varied considerably. Some investigations use more than one complementary technique which allows a holistic investigation of properties of the nanoparticles, while others only use one or two analytical techniques and thus the conclusions drawn may be less valid. Moreover, the particle size obtained by electron microscopy and the hydrodynamic diameter obtained by dynamic light scattering is different, due to the different physical properties measured by each technique. The methodological differences prevent comparison between studies and make it difficult to understand the performance of nanoparticles. This resulted in several reviews which propose a standardisation of characterization protocols for enhanced reproducibility and meaningful comparison of various green synthesis studies (Jadoun et al., 2021).

With recent development in green synthesis, the diversity of metal oxide nanoparticles synthesized by plant extract has also increased. Zinc oxide nanoparticles are one of the most-investigated and studied nanoparticles due to their antimicrobial, ultraviolet absorption and photocatalytic activity. The photocatalytic activity of titanium dioxide nanoparticles under the light makes them promising materials in the field of environmental cleaning, where they are still under intense research. The use of iron oxide nanoparticles has found specific applications in the treatment of wastewater owing to their adsorption capacity and magnetic recoverability, and copper oxide, magnesium oxide, cerium oxide, and nickel oxide nanoparticles have exhibited promising applications in antimicrobial technologies, catalysis and environmental engineering (Khan et al., 2022; Rai et al., 2023). These studies taken together demonstrate the versatility of plant-mediated synthesis; however, there are not many direct comparative tests of different metal oxide systems and so can help to establish general design principles.

Overall, modern literatures indicate that the green synthesis has evolved from its infancy to a scientific valid, sustainable and rapidly emerging field of nanotechnology. The plant mediated synthesis and the key role of phytochemicals in the synthesis of nanoparticles has been strongly agreed upon. However, there are still substantial differences with respect to the mechanism, replicability of the process, optimization and industrial scale-up. The problems still to be solved suggest that additional progress will depend on both the discovery of additional plant resources and on mechanistic understanding, methodological standardization and interdisciplinary integration. Based on this, the following will summarize the applications of plant mediated metal oxide nanoparticles in antimicrobial technologies and environmental cleanup, and critically discuss the benefits and constraints, and the future prospects of the research.

Based on the mechanistic and physicochemical aspects mentioned above, recent literature highlights the potential application of metal oxide nanoparticles in solving two global issues such as antimicrobial resistance and environmental pollution by harnessing their practical applications in plants. While these applications have been investigated individually in the past, recent investigations reveal that they have some important common properties of nanoparticles such as high surface reactivity, tunable morphology, catalytic activity, surface residues of bioactive phytochemicals. Thus, a more holistic view of the application of green-synthesised nanoparticles is emerging that sees them as multifunctional materials that can contribute to biomedical innovation and environmental sustainability (Rai et al., 2023; Singh et al., 2023).

Increasingly, conventional antibiotics have failed to have enough effect on multidrug-resistant microorganisms and antimicrobial activity has been the most studied field of application. With the increasing spread of antimicrobial resistance, researchers are

looking for new antimicrobial agents which have the ability to circumvent resistance mechanisms without being toxic to the host organism. In this context, green-synthesized metal oxide nanoparticles has showing a good potential to combat various Gram-positive and Gram negative bacteria and several pathogenic fungi. Conventional antimicrobial agents are known to target specific biochemical pathways while the metal oxide nanoparticles are known to target multiple biochemical pathways simultaneously, reducing the chances of antimicrobial resistance (Hussain et al., 2023).

A variety of complementary mechanisms have been reported in the literature that account for the antimicrobial effect of metal oxide nanoparticles. Generation of ROS such as hydroxyl radical, superoxide radical and hydrogen peroxide which leads to the development of oxidative stress in microbial cells is one of the most accepted mechanism. Oxidative stress can cause damage to membranes, proteins, the nucleic acids, impair enzymatic activity, and cause irreversible cell damage. Moreover, nanoparticles have the ability to directly interact with cell membrane of microbes, disrupting the cell membrane making it hyper-permeable and leaking intracellular contents. Some metal oxide nanocrystals are also known to release metal ions which disrupt metabolic regulation, protein synthesis and respiration. The antimicrobial activity they can exert is actually more complex than the activity of conventional antimicrobial agents, and this is the reason why in general the antimicrobial activity of nanoparticles is more resistant to microbial resistance to the drug. (Khan et al., 2022; Rai et al., 2023).

While there is general consensus that these mechanisms are involved, there are discrepancies on the relative importance of each mechanism. The killing mechanism of microorganisms is still a subject of controversy. Some studies showed that ROS production is the main antimicrobial mechanism, while others highlighted that the mechanism of action of the NP, depending on its composition, particle size, microbial species and experimental conditions, is membrane disruption or ion release. The differences indicate that there is no single universal mechanism for the antimicrobial activity. Rather, biological responses seem to be a function of the dynamic interplay of the physicochemical properties of the nanoparticles, microbial physiology, and environmental conditions. This is reflected in the requirement for greater standardisation of experimental designs and mechanistic studies designed to deconvolve the contributions of each antimicrobial pathway.

The ability of the phytochemical capping agents as antimicrobial properties is also a new trend. The advantage of biomediated nanoparticles is that unlike chemically synthesized nanoparticles, they are coated with biomolecules from the plants used to synthesize them, which can give the nanoparticles additional antimicrobial and/or antioxidant properties. Researchers have suggested that the surfaces of nanoparticles can be modified with phytochemicals so that they can interact with microbial membrane at a greater level to provide additional stability and dispersibility to the nanoparticles. There is, however, no definite evidence available at present, which is owed to the fact that there are relatively few studies, where capped and uncapped nanoparticles have been prepared under identical experimental conditions. Thus, the synergistic effect of phytochemicals and metal oxide nanoparticles is an interesting research field, deserving further work.

The applications of green synthesized metal oxide nanoparticles is not restricted to antimicrobial assays and more agricultural applications are to be explored. They have recently been reported in biomedical devices, as a coating for implants, as a component of wound dressings, as a coating in food packaging materials, as a component in water disinfection systems and as a coating for textiles. In these uses, nanoparticles can offer extended antiseptic activity, and minimize the need for standard antibiotics and chemical disinfectants. Relatively less information is available, however, on long-term clinical outcomes, cytotoxicity, regulatory approval routes and commercialization of these promising laboratory results. Finally, although the antimicrobial activity of the green synthesized nanoparticles has already been reported experimentally, there is a need for more interdisciplinary studies involving nanotechnology, microbiology, toxicology, and biomedical engineering to be able to use these nanoparticles successfully in the healthcare industry.

Environmental remediation is one of the new fields of contemporary green nanotechnology research along with antimicrobial uses. Water, soil and air pollution due to artificial dyes, pharmaceutical residues, pesticides, heavy metals and other long-term contaminants has grown as a result of fast industrialization and urbanization. Chemical treatments impart secondary pollution and traditional remediation technologies are very expensive to operate, and do not remove all contaminants. As a result, researchers have started to look at nanotechnology-derived remediation strategies that can aid in improving the efficiency of remediation and mitigate environmental impacts (Sharma et al., 2022).

Of all these approaches, photocatalytic degradation has garnered special interest due to the excellent catalytic activity of several metal oxide nanoparticles. These nanoparticles (such as TiO_2 and ZnO) form electron-hole pairs, that then become attracted to the

water and oxygen molecules and generate highly reactive oxygen species (ROS) upon the exposure of UV or visible light. They break down complex organic compounds to simpler and relatively harmless products, thereby breaking industrial dyes, pharmaceuticals, pesticides and other toxic substances. Numerous studies have been found to be consistently photocatalytic efficiency at least equal to nanoparticles made by the conventional technique. Phytochemical capping is often believed to be responsible for this performance due to the reduction in particle size, their increased functionalization, and dispersion (Singh et al., 2023).

Another area of research is surfacing for the treatment of heavy metals. The surface area and active adsorption sites of Iron oxide, Magnesium oxide, Zinc oxide and Cerium oxide nanoparticles is very large; hence they are very effective in binding the toxic metal ions such as Lead, Cadmium, Chromium, Mercury and Arsenic. It is said that these contaminants are removed efficiently from the water environment by adsorption, ion exchange or surface complexation process. The magnetic separation process is also used for efficient post-treatment recovery and re-use, increasing the economic viability and the environmental sustainability of magnetic nanoparticles, like magnetic iron oxide nanoparticles. Remediation performance in controlled laboratory environments may, however, not be directly applicable to natural environments, as several environmental parameters, including pH, competitive ions, pollutant concentration, temperature and stability of the nanoparticles, are known to affect the adsorption efficiency.

The literature indicates, however, that there are many caveats to be mentioned, but the evidence supporting environmental applications is promising. Many remediation studies have been conducted with wastewater containing a single contaminant rather than multi-contaminants in wastewater of a complex nature that interact with one another. Therefore, reported treatment efficiencies in the lab may actually be more than would be in the field. Similarly, attention has been limited to the recovery of the nanoparticles, the long term stability of the recovered nanoparticles, the ability to regenerate them and the fate of the nanoparticles following remediation in the environment. Although green synthesis would minimize the use of toxic chemicals in the production process, larger-scale production of nanoparticles and their potential for release into the aquatic and terrestrial environments should be considered. Such worries have resulted in an increasing need for a more comprehensive assessment of the ecotoxicological and life cycle impacts that can quantify the overall sustainability of remediation systems using nanotechnology.

Comparative study of plant mediated and conventional synthesis method reveals that there is a general consensus towards the merits of plant mediated synthesis over the conventional method from an environmental point of view, though there are some reservations. Green synthesis methods always lead to the minimization of harmful chemical use, energy consumption, use of renewable biological materials, and sometimes even improve the biocompatibility of the nanoparticles. Furthermore, plant extracts are widely available, readily accessible and inexpensive and can be utilized for sustainable manufacturing. For more specialised industrial applications, however, the crystallinity, morphology, purity and reproducibility of the nanoparticles is desirable and can be better controlled by traditional physical and chemical synthesis methods. The literature was largely dominated by the concept of competing green and conventional approaches in the past, but recent literature is proponents of the complementary use of green and conventional approach, i.e., depending on the context and requirements of the application.

Another important issue emerging from recent research and discussion on the inclusion of “green synthesis” in other sustainability frameworks. As of recently, the concept of green nanotechnology is becoming more in line with the principles of green chemistry, which focus on waste prevention, sustainable feedstocks, safer chemical design, energy conservation, and diminished environmental toxicity (Anastas & Warner, 1998). Furthermore, other biomass wastes, such as agricultural wastes, fruit peels, waste from medicinal plants and other wastes, also support the ideals of the circular bioeconomy, turning waste into valuable nanomaterials. These practices include measures to reduce waste, as well as sustainable use of resources and the creation of new economic opportunities. A few studies however using standardised life cycle assessment methods quantify the sustainability benefits. That is, many environmental claims are not substantiated but only qualitative.

A literature review also brings up problems with plant mediated synthesis in scientific and technological research that has prevented its widespread use. One of the most important concerns is process reproducibility as the phytochemical composition is dependent on the plant species, geographical origin, climatic conditions, seasonal variation, cultivation practices and extraction processes. The differences are directly reflected on the size, shape, crystallinity, surface chemistry and biological activity of the nanoparticles and rules for universally applicable synthesis protocols are difficult to determine. In a similar way, batch to batch variation is a significant challenge for the industrial production, quality control and regulatory approval. Several of the

researchers therefore stress the need for optimized reaction conditions and internationally accepted characterization protocols, in order to obtain enhanced reproducibility of the extraction of THPs (Jadoun et al., 2021).

An issue that has yet to be discussed is the understanding of mechanisms. Phytochemicals are generally known to be reducing and stabilizing agents but surprisingly few studies systematically characterize the phytometabolites that form nanoparticles. Most investigations are conducted with total plant extract (i.e., on phytochemicals collectively), rather than using individual phytochemicals, limiting our understanding of molecular interactions for nucleation and growth of nanoparticles. The knowledge gaps could be satisfied by the development of metabolomics, computational chemistry, molecular spectroscopy and AI assisted reaction modelling techniques.

Despite many experimental studies that have been performed in the lab, there is only limited industrial translation. Large-scale production requires quality of the raw material, the reproducibility of the synthesis, economic viability, regulatory compliance and full safety evaluation. Furthermore, there is a need for more long term stability, purification of the nanoparticles, optimization and scalability of the manufacturing process. This will involve working across disciplines from chemists to materials scientists, to engineers, environmental researchers, microbiologists, industrial manufacturers and regulatory agencies in an effort to bridge the gap between experimental research and commercial implementation.

There are important potential scientific advances, but also some areas of critical research need, indicated in the literature. Comparative studies with standardised experimental designs, mechanistic studies of correlation between phytochemicals and functionality of the nanoparticles, comprehensive toxicological studies, industrial scale validation studies and life cycle sustainability studies should be emphasized. Multifunctional nanoparticles to be used in antimicrobial, catalytic, sensing and environmental applications will also be investigated in future, to maximise the practical applications of green nanotechnology. Rapid synthesis optimization, increased reproducibility are other promises afforded by the use of machine learning, computational modelling and advanced characterization techniques.

Based on the present literature, it is concluded that the plant mediated green synthesis is a scientific approach and environment friendly technique for the preparation of metal oxide nanoparticles for various biomedical and environmental applications. There is still a lot of methodological diversity, lack of understanding of the mechanisms and translation of the field to the industry, however. Interdisciplinary and standardized research will be required to provide answers to these unanswered questions in order to achieve the potential of sustainable nanotechnology. The overall objective of the present qualitative review is to discuss the current knowledge in a critical synthesis, provide an identification of the points of consensus and disagreement, and indicate a way forward for future research that can contribute to scientific research and practical applications of green-synthesized metal oxide nanoparticles.

Research Methodology

This study used an interpretivist position that views scientific knowledge of green synthesis of metal oxide nanoparticles as a constant process of the interpretation, comparison and critical analysis of previously published work instead of new experimental work. The interpretivist approach is particularly appropriate to QES because it enables a "theory of change," "methodology of change" and "scientific conversation" to be fully understood in fields that are interdisciplinary, such as nanotechnology, green chemistry, materials science, and environmental sustainability (Lincoln & Guba, 1985; Creswell & Poth, 2018). This study was conducted to critically review and collect available literature to identify the patterns, consensus, conflicts, trends and gaps in the research fields of plant mediated synthesis of metal oxide nanoparticles and their applications in antimicrobial and environmental applications.

Therefore, for this study, a qualitative research design using a systematic literature review was used. A systematic review is a systematic, comprehensive and transparent process to identify, evaluate and synthesize published evidence performed with minimal selection bias (Page et al., 2021). Narrative review can be unsystematic as far as article selection but systematic review approach has pre-established processes to identify and screen literature, assess eligibility, and synthesize evidence. Considering the huge number of publications about the green synthesis of nanoparticles, it was deemed suitable to create a comprehensive and balanced overview of the status of the art and critically assess the methodological advantages and disadvantages of the various published works.

The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 statement, which contains internationally agreed upon guidelines for systematic reviews and meta-analyses, was followed for the review process, as appropriate (Page et al., 2021). The principles of PRISMA were developed for use in research in healthcare, but have been adopted by scientific professions for use in the field of scientific communication, to improve methodological transparency in evidence synthesis. The review was systematic and the main steps of the literature search (literature identification and screening, eligibility assessment and inclusion of relevant literature, and analysis) were documented.

A thorough literature review was carried out by searching internationally known scientific databases which index high quality peer-reviewed publications in the fields of nanotechnology, materials science, chemistry, environmental science and biomedical science. The databases that have been searched are: Scopus, Web of Science Core Collection, ScienceDirect, SpringerLink, Wiley Online Library and PubMed. The selection of these databases is based on the fact that they span a long time and have become very popular for indexing high impact scientific literature, which is peer-reviewed. To make sure that pertinent studies were not overlooked in the initial electronic database search, a follow-up cross-reference of the relevant review articles and reference lists was done, followed by the cross-reference of each of the original search results. To avoid missing pertinent studies, a follow-up cross-reference of the relevant review articles and reference lists was performed, followed by cross-reference of each of the original search results. The supplementary searching was used to make sure that all seminal publications were covered and that the chance of omitting highly relevant publications was minimised.

To maximize relevant publications retrieved, combinations of carefully selected words/phrases were used in conjunction with Boolean operators in a literature search. The keywords used for primary search were "green synthesis," "plant-mediated synthesis," "plant extracts," "metal oxide nanoparticles," "phytochemicals," "nanotechnology," "green nanotechnology," "antimicrobial activity," "antibacterial," "antifungal," "environmental remediation," "photocatalysis," "wastewater treatment," "heavy metal removal," "green chemistry," and "sustainable nanotechnology. In the database, Boolean logic (AND, OR) was used to broaden and/or narrow search results, as necessary. Several variations of the search were attempted, with the aim of making the search more sensitive, but without making the number of potentially relevant interdisciplinary studies too large to be excluded.

Studies published primarily between 2020 and 2026 were included in the publication period to reflect the latest advances in science and to acknowledge the pioneering studies. This time interval was selected because in the last few years, there have been considerable advances in the synthesis of nanoparticles by plants, in the sustainable production of nanotechnology, and in the use of nanotechnology for environmental applications. However, seminal publications which would be identified as relevant before 2020 but which are still relevant to current research were also included. In order to keep the review as recent as possible and grant the synthesis the proper orientation in current research, only the more recent literature was reviewed, while at the same time enough background was given.

Explicit inclusion and exclusion criteria were formulated prior to study selection to improve the transparency and reduce the selection bias. The studies were selected when they were published in peer-reviewed journals with Scopus or Web of Science database, they were written in English, and the use of plant extracts in green synthesis of metal oxide nanoparticles or study their antimicrobial, environmental remediation, physicochemical and sustainability related applications were directly related. Articles of original research and review papers that provided significant theoretical or empirical contribution that related to the aims of this review were considered. On the other hand, abstracts, editorials, opinion articles, book chapters, theses, patents, duplicate publications, and studies that were not detailed enough in methodology were not included. However, the publications which were exclusively chemically synthesized nanoparticles, microbial synthesis without the use of plant materials, and nanomaterials which were not related to metal oxides were not included as they were outside the scope of the present review.

Selection of studies was done in a systematic multistage screening process. The titles and abstracts obtained from the electronic databases were initially screened to identify publications that were clearly irrelevant, and to eliminate duplicate publications. The other studies were then subsequently assessed for full-text to see if they met the set inclusion/exclusion criteria. This stage resulted in discussions about the role of each publication in the plant-mediated synthesis mechanisms, phytochemical interaction, characterization of nanoparticles, antimicrobial usage, environmental remediation, sustainability and methodological quality. Studies that met all the eligibility criteria were subjected to qualitative synthesis and publications that failed to meet the selection criteria were excluded following systematic evaluation.

Data extraction was done qualitatively in a standardised way to have uniformity among the studies included. The necessary information was extracted from each publication including author(s), year of publication, country of study, plant species used, metal oxide nanoparticles synthesized, method of synthesis, phytochemicals used in the synthesis, characterization technique(s), main application, reported benefits, reported limitations, and main conclusions. Additional information on methodological strategies, on perspectives from sustainability, on mechanistic insights and future research ideas was also gathered. The information extracted was put into conceptual categories rather than compile quantitative data for analysis.

During the appraisal of the evidences, a methodological quality appraisal has been performed, to increase the credibility of the review. It is noteworthy that in interdisciplinary scientific subjects, qualitative systematic review often use flexible appraisal methods, and in this review some quality indicators were identified and used to critically assess the studies included: clarity of research objectives, transparency of synthesis methodology, adequacy of characterization of nanoparticles, consistency of experimental procedures, validity of interpretations, relevance of the study to the review objectives, and overall scientific rigor. Special effort was made on publications in peer-reviewed journals that have good impact and reputation in the field of nanotechnology, materials science, environmental science and green chemistry. In the evidence synthesis, studies that reported low quality methodology or did not provide results with supporting evidence were evaluated with caution.

The literature was analyzed by the qualitative thematic synthesis which was supported with qualitative content analysis. Thematic synthesis is a methodical process for recognizing common ideas, patterns and relationships in several studies and for interpreting the ideas that go beyond the findings of individual studies (Thomas & Harden, 2008). Initially publications were read multiple times to become accustomed with their theory, techniques and primary results. Subsequently conceptual similarity was used to code meaningful portions of text that were congruent with the review objectives. These related codes were then organized into larger analytical themes which are representative of the main scientific fields of interest such as the theoretical foundations of green nanotechnology, phytochemical mechanisms, synthesis processes, characterization methods, antimicrobial applications, environmental remediation, sustainability perspectives, methodological challenges and future research priorities. Comparisons were performed throughout the analytical process to identify consensus, conflict, and/or changing consensus and remaining scientific uncertainties.

Qualitative content analysis was used in tandem with thematic synthesis to aid the systematic understanding of common scientific themes, and to retain the context of individual studies. The analysis was not simple or straightforward to produce a report of published results, but focussed on critical comparison of method, theory and conclusions published. Specific attention was paid to the relation between the phytochemical composition, synthesis parameters, properties of the nanoparticles and their specific performance in applications. This analytical approach proved useful in the conceptualization of the overall plant mediated metal oxide nanoparticles synthesis process and also helped to look for discrepancies and further investigation.

The integrative narrative approach for data synthesis involved comparing, interpreting and synthesizing data with regard to their relevance to the individual studies to thematic discussions. This was not just about reporting single experimental results but more about the similarities and differences, advances in concepts and gaps in research were highlighted. Competing results were compared with the different species of plants used, synthesis processes, composition of nanoparticles, analytical techniques and application. This comparative synthesis allowed for greater conclusions of the state of the knowledge while not overgeneralizing on individual investigations.

Ethical issues were taken care of through responsible conduct of secondary research. No human participants, experimental animals, or primary data collection took place in this study, and so formal ethical approval was not required. During the review, though, ethical issues relating to integrity in academic work, to representing findings from other people's published works and to acknowledging others' intellectual contributions and avoiding plagiarism were respected. These all were interpreted based on the published evidence and have been backed up by the appropriate APA 7th edition in-text citations.

The qualitative trustworthiness criteria that were developed by Lincoln and Guba (1985) were used to enhance methodological rigor. The credibility was strengthened by the wide search in the databases, the inclusion of all the studies that met the inclusion criteria, as well as the critical analysis of several studies and the systematic thematic analysis of the selected studies. The dependability was supported by predefined review procedures and the clearly documented inclusion criteria, whilst the analysis could be reproduced by future research. Confirmability was encouraged by the evidence based interpretation that was based on published literature and not on the assumption of the researcher or their own biases. Studies were selected to facilitate

transferability that encompassed studies from a wide range of application contexts, the use of different types of nanoparticles and plant species that allowed for conceptually broader applicability of the conclusions drawn from the studies, but also recognized the contextual differences among individual studies.

But there are several methodological issues of interest. This review may have limited the evidence found to the English-language peer-review publications, which could have resulted in the loss of other relevant evidence being published in other languages. Some differences were also found in methodology, plants studied, characterization methods, and reporting formats for the primary studies, making it difficult to compare across studies. Furthermore, there may be publication bias, that is studies that did not synthesize the nanoparticles or that the application did not produce a positive result may have been missed. Due to the qualitative nature of the review, also no statistical meta analyses or quantitative estimation of effect sizes could be performed, which also meant that the conceptual interpretation of the reviews would be more important than the numerical interpretation.

Findings and Discussion

The information given in this review has been gathered from the latest peer reviewed research articles, which have been published in the field of green synthesis of metal oxide nanoparticles (MONPs) using plant extracts. This section does not include primary experimental results but rather presents the results of studies published the last 6 years (2020-2026), including seminal works that provided the theoretical and mechanistic foundations for green nanotechnology. The plant mediated synthesis is developed and a promising method for synthesis of nanoparticles with wide biomedical and environmental application which is an environment friendly which is shown in thematic synthesis. The following 7 observations are found in the literature reviewed across the board. Due to the diversity in phytochemical composition, each extract is multi-purpose that is, reducing, stabilizing and capping agents. Secondly, the parameters of the synthesis and the properties of the nanoparticles are very critical and sensitive to reaction parameters, plant species and the chemistry of precursors. Third, the green synthesized metal oxide nanoparticles exhibit high antimicrobial activity against Gram-positive and Gram-negative microbes by various synergistic mechanisms. Last, the effectiveness of these nanoparticles, for environmental remediation applications like photocatalytic degradation of pollutants, adsorption of toxic metal ions, and wastewater treatment has been proven. Fifth, green processes have important environmental, economic and sustainability advantages over traditional chemical processes, yet are faced with reproducibility, standardisation and scale up problems. The different themes presented in this book may be summarized as the development of plant mediated nanotechnology as a new branch of the sustainable materials science and green chemistry (Iravani, 2011; Ahmed et al., 2016; Singh et al., 2021; Jeevanandam et al., 2022).

The reviewed studies also provide important suggestions for research priorities which change with the course of the study. While earlier studies have been mainly concerned with successful synthesis and characterization, recent studies have shifted focus to understanding the synthesis mechanisms, optimizing biological performance, improving environmental applications, and scalability to enable industrial implementation. The change is a sign of the development of green nanotechnology from experimental proof-of-concept development activities to actual and marketable products. Therefore, the next thematic discussion critically analyzes the developments and focuses on strengths, weaknesses and future research possibilities.

Theme 1. The synthesis of Metal Oxide Nanoparticles using plant-mediated methods

The plant mediated synthesis is one of the greatest advances in the field of sustainable nanotechnology as it makes use of naturally occurring phytochemicals as reducing agents instead of hazardous ones. Plant-assisted synthesis avoids using toxic solvents, high temperatures and other reducing agents like sodium borohydride and hydrazine, that are commonly used in chemical synthesis. This biological approach also not only reduces metal ions but also prevents aggregation of the new nanoparticles and stabilizes them without the need for any additional synthetic stabilizers, thus minimizing the environmental toxicity and production costs (Ahmed et al., 2016; Singh et al., 2021).

The systematic review demonstrates that plant extracts contain an incredible variety of bioactive molecules which can be engaged in the formation of nanoparticles. The polyphenolic, flavonoid, tannin, alkaloid, terpenoid, saponin, amino acid, carbohydrate, protein and phenolic-acid properties have all been shown to act in reducing the metal precursors to nano scale metal oxides. These metabolites contain hydroxyl, carbonyl, amino and carboxyl groups which are easily able to donate electrons in oxidation reactions. These phytochemicals get oxidized and the metal ions (Zn^{2+} , Fe^{3+} , Cu^{2+} , Ti^{4+} , Mg^{2+} and Ni^{2+}) are reduced and then nucleate into solid nanoparticle structures. Concurrently, biomolecules are also adsorbed on the surface of the nanoparticles to

create a natural capping agent and to render the nanoparticles more stable in the colloids and to stop aggregation of nanoparticles (Iravani, 2011; Ahmed et al., 2016; Jeevanandam et al., 2022).

This process is much more complicated than it seems in the recent investigations, which illustrate only a reduction reaction. On the contrary, the biosynthesis process of nanoparticles is a multistaged process which is interwoven with activation, nucleation, crystal growth, stabilization and maturation process. In the activation phase, the phytochemicals react with the dissolved metal ions, and activate the electron transfer reaction. Once enough metal atoms are reduced to create an adequate number of nuclei, nucleation takes place, and stable clusters of atoms are the nuclei for the next step of the crystal growth process. The surrounding phytochemicals then influence the growth of the crystals, through interactions with the facets of the crystal, which will influence the shape and size of the crystal, crystallinity and surface properties. Finally, biomolecules attached to the surface of NPs provide steric and electrostatic stabilization which minimizes further growth and aggregation of the NPs (Singh et al., 2021; Khan et al., 2022).

One of the key observations from the literature reviewed was the marked differences in the efficiency of nanoparticle synthesis in different plants species due to differences in phytochemical content. The ability to form nanoparticles faster with a small size and high colloidal stability is attributed to medicinal plants with high phenolic content. Plants such as *Azadirachta indica* (neem), *Moringa oleifera*, *Camellia sinensis* (green tea), *Aloe vera* and *Ocimum sanctum* (holy basil) have consistently shown the best synthesis properties due to the antioxidants they contain. These antioxidants not only enable quick electron transfer, but also serve as a barrier against the oxidation and aggregation of nanoparticles surfaces (Sharmila et al., 2020; Singh et al., 2021).

Species differences, but also the efficiency of synthesis varies considerably between the different tissues. Although numerous, the use of leaf extracts is the biotic resource which is most readily available, renewable, cheap and provides the highest amount of PSMs. A few studies have, however, indicated that flowers, fruits, bark, roots, peels and seeds could have their own particular phytochemical profile that could result in the production of nanoparticles with different physicochemical properties. For instance, citrus peelings contain condensed tannins and a significant amount of flavonoids and organic acids which have proven to be excellent chelators of zinc and iron sources, and extracts of citrus bark with condensed tannins are frequently very good for producing more stable nanoparticles. In addition to plant species selection, plant tissue selection may be important in sustainable synthesis protocols design (Roy et al., 2022; Elango et al., 2023).

A consistent result is that there are many metal oxide systems where the synthesis process is flexible. Zinc oxide (ZnO) is the most commonly investigated material because of its good antimicrobial activity and its high ultraviolet absorbing capacity as well as low toxicity, and photocatalytic properties. Similarly, the use of Iron Oxide Nanoparticles for wastewater remediation is popular because of their magnetic properties. The antimicrobial property and catalytic property of copper oxide nanoparticles is attracting significant interest, and the photocatalytic degradation of organic pollutants of TiO₂ nanoparticles remains attractive. Moreover the green synthesis methods have also been used for the synthesis of magnesium oxide, nickel oxide, cerium oxide and manganese oxide nanoparticles which have shown interesting biomedical and environmental applications (Jeevanandam et al., 2022; Khan et al., 2022).

The literature reviewed indicates that the capping of molecules obtained from plants may impact the stability of these nanoparticles, as well as their biological activity. Phytochemicals attached to the surface change the surface charge, hydrophilicity, protein adsorption, cellular uptake and interactions with the membrane of microbial cells of the nanoparticles. As a result, the antimicrobial activity of biologically synthesized nanoparticles is often greater than that of chemically synthesized nanoparticles with similar particle sizes. Such an improvement is probably due to synergistic effects between the antimicrobial activity of the metal oxides and residues of phytochemicals. Such synergism is one of the unique advantages of plant-mediated synthesis and is a step different than the physicochemical methods of synthesis (Ahmed et al., 2016; Singh et al., 2021).

The disadvantages are notwithstanding: there are uncertainties about the mechanisms. While Fourier-transform infrared spectroscopy (FTIR), ultraviolet-visible spectroscopy (UV-Vis), X-ray diffraction (XRD), transmission electron microscopy (TEM), scanning electron microscopy (SEM), dynamic light scattering (DLS) and zeta potential analyses are indirect evidences of the role of phytochemicals, the exact molecular mechanisms involved in electron transfer are still not well understood. Functional groups that are important in the formation of nanoparticles have been published, but not many have identified individual phytochemicals that are involved in reduction and stabilization. Thus it is difficult to discern the relative contribution of the flavonoids, tannins, proteins, carbohydrates or terpenoids. As these biochemical interactions become more complex, advanced metabolomics,

molecular docking, proteomics and computational chemistry studies are suggested to comprehend the interactions and understand mechanisms (Jeevanandam et al., 2022; Roy et al., 2022).

Reproducibility is another major concern that is prominent. The nature and amount of phytochemicals produced are dependent on the genotype of the plant, geography, climate, time of harvest, soil conditions, extraction solvents and storage conditions and may yield different sizes, shapes and biological activity for the plant under the same extraction conditions. The diversity makes it difficult to compare different publications and it causes considerable difficulties for industrial standardization. One of the most significant challenges as mentioned in several reviews in the recent past is reproducibility before commercialization at large scale (Elango et al., Khan et al.). The phytochemical composition is genotype-dependent, geographically dependent, climate-dependent, harvesting season-dependent, soil-dependent, solvent-dependent in extraction process, and dependent on storage process, which means that there can be different biological activities, sizes and shapes of the identical synthesis process. This instability makes it difficult to compare different published studies and a great challenge for industrial standardisation. In order to implement large scale commercialization, several recent reviews have emphasized the requirement of standard extraction methods and phytochemical profiling and quality control (Elango et al., 2023; Khan et al., 2022). The other significant problem that comes to mind is reproducibility. The size, shape, and biological activity of the nanoparticles can be different, depending on the same synthesis procedure, due to differences in the phytochemical composition, which depends on the plant genotype, geographical origin, climatic conditions, harvest time, soil characteristics, extraction solvents, and storage conditions. These variations make it hard to compare the various published studies and also pose a challenge of standardization in industry. As such, there is a need for the establishment of standard extraction methodology, phytochemical profile and quality control measures before the commercialisation of large scale production (Elango et al., 2023; Khan et al., 2022). The results collected from the literature reported here fully support the conclusion that the synthesis of nanoparticles by plant mediated has considerable scientific soundness and is an environmentally friendly process. But, the efficiency in the lab will have to be scaled up for industrial use, and it will require a deeper understanding of the mechanisms, the standardization of synthetic protocols and increased process reproducibility. The integration of green chemistry, systems biology, metabolomics, and AI-driven optimization could greatly improve the control of nanoparticle formation while ensuring the environmental benefits of nanotechnology from plants are preserved.

Table 1. Representative Studies on Plant-Mediated Green Synthesis of Metal Oxide Nanoparticles

Study	Plant Source	Metal Oxide Nanoparticle	Major Phytochemicals Reported	Key Characterization Techniques	Principal Findings
Ahmed et al. (2016)	Multiple medicinal plants (Review)	ZnO, Fe ₃ O ₄ , CuO, TiO ₂	Polyphenols, flavonoids, proteins	UV-Vis, FTIR, XRD, SEM, TEM	Plant metabolites simultaneously reduce, cap, and stabilize nanoparticles, providing an eco-friendly synthesis route.
Singh et al. (2021)	Various medicinal plants	ZnO and other MONPs	Phenolics, tannins, alkaloids, terpenoids	FTIR, XRD, TEM, DLS	Phytochemicals determine nanoparticle morphology, stability, and biological performance.
Jeevanandam et al. (2022)	Comprehensive review	Multiple MONPs	Flavonoids, amino acids, carbohydrates	XRD, SEM, TEM, FTIR, Zeta Potential	Green synthesis is increasingly preferred because of sustainability, low toxicity, and multifunctionality.
Khan et al. (2022)	Various botanical extracts	ZnO, CuO, Fe ₂ O ₃	Polyphenols and antioxidants	TEM, SEM, FTIR, UV-Vis	Reaction mechanisms involve nucleation, growth, stabilization, and

					phytochemical capping.
Roy et al. (2022)	Medicinal plant extracts	ZnO and Fe ₃ O ₄	Flavonoids, tannins, phenolic acids	FTIR, XRD, TEM	Plant species and phytochemical composition strongly influence nanoparticle size and morphology.
Elango et al. (2023)	Diverse medicinal plants	Various MONPs	Secondary metabolites	FTIR, SEM, TEM, XRD	Standardization of plant extracts remains a major challenge for industrial-scale production.

Source: Compiled and synthesized from Ahmed et al. (2016), Singh et al. (2021), Jeevanandam et al. (2022), Khan et al. (2022), Roy et al. (2022), and Elango et al. (2023).

Theme 2. The role of phytochemicals and factors that influence the characteristic of metal oxide nanoparticles

One of the important observations made during the course of the reviewed literature is that the physicochemical property of metal oxide nanoparticles depends not only on the nature of the metal precursor used but also on the phytochemical composition of plant extract used in the synthesis process and the synthesis conditions. Plant extracts have several functions compared to the chemical method in which reducing and stabilizing agents are added respectively. Thus, changes in phytochemicals composition affect the nucleation growth, shape, crystallinity, stability, and biological activity of nanoparticles (Iravani, 2011; Ahmed et al., 2016; Singh et al., 2021).

In the latest research, phenolic compounds and flavonoids have always been found to be the main biomolecules used to prepare nanoparticles. These have hydroxyl and carbonyl functional groups which donate the electrons to the metal ion, reducing them to the metal oxide nanoparticles. Simultaneously, these molecules attach to the surface of the nanoparticles, thus inhibiting aggregation and enhancing the colloidal stability. FTIR analysis is also often used to confirm the presence of hydroxyl (–OH), carbonyl (C=O) and amino (–NH) groups within the nanoparticles, suggesting that phytochemicals are still bound to the surface of the nanoparticles after the synthesis process (Jeevanandam et al., 2022; Roy et al., 2022).

Apart from polyphenols, tannins, terpenoids, alkaloids, saponins, proteins, carbohydrates and organic acids are responsible for the formation of nanoparticles. These metabolites regulate crystal growth in different ways for various plants and affect the morphology of nanoparticles. Proteins and polysaccharides are usually used as natural capping agents and phenol antioxidants act as the main reductive agents. This cooperation in the action of various classes of phytochemicals is responsible for the ability of the plant extracts to generate stable nanoparticles without the need for extra chemical stabilizers (Ahmed et al., 2016; Elango et al., 2023).

The review also shows that one of the most important factors in the synthesis is the concentration of the plant extract. If the concentration of the extracts is too low, the biomolecules capable of reduction may not be present in sufficient quantities to achieve complete reduction of the metal ions and yield of the nanoparticles. On the other hand, too high concentrations of extract can lead to higher concentrations of capping agents, which can further decrease the growth rate of the crystals and sometimes cause particle aggregation by too much organic adsorption. Hence, it is noted that optimum plant extract to metal precursor ratio is needed to achieve uniform morphology and narrow size distribution of the nanoparticles (Singh et al., 2021; Khan et al., 2022).

Another important factor that affects the characteristics of nanoparticles is the pH of the reaction. The pH affects the ionization of phytochemicals and thus their reducing power and binding to metal ions. The majority of the studies found increase the formation of nanoparticles under alkaline conditions due to improved electron transfer and the accessibility of negatively charged functional groups. Nucleation is often faster than crystal growth, and smaller and more uniform nanoparticles are produced under alkaline conditions. In contrast, the reduction kinetics can be retarded in acidic conditions, resulting in large particles and wide size distributions (Jeevanandam et al., 2022; Roy et al., 2022).

The temperature also plays a significant role in nanoparticle synthesis. Rate of reduction reactions is generally increased with increasing the temperature of the reaction, reduce the time of the synthesis, and increase the crystallization rate. Very high temperatures can, however, cause loss of heat-sensitive phytochemicals that are natural reducing and stabilizing agents. Hence, moderate reaction temperatures which ensure fast nanoparticle formation and retention of bioactive compounds are recommended by several studies. This result presents an important benefit of green synthesis over many other plant-mediated reactions that occur efficiently under relatively mild conditions, as opposed to conventional chemical synthesis (Ahmed et al., 2016; Khan et al., 2022).

Similarly, reaction time influences the growth of nanoparticles and their crystallinity. A short reaction time can also yield nanoparticles that are not fully developed, while a longer reaction time can allow particles to grow and clump together. Therefore, optimization of reaction time is essential to obtain the desired dimension and surface properties of nanoparticles. In recent investigations, the use of spectroscopic monitoring techniques like UV-Visible spectroscopy has become more common to determine the completion of the formation of nanoparticles which allows for better control of the synthesis conditions (Singh et al., 2021).

The type of metal precursor is also a significant factor in determining the properties of nanoparticles. The solution properties, hydrolysis reaction and the reaction rates of zinc acetate, zinc nitrate, ferric chloride, copper sulfate, titanium isopropoxide and magnesium nitrate are different. These differences have an effect on the nucleation rate, which in turn can impact the size and crystallinity, as well as the morphology, of the nanoparticles formed. Therefore, the same plant extract can yield varying and different nanoparticles with different physicochemical properties when different metal salts are used. The successful green synthesis involves optimization of biological and chemical aspects, which can be demonstrated by such observations, instead of relying on plant extracts only (Roy et al., 2022).

Validation of the successful synthesis of nanoparticles and understanding the influence of the synthesis parameters is of crucial importance, and this is where characterization techniques come into the picture. Preliminary confirmation of the formation of nanoparticles can be made by using UV-Visible spectroscopy, which will identify characteristic absorption peaks. Crystalline structure and phase purity were confirmed by X-ray diffraction (XRD) and Fourier-transform infrared spectroscopy (FTIR) was used to identify phytochemical functional groups associated with NP surfaces. The scanning electron microscopy (SEM) and transmission electron microscopy (TEM) methods give detailed information on particle form and size, while dynamic light scattering (DLS) and zeta potential analysis measures particle size ranges and particle stability in suspension. These methods can be used together to give a complete picture of the quality and efficiency of the synthesis of nanoparticles (Jeevanandam et al., 2022; Elango et al., 2023).

Another significant conclusion that arises from the literature is the close correlation between the size of nanoparticles and their functionality. Smaller nanoparticles have higher surface-to-volume ratios, which leads to greater reactions with microbial cells and environmental pollutants. Thus, nanoparticles with a diameter smaller than about 50 nm frequently exhibit better antimicrobial properties, higher photocatalytic activity and better adsorption properties than larger particles. However, very small nanoparticles can also be prone to aggregation or have modified toxicity profiles, and there is a need to weigh particle size with the requirements of the application and long-term stability of the product (Singh et al., 2021; Khan et al., 2022).

The review reveals, however, that even after all this progress there are still problems with standardization and reproducibility. The direct comparison of most publishing studies is difficult due to the use of varying plant species, extraction techniques, precursor concentration, reaction conditions, and characterization techniques. In addition, several studies only provide partial phytochemical composition of the plant extracts, thereby limiting the plant molecule knowledge necessary to understand the biomolecules that are responsible for the formation of nanoparticles. The future research should combine metabolomic profiling with the standardized synthesis procedure to build more robust links between phytochemical composition and the properties of nanoparticles. Thus, such approaches would aid in achieving reproducibility, large-scale production, and commercialization of green-synthesized metal oxide nanoparticles (Elango et al., 2023; Jeevanandam et al., 2022).

In general, the findings suggest that the phytochemicals and synthesis process factors play a significant role in the quality and functional properties of green-synthesized metal oxide nanoparticles. The optimization of these parameters is crucial to achieve nanoparticles with uniform physicochemical characteristics and a predictable biological and environmental behavior. The trend in

research is now shifting to industrial applications, and methods to develop a process understanding and process standardization will become a new requirement in order to take synthesis results from the lab to the commercial equipment.

Table 2. Influence of Plant Phytochemicals and Synthesis Parameters on Metal Oxide Nanoparticle Characteristics

Study	Plant Source	Major Phytochemicals	Key Synthesis Parameters	Characterization Techniques	Main Findings
Ahmed et al. (2016)	Various medicinal plants	Polyphenols, flavonoids, proteins	Plant extract concentration, temperature	UV-Vis, FTIR, XRD, SEM	Phytochemicals act as reducing and stabilizing agents, producing stable nanoparticles under mild conditions.
Singh et al. (2021)	<i>Azadirachta indica</i> , <i>Moringa oleifera</i> , <i>Aloe vera</i> and others	Flavonoids, tannins, alkaloids	pH, precursor concentration, reaction time	FTIR, XRD, TEM, DLS	Optimized reaction conditions produce smaller nanoparticles with improved biological activity.
Roy et al. (2022)	Medicinal plant extracts	Phenolic acids, flavonoids	Metal precursor type, reaction temperature	TEM, SEM, XRD	Plant species and precursor chemistry significantly affect nanoparticle size and morphology.
Khan et al. (2022)	Various botanical extracts	Polyphenols, antioxidants	Temperature, pH, extract-to-metal ratio	UV-Vis, FTIR, TEM	Alkaline conditions generally enhance nucleation and produce more uniform nanoparticles.
Elango et al. (2023)	Diverse medicinal plants	Mixed secondary metabolites	Extraction method, synthesis optimization	FTIR, SEM, XRD, Zeta Potential	Standardization of extraction and synthesis protocols remains essential for reproducible nanoparticle production.

Source: Compiled and synthesized from Ahmed et al. (2016), Singh et al. (2021), Roy et al. (2022), Khan et al. (2022), Jeevanandam et al. (2022), and Elango et al. (2023).

Lastly, the research philosophy, review design, search strategy, inclusion/exclusion criteria, data analysis and quality appraisal framework were reported in a transparent manner to facilitate reproducibility. The study follows each stage of the methodologically applied procedure in a structured manner following the principles of systematic reviews, which enables the use of the process for further research activities on the subject of sustainable nanotechnology, plant-mediated synthesis and applications of metal oxide nanoparticles. Such methodological openness enhances the credibility of the review and is helpful for further evidence syntheses in this multidisciplinary field which is changing rapidly.

Theme 3. The antimicrobial applications and mechanisms of green-synthesized metal oxide nanoparticles (MONPs)

The common conclusion across the literature reviewed is the plant-made metal oxide nanoparticles have broad-spectrum antimicrobial activity against a wide range of pathogenic microorganisms. With the rising rate of antimicrobial resistance (AMR) worldwide, there is a growing interest in alternative antimicrobial agents, and green-synthesized nanoparticles are emerging as potential antimicrobial agents which are able to inhibit microbial growth by several mechanisms. Metal oxide nanoparticles work on multiple cellular structures at a time as opposed to conventional antibiotics that usually target a single process, making it difficult to develop resistance (Rai et al., 2012; Singh et al., 2021; Jeevanandam et al., 2022).

Zinc Oxide (ZnO) nanoparticles are the most widely studied among the various metal oxides due to their high antimicrobial properties, low toxicity and good biocompatibility. Several works have confirmed that the green synthesized ZnO nanoparticles are effective against both Gram-positive (*Staphylococcus aureus*, *Bacillus subtilis*) and Gram-negative (*Escherichia coli*, *Pseudomonas aeruginosa*, *Klebsiella pneumoniae*) bacteria. Moreover, ZnO nanoparticles have been shown to have antifungal effects against various fungal species like *Candida albicans* and *Aspergillus niger*, indicating their wide range of antimicrobial activity (Ahmed et al., 2016; Khan et al., 2022).

Chromia nanoparticles namely iron oxide (Fe_3O_4 , Fe_2O_3) have been also a point of a great interest due to their antimicrobial properties and to their magnetic properties which allow their recovery and reuse in biomedical and environmental applications. Despite their weaker antimicrobial activities compared to that of the ZnO and CuO nanoparticles, Fe_3O_4 nanoparticles display good stability, less cytotoxicity, and applicability in targeted drug delivery and magnetic separation technologies. Copper oxide (CuO) nanoparticles are also known for their strong antimicrobial activity, especially against multidrug-resistant (MDR) bacterial strains, which is attributed to their release of copper ions, causing oxidative stress in microbial cells (Jeevanandam et al., 2022; Roy et al., 2022).

Generation of Reactive Oxygen Species (ROS) is one of the major mechanisms responsible for antimicrobial activity of metal oxide nanoparticles as stated in literature. In the contact with the cells of the microbe, the nanoparticles produce reactive oxygen species like hydroxyl radicals ($\bullet\text{OH}$), superoxide radicals ($\text{O}_2^{\bullet-}$), hydrogen peroxide (H_2O_2). These molecules are highly reactive and react with important cell components such as lipids, proteins, enzymes and nucleic acids. Finally, the excessive oxidative stress results in abnormal cellular metabolism and death of microorganisms. Due to this multi-target approach, microorganisms are not very likely to develop resistance to this mechanism (Raghupathi et al., 2011; Singh et al., 2021).

Besides oxidative stress, direct damage to the microbial cell membrane is another antimicrobial mechanism. Most metal oxide nanoparticles have high surface area/volume ratios, allowing them to interact closely with the walls of bacteria. The electrostatic force of attraction between the positively charged nanoparticles and negatively charged microbial membranes leads to increased permeability, leakage of intracellular content and ultimately cell lysis. In a few studies, microscopic observations also showed that the bacterial cells undergo deformation after the exposure of nanoparticles, indicating that disruption of the membrane is one of the most important mechanisms by which the bacteria are killed (Jeevanandam et al., 2022; Khan et al., 2022).

The other mechanism is the desorption of metal ions from the surface of nanoparticles. The released zinc and copper ions during the dissolution of the nanoparticles can enter the microbial cells and disrupt their enzyme activities, protein synthesis, and DNA replication. These ions react with the sulfur containing protein and phosphate groups in nucleic acids, interfere in normal cellular processes and inhibit microbial growth. This antimicrobial activity is complimentary with oxidative stress and membrane disruption, leading to synergistic antimicrobial activity (Ahmed et al., 2016; Roy et al., 2022).

One of the key findings in all the studies reviewed is the important role of the size of nanoparticles in antimicrobial activity. The specific surface area increases as the size of nanoparticles decreases, and they can penetrate microbial cell envelopes more easily than larger nanoparticles, thus showing higher antimicrobial activity. Nanoparticles of less than about 50 nm size are often more effective at killing bacteria than larger particles, mainly because there are more sites of contact with microbial cells and more generation of reactive oxygen species. However, particle morphology and surface charge also play a role in the antimicrobial activity, suggesting that biological activity is not solely dependent on the particle size (Singh et al., 2021; Elango et al., 2023).

The literature reviewed also indicated that the phytochemicals that are left on the surface of the nanoparticles after green synthesis can be beneficial for antimicrobial activity. Residual flavonoids, phenolic compounds, terpenoids and tannins have intrinsic antimicrobial properties and could have an additive effect with metal oxide nanoparticles. This synergistic effect is unique to green-synthesized nanoparticles and not found in chemically synthesized nanoparticles that are usually not surface coated with biologically active molecules. While the exact mechanism by which these phytochemicals affect the antimicrobial activity is still being studied, some comparative studies have shown enhanced antimicrobial activity for plant-made nanoparticles prepared under similar conditions (Ahmed et al., 2016; Jeevanandam et al., 2022).

Although promising laboratory results are identified, the review also notes some limitations that should be remedied before clinical use becomes widespread. The majority of antimicrobial studies have been performed in vitro with limited studies of long-term toxicity, pharmacokinetics and clinical efficacy. Comparisons between studies are also complicated by differences in the

methods of synthesis, the size of particles, different extracts from plants, different strains of microorganism, and testing procedures. Standardized methods of antimicrobial testing are required for better reproducibility and for comparison of the performance of nanoparticles (Khan et al., 2022; Elango et al., 2023).

Yet another research frontier is the integration of green synthesized nanoparticles with the conventional antimicrobial agents. There are several studies that show that the activity of some existing antibiotics can be increased through the use of nanoparticles, enhancing the permeability of the membrane and disrupting the defense mechanisms of bacteria. These combinations can deliver synergistic effects and lower the dose needed for antibiotics, and may be more effective against resistant pathogens. While encouraging results have been obtained these methods still need further in vivo experimentation and clinical trials for their application in practice (Singh et al., 2021).

In summary, the available evidence suggests that the green synthesized metal oxide nanoparticles have high antimicrobial activity by various mechanisms such as generation of ROS, disruption of membrane, release of metal ions, etc. They are potentially suitable for applications in healthcare, food preservation, biomedical coatings and antimicrobial packaging due to their broad-spectrum activity and environmentally friendly synthesis process using plants. Future investigations should focus on standardized biological testing, toxicity studies, and clinical validation, however, to facilitate their safe and effective use.

Table 3. Representative Studies on the Antimicrobial Applications of Green-Synthesized Metal Oxide Nanoparticles

Study	Plant Source	Metal Oxide Nanoparticle	Target Microorganisms	Major Antimicrobial Mechanism	Key Findings
Ahmed et al. (2016)	Various medicinal plants	ZnO, CuO, Fe ₃ O ₄	<i>E. coli</i> , <i>S. aureus</i> , <i>P. aeruginosa</i>	ROS generation, membrane disruption	Green-synthesized nanoparticles exhibited broad-spectrum antibacterial activity with reduced use of toxic chemicals.
Singh et al. (2021)	<i>Azadirachta indica</i> , <i>Moringa oleifera</i> , <i>Aloe vera</i> and others	ZnO	Gram-positive and Gram-negative bacteria	Oxidative stress, metal ion release	Smaller nanoparticles showed enhanced antimicrobial performance because of higher surface area.
Jeevanandam et al. (2022)	Multiple medicinal plants	ZnO, Fe ₃ O ₄ , CuO	Bacteria and fungi	Combined ROS production and cell membrane damage	Plant-mediated nanoparticles demonstrated multifunctional antimicrobial properties suitable for biomedical applications.
Roy et al. (2022)	Various plant extracts	Fe ₃ O ₄ and CuO	<i>S. aureus</i> , <i>E. coli</i> , <i>Candida albicans</i>	Membrane damage and intracellular ion release	Iron oxide nanoparticles offered good antimicrobial activity with additional magnetic functionality.
Khan et al. (2022)	Botanical extracts	ZnO and CuO	Multidrug-resistant bacterial strains	ROS generation, protein and DNA damage	Green synthesis produced stable nanoparticles with promising antibacterial activity against resistant

					pathogens.
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Source: Compiled and synthesized from Ahmed et al. (2016), Singh et al. (2021), Jeevanandam et al. (2021/2022 review), Roy et al. (2022), Khan et al. (2022), and related peer-reviewed studies.

Theme 4. Metal Oxide Nanoparticles (MONs) as a Novel Remediation Technology for the Environment

It is pointed out that environmental remediation is among the best research fields for plant mediated metal oxide nanoparticles by reviewing the literature. The intensive spread of organic pollutants, heavy metals, dyes, pesticides, pharmaceuticals, and pathogenic microorganisms in water and soil has been the result of increasing industrialization, urbanization and agricultural activities. Traditional methods of remediation such as chemical oxidation, coagulation and activated carbon adsorption are usually costly, energy intensive and can produce secondary pollutants. Hence, the green synthesized metal oxide nanoparticles have proved as a sustainable alternative due to their high surface area, catalytic activity, adsorption capacity, and environmentally friendly production process (Jeevanandam et al., 2022; Singh et al., 2021).

Of all these materials, zinc oxide (ZnO) and titanium dioxide (TiO₂) nanoparticles are well known for their photocatalytic properties. When the nanoparticles are exposed to ultra-violet or visible light, they form pairs of electrons and holes which interact with water and oxygen to create reactive oxygen species. These reactive species oxidize more complex organic pollutants to simpler and less harmful products. The results of several studies have been shown that plant synthesized ZnO and TiO₂ nanoparticles are efficient dye decolorizers for various dyes like methylene blue, methyl orange, rhodamine B and Congo red. Green synthesized materials typically have similar photocatalytic activity to the conventionally synthesized materials and they do not use hazardous chemicals during their production (Ahmed et al., 2016; Roy et al., 2022).

Another use for iron oxide nanoparticles is in environmental cleanup, thanks to their magnetic characteristics. These nanoparticles exhibit properties of high adsorption efficiency and can successfully remove lead (Pb), cadmium (Cd), chromium (Cr) and arsenic (As) ions from polluted water. They are also magnetic, allowing them to be easily collected with an external magnetic field, minimizing material losses and enabling recycling. This property is a major practical advantage over many of the traditional adsorbents that are difficult to separate after adsorption (Jeevanandam et al., 2022).

Green-synthesized metal oxide nanoparticles have also been found to have the potential to degrade pharmaceutical residues, pesticides, and other emerging contaminants as well as dye degradation and heavy metal removal. Agricultural practices and the pharmaceutical and medical sectors are increasingly releasing persistent compounds that are being found in water bodies and threatening to harm the environment and human health. In recent years, researchers have shown that photocatalytic nanoparticles are capable of degrading several of these contaminants, with the efficiency of the treatment depending on the type of the nanoparticles, the concentration of the pollutant, the type of light source, and the environmental conditions (Khan et al., 2022).

The literature also shows that the performance of the remediation is highly dependent on the characteristics of the nanoparticles. The smaller the particle size, the larger the active surface area for adsorption and catalytic reactions, and the higher the crystallinity, the higher the photocatalytic efficiency, which is related to the reduction of electron-hole recombination. Surface functional groups generated by the plant phytochemicals can also improve the adsorption of pollutants by increasing the interaction between the nanoparticles and pollutant molecules. Therefore, optimization of synthesis conditions is still important for achieving the optimum environmental performance (Singh et al., 2021).

Although it has been found to be encouraging in the laboratory, there are some drawbacks. Through most remediation studies, concentrations of contaminants in wastewater have been modeled in synthetic wastewater and in controlled experimental conditions. In practice, the efficiency of the treatment may be less than that described above due to pH variation, competing ions, natural organic matter and changing temperatures. In addition, little information exists about the fate and potential ecotoxic effects of released nanoparticles in the environment over the long term. Pilot-scale studies and detailed environmental risk assessments will be crucial to overcome these problems before scaling up can be implemented (Elango et al., 2023).

In conclusion, the analysed data shows a promising possibility for the use of green-synthesized metal oxide nanoparticles in sustainable water purification, pollutant degradation and heavy metal removal. The properties they exhibit in a number of

applications, coupled with their environmentally-friendly synthesis, make them interesting for future environmental technologies. But enhancing the recyclability and validation in the field and environmental safety are key research needs.

Table 4. Representative Studies on Environmental Remediation Applications of Green-Synthesized Metal Oxide Nanoparticles

Study	Plant Source	Metal Oxide Nanoparticle	Environmental Application	Main Findings	Research Gap
Ahmed et al. (2016)	Various medicinal plants	ZnO, TiO ₂	Photocatalytic degradation of dyes	Green nanoparticles efficiently degraded common organic dyes under light irradiation.	Limited large-scale validation.
Singh et al. (2021)	Various plant extracts	ZnO	Wastewater treatment	High photocatalytic activity and pollutant removal efficiency.	Need for standardized field studies.
Jeevanandam et al. (2022)	Multiple medicinal plants	Fe ₃ O ₄	Heavy metal adsorption	Magnetic nanoparticles enabled efficient adsorption and easy recovery.	Long-term environmental impacts require investigation.
Roy et al. (2022)	Medicinal plant extracts	TiO ₂ , ZnO	Organic pollutant degradation	Nanoparticles effectively degraded dyes and other organic contaminants.	More studies under real wastewater conditions are needed.
Khan et al. (2022)	Botanical extracts	ZnO, CuO	Removal of emerging contaminants	Green nanoparticles showed potential for pharmaceutical and pesticide degradation.	Limited pilot-scale applications.

Source: Compiled and synthesized from Ahmed et al. (2016), Singh et al. (2021), Jeevanandam et al. (2022), Roy et al. (2022), Khan et al. (2022), and related peer-reviewed literature.

Theme 5. Sustainability Benefits, Current Challenges, Research Gaps, and Future Directions

The results presented in this review show that the plant-based synthesis of metal oxide nanoparticles is very similar to green chemistry principles and sustainable development. In green synthesis, the use of harmful chemicals is minimized, energy is consumed less and biological resources are used as reducing and stabilizing reagents compared to the conventional synthesis methods. The plant materials are readily available, inexpensive, biodegradable and can generate nanoparticles under relatively mild reaction conditions. These properties help to reduce the environmental impact and simultaneously, ensure a safe production of nano materials with biomedical and environmental applications (Iravani, 2011; Ahmed et al., 2016).

Another sustainability benefit cited in the reviewed studies is that of using agricultural residues and plant waste. The plant by-products like fruit peels, leaves, bark, seeds, etc., which are generally thrown away, can be used as a source of valuable bioactive phytochemicals for the synthesis of nanoparticles. Such strategy facilitates waste valorization and fosters circular economy by utilizing biological waste to fabricate high value nanomaterials. These not only lower production costs, but are also viewed as ways to achieve sustainable resource management (Singh et al., 2021).

Despite these benefits, one of the most important hurdles to commercialization is reproducibility that has been identified repeatedly in the literature. The chemical constituents of plant extracts change depending on plant species, geographical location, climatic conditions, harvest date, plant age and methods of extraction. The differences influence the activity of the nanoparticles as well as their size and shape; crystallinity and biological activity, which makes it challenging to replicate nanoparticles from one

laboratory to the next. Hence, there is a need for standardisation of process of plant selection, extraction, synthesis and characterization which is a critical research priority (Jeevanandam et al., 2022; Elango et al., 2023).

Another significant challenge in scale up production is finding the right equipment for the job. The majority of work reported in the literature has focused on laboratory-scale production in small-scale reactors. Industrial production demands continual, reproducible, and affordable manufacturing systems that can ensure the consistent quality of nanoparticles. To accomplish this goal, optimization of reaction parameters, quality control procedures and engineering processes, compatible with large-scale synthesis, without sacrificing the environmental benefits of green synthesis (Khan et al., 2022) will be required.

Assessment for safety is also a significant factor. While this plant-mediated synthesis minimizes the use of toxic chemicals, the nanoparticles may still affect the cells of human beings and of environmental organisms. There is limited existing information on the long term toxicity, bioaccumulation, environmental persistence and ecological effects of many metal oxide nanoparticles. Toxicity studies must thus be conducted in a comprehensive manner with standard protocols and procedures before any broad clinical or commercial use is recommended (Singh et al., 2021).

There are also some key research gaps noted in the review. First, there are relatively few studies that comprehensively characterize the phytochemicals that form nanoparticles, which also limit mechanistic understanding. Secondly, standardized synthesis conditions for direct comparisons among different plant species are still limited. Third, most investigations are limited to nanoparticle synthesis and characterization, with little consideration given to evaluating long-term stability, reusability, and performance in real-world applications. Last, few pilot scale and industrial studies are available to prove that green nanoparticles synthesized can be practically used in healthcare or environmental remediation.

It is thus recommended that further studies be explored that involve the application of advanced analytical methods, like metabolomics, proteomics and computational modelling, to more thoroughly understand plant-nanoparticle interactions. AI and machine learning can also help to forecast the best synthesis conditions and enhance process repeatability. Moreover, interdisciplinary research and interaction between materials scientists, chemists, microbiologists, environmental engineers and toxicologists will be necessary to convert the laboratory innovations into commercial and environmentally friendly technologies. The increase in pilot scale studies, life cycle assessments and regulatory evaluations will help promote the safe application of green nanotechnology in the industrial and environmental sector (Jeevanandam et al., 2022; Elango et al., 2023).

To summarize, the literature reviewed shows that green synthesis using plant extracts is a sustainable and versatile approach for the synthesis of metal oxide nanoparticles with great antimicrobial and environmental applications. Although significant strides have been made, the standardization, scalability, and safety assessment are still hurdles that must be surmounted for the future success of this rapidly growing field.

Table 5. Sustainability Benefits, Challenges, and Future Research Directions in Green Synthesis of Metal Oxide Nanoparticles

Aspect	Current Findings	Challenges	Future Research Direction
Sustainability	Eco-friendly synthesis with renewable plant resources and reduced hazardous chemicals	Variability in plant extracts	Standardized extraction and synthesis protocols
Cost-effectiveness	Low-cost raw materials and mild reaction conditions	Scale-up production costs	Industrial process optimization
Nanoparticle Quality	Good stability and multifunctional properties	Reproducibility across laboratories	Quality-control frameworks and standardized characterization
Biomedical Applications	Promising antimicrobial performance	Limited long-term toxicity data	Comprehensive in vivo and clinical studies

Environmental Remediation	Effective pollutant degradation and heavy metal removal	Limited field-scale validation	Pilot-scale implementation and life-cycle assessment
Mechanistic Understanding	General roles of phytochemicals identified	Specific molecular pathways remain unclear	Metabolomics, proteomics, and computational modelling
Commercialization	Increasing industrial interest	Regulatory uncertainty and manufacturing challenges	Development of regulatory standards and scalable production technologies

Source: Compiled and synthesized from Iravani (2011), Ahmed et al. (2016), Singh et al. (2021), Jeevanandam et al. (2022), Khan et al. (2022), Roy et al. (2022), and Elango et al. (2023).

Conclusion

As demand for environmentally friendly nanomaterials has been on the rise, the shift is towards more sustainable and resource-efficient production methods from the traditional physicochemical synthesis. This qualitative review critically compiled recent evidence for the use of plants to synthesize metal oxide nanoparticles (MONPs) and their applications for antimicrobial therapy and environmental remediation. The results indicate that the plant extracts are an effective green, eco-friendly and versatile medium for the synthesis of nanoparticles where naturally occurring phytochemicals such as flavonoids, phenolic compounds, terpenoids, alkaloids, tannins, proteins and carbohydrates played a dual role of reducing, stabilizing and capping agents. All these reviewed literature reported that these biomolecules can assist in the fabrication of nanoparticles at mild reaction conditions and their physicochemical property and functionality of the synthesized materials. Therefore, plant-mediated synthesis has gained considerable interest as an alternative to the conventional methods, which often require the use of toxic chemicals and high energy consumption and by-products harmful to the environment (Iravani, 2011; Ahmed et al., 2016; Singh et al., 2021).

One of the key strengths of this review is its holistic and comprehensive synthesis of mechanisms of green synthesis, their influence on the characteristics of the nanoparticles and the increasing evidence of their biomedical and environmental applications. These topics are not explored separately here, but it is clear from the above that the antimicrobial activity and environmental remediation ability are dictated by the phytochemical composition, synthetic conditions, morphology and surface properties of the nanoparticles. This comprehensive view fills a crucial lack in the current literature, as many studies are available that describe only the synthesis methods or the application of the products without critically linking the biological mechanisms involved with functional performance. The review brings together existing evidence in a themed format, thus offering a comprehensive picture of the role of plant-mediated synthesis in the overall mission of sustainable nanotechnology.

The compiled evidence also shows that the green synthesized metal oxide nanoparticles have great potential to tackle AMR and environmental pollution. Their wide antimicrobial spectrum is due to several synergistic mechanisms, such as the generation of reactive oxygen species, the disruption of microbial membranes and the controlled release of metal ions, which decreases reliance on conventional antibiotics and the risk of the development of antimicrobial resistance. Likewise, their ability in photocatalytic degradation of organic pollutants, toxic heavy metal adsorption, wastewater treatment suggests their applications in relation to cleaner production technologies and environmental protection. The versatility of these properties highlights the potential of green nanotechnology as a cross-disciplinary approach that can solve multiple problems associated with various global challenges (Jeevanandam et al., 2022; Khan et al., 2022).

Theoretically this review adds to the growing body of knowledge in green chemistry, sustainable materials science and nanobiotechnology by summarizing the present knowledge about the interactions between plants and nanoparticles. The synthesis underscores the pivotal role of naturally occurring phytochemicals in the control of the nucleation, growth, stabilization, and biological activity of nanoparticles and establishes a conceptual basis for the mechanistic studies of these processes in the future. In addition, the review highlights the importance of recognizing successful synthesis of nanoparticles as an interplay between biological molecules, reaction conditions and material properties, instead of a straightforward reduction procedure. This type of a framework is helpful for future interdisciplinary studies that combine the disciplines of chemistry, biology, materials science, environmental engineering, and computational modelling.

The implications of this review are also very pertinent. Synthesis of functional nanomaterials by plants is an environmentally and economically friendly way of manufacturing them, suitable for use in medicine, agriculture, food safety, water treatment and environmental remediation. The application of renewable plant resources such as plant waste and agricultural residues as feedstocks for the production of high value nanomaterials promotes the principle of circular economy. In addition, the removal or significant reduction of toxic reducing agents and stabilizers are in line with international initiatives to improve production technologies and sustainable industry. With the growing trend towards more environmentally friendly methods in industrial production, green synthesis provides significant potential for the implementation of more sustainable production systems for nanoparticles (Singh et al., 2021; Elango et al., 2023).

Despite this good news, the review also points to a number of key gaps in the current literature. It is difficult to compare between the different studies published due to the high level of variability that exists in plant selection, extraction methods, precursor chemistry, synthesis conditions and characterization techniques. The phytochemical differences caused by geographical origin, seasonal changes, farming and extraction methods continue to impact the reproducibility of nanoparticles and make it difficult to develop standardized synthesis methods. Furthermore, numerous studies are restricted to laboratory-scale experiments, and only a small portion of them consider a pilot-scale production, industrial feasibility, life-cycle assessment or long-term environmental safety. While antimicrobial and environmental applications have shown good performance in controlled settings, relatively few studies have tested real-world operating conditions and have considered the ecological risks of releasing nanoparticles. Overcoming these drawbacks will be crucial to make laboratory innovations into viable commercial technologies (Jeevanandam et al., 2022; Roy et al., 2022).

In the future, synthesis protocols should be more standardized, the detailed phytochemical characterization should be done, and systematic studies should be carried out on the relationship between plant metabolites and nanoparticle properties. The use of advanced analytical methods such as metabolomics, proteomics, high resolution spectroscopy and computational modelling could significantly enhance the understanding of the mechanisms of plant-mediated synthesis. Moreover, the use of AI and machine learning methods in process optimization could aid in achieving more uniform nanoparticle manufacturing and minimize experimental variations. Prior to large-scale industrial and clinical use, studies such as long-term toxicity, environmental risk assessment, and life-cycle analysis should be a major focus. The formulation of internationally coordinated regulatory regimes that set quality-control standards for green-synthesized nanoparticles and keep them environmentally and humanely safe during synthesis, use and disposal is also significant.

In a policy sense, the governments and funding agencies should foster interdisciplinary collaborations between academic researchers, industry, environmental organizations, and regulatory agencies that would speed up the responsible development of sustainable nanotechnologies. More investments in green manufacturing facilities, environmentally friendly production systems and in translational research will help to make the transition to commercialization and will help achieve national and global sustainability goals. Further strengthening of the scientific workforce needed to foster the progress of this rapidly emerging field may be achieved through education initiatives fostering green chemistry principles and sustainable materials engineering.

To conclude, the synthesized evidence from this review clearly shows that green synthesis of metal oxide nanoparticles using plants is one of the most viable and sustainable methods. This approach allows for the production of multifunctional nanomaterials with remarkable antimicrobial and environmental remediation potential and simultaneously overcomes many drawbacks of conventional methods for producing nanoparticles, by using renewable biological resources and environmentally friendly synthesis processes. However, as more research advances in understanding mechanisms, standardizing processes, scaling up and assessing the safety of green-synthesized metal oxide nanoparticles (MONs), the translation of these nanoparticles from lab to industry and environment may be faster. Finally, green synthesis with plants will not only be one of the more environmentally friendly alternatives to nanomaterial production but also play an important role in the other objectives of sustainable nanotechnology, green innovation, and responsible scientific development in the 21st century.

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