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HARNESSING THE POWER OF MN_3O_4 NANOPARTICLES: GREEN SYNTHESIS AND METAL DOPING FOR COMBATING MULTIDRUG-RESISTANT BACTERIA

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ABSTRACT
The production, characterization, and antibacterial uses of manganese oxide (Mn_3O_4) nanoparticles particularly against multidrug-resistant (MDR) bacteria are highlighted in this thorough study of the material. Reactive oxygen species (ROS) formation and bacterial membrane rupture are two of the special characteristics of Mn_3O_4 nanoparticles that contribute to their potent antibacterial action. These characteristics include increased surface area, varied band-gap energies, and improved redox activity. As environmentally benign substitutes for traditional chemical approaches, the review emphasizes green synthesis techniques that use plant extracts and have benefits including lower toxicity, cost-effectiveness and environmental sustainability. Additionally, by changing their electrical structures and increasing the formation of ROS, doping Mn_3O_4 nanoparticles with metals including ruthenium, zinc and palladium enhances their antibacterial efficacy. Numerous synthesis methods are described, such as sol-gel, co-precipitation, chemical reduction, hydrothermal, and physical processes; co-precipitation is preferred due to its ease of use and compatibility with the environment. To ascertain the size and shape of nanoparticles, characterization techniques such as FTIR, UV spectroscopy, SEM and XRD are employed. There are still issues with synthesis repeatability, toxicity evaluation, and targeted delivery despite encouraging antibacterial and biocompatibility results. In order to address pressing global health and environmental issues and advance sustainable nanotechnology development, the review concludes that green synthesis combined with doping strategies provides a flexible platform for creating advanced Mn_3O_4 nanomaterials with potential uses in biomedicine, water purification, and infection control.

KEYWORDS: These characteristics include increased surface area, varied band-gap energies, and improved redox activity.

INTRODUCTION
A diverse class of nanomaterial, manganese oxide nanoparticles have attracted significant attention for a wide range of uses, from energy storage and catalysis to environmental remediation and biomedicine. Their inherent antimicrobial qualities and ability to modify their functionality through doping and green synthesis techniques make them especially promising in the field of microbiology. Hausmannite, also known as Mn_3O_4, adds special qualities including a high surface area that is essential for maximizing interactions with microbial cells, variable band-gap energies, and increased redox activity. By producing reactive oxygen species (ROS) and disrupting bacterial membranes, these nanoparticle's notable surface to volume ratio naturally allows for increased exposure of active sites, which improves catalytic performance and boosts antimicrobial activity (Hessien et al., 2024). Since microbial resistance is becoming a more serious global public health concern, it is necessary to investigate alternate approaches. These nanomaterials are becoming more widely acknowledged as viable options to get around the drawbacks of traditional antimicrobial agents and disinfectants. According to current research developments, doping Mn3O4 nanoparticles with different metal ions improves their antimicrobial and photocatalytic efficiencies by altering their electronic structure and enabling charge separation, which eventually increases the production of ROS and encourages antibacterial mechanisms (Binjawhar et al., 2024). Green synthesis approaches, which go further metal doping, have become a very appealing substitute for traditional methods. In the end, the information presented here highlights the revolutionary potential of

Mn_3O_4 nanoparticles as multipurpose microbiological agents that can solve urgent problems in biomedicine, water purification, and infection control, opening the door for contemporary antimicrobial materials. The combination of green synthesis and doping techniques in the production of Mn3O4 nanoparticles, in conclusion, provides a flexible platform for the engineering of advanced nanomaterials with specific properties that are essential for efficient microbial inhibition, showing great promise in the battle against environmental contaminants and pathogenic organisms (Sukhdev et al., 2020). Beginning with basic concepts and synthesis techniques, this review covers the complex mechanisms behind antimicrobial activity. It concludes with a discussion of present issues and potential directions for future research and use of doped Mn_3O_4 nanoparticles in the field of microbiology. Furthermore, by clarifying the relationship between the structural characteristics of nanoparticles and antimicrobial mechanisms, this research seeks to offer important insights that can guide the logical development of next-generation nanomaterials, promoting innovations that are both environmentally sound and scientifically sound (S. et al., 2023). In conclusion, the study of Mn_3O_4 nanoparticles produced using environmentally friendly techniques and enhanced by doping represents the cutting edge of nanobiotechnology, providing promising answers that connect basic science with real-world applications in environmental management, agriculture, and medicine. This is especially important as the world's scientific community continues to face the simultaneous challenges of environmental contamination and resistance to antibiotics.

Literature Review

In the battle against multidrug-resistant (MDR) bacteria, manganese oxide nanoparticles more specifically, Mn_3O_4 nanoparticles have shown themselves to be a promising substitute for traditional antibiotic treatments, according to recently published research (Aseef & Venkatkumar, 2025). Green synthesis methods have been used to comprehensively investigate and refine the special physicochemical characteristics of Mn_3O_4 nanoparticles, such as their large surface area to volume ratio, unusual morphologies, and inherent catalytic activity. When it comes to creating Mn_3O_4 nanoparticles with regulated sizes, improved dispersion, and fewer toxicological problems, green synthesis techniques which use naturally occurring reducing and stabilizing chemicals from plant extracts have shown themselves to be quite successful (Jayandran et al., 2015). Green-synthesized Mn_3O_4 nanoparticles are discussed in this review along with their production, characterization, antimicrobial actions, and possible biological uses as medicinal products against MDR microbes. Eco-Friendly Production of Mn_3O_4 nanoparticles green synthesis offers a sustainable, economical, and environmentally beneficial method of creating metal oxide nanoparticles. Manganese precursors have been reduced into Mn_3O_4 nanoparticles in a number of investigations using extracts from natural sources such lemon, turmeric, coriander (Elbasuney et al., 2024). In one study, for example, spherical Mn_3O_4 nanoparticles in the 40 to 60 nm size range were produced using lemon extract as a reducing agent and turmeric curcumin extract as a capping agent. When these nanoparticles are further biofunctionalized with biocompatible polymers such as salicylalchitosan, they not only show good dispersion but also increased antibacterial properties, adding an additional layer of stability and bioactivity.

A different method involves using leaf extract from ***Coriandrum sativum*** to create Mn_3O_4 nanoparticles, which have shown broad-spectrum antibacterial activity against both Gram-positive and Gram-negative bacteria (Hanif et al., 2024). By using fewer dangerous chemicals, the green synthesis method lowers toxicity and its impact on the environment while guaranteeing that the nanoparticles are highly pure and crystallized, as shown by electron microscopy, Fourier-transform infrared spectroscopy, and X-ray diffraction. Beyond straightforward reduction procedures, numerous groups have also used microwave-assisted hydrothermal synthesis to incorporate dopants into Mn_3O_4 nanoparticles (Khan et al., 2024). In order to overcome microbial resistance, ruthenium doped Mn_3O_4 nanoflowers, for instance, that are manufactured with the use of microwaves have demonstrated improved antibacterial efficacy and a regulated size distribution.

An additional novel method involves the incorporation of zinc into Mn_3O_4 nanocomposites, resulting in Zn-MnO structures. Both components complimentary antibacterial qualities are advantageous to these composites. Mn_3O_4 provides regulated ion release and catalytic activity, whereas Zn contributes to further ROS production and membrane rupture (Tasnim et al., 2024). According to studies, Zn-MnO nanocomposites offer a wider spectrum of antibacterial action and much lower MIC values, effectively resolving the problems of drug resistance and creation of biofilm.

Likewise, the addition of noble metals to Mn_3O_4 matrices has enhanced their antibacterial properties. For instance, palladium-doped Mn_3O_4 nanoparticles made using bioinspired synthesis methods have shown exceptional antibacterial activity against human and phytopathogenic diseases. By adding more lattice defects and altering the Mn_3O_4 matrix's electrical characteristics, the dopant increases the production of ROS and improves the disruption of bacterial membranes (Taghavi Fardood et al., 2024). Targeting multidrug-resistant bacteria, which frequently acquire resistance through complex routes, benefits greatly from this synergistic effect.

Green synthesis adaptability also makes it possible to create multipurpose nanomaterials with antibacterial, antioxidant, and anti-inflammatory qualities. Ru-doped and Pd-doped Mn_3O_4 nanoparticles, for instance, it shows other biological advantages such decreased inflammation and enhanced biocompatibility (Vikal et al., 2023). In order to address the complicated pathophysiology linked to MDR bacterial infections, these multifunctional qualities are especially valuable when developing therapeutic drugs that not only eradicate germs but also encourage tissue regeneration and recovery. There are still a number of issues and potential study fields despite the green-synthesized Mn_3O_4 nanoparticles encouraging antibacterial activity and good biocompatibility profiles. The repeatability of the green synthesis techniques is one obstacle.

The thorough assessment of toxicity, both in vitro and in vivo, presents another difficulty. Comprehensive studies into long-term effects, biodistribution, and the capacity to induce oxidative stress in mammalian cells are necessary, despite the fact that numerous studies demonstrate little cytotoxicity for green-synthesized Mn_3O_4 nanoparticles. Such research would aid in addressing any adverse effect concerns and directing clinical translations in a safe and efficient manner (Saod et al., 2022). Future studies should concentrate on improving Mn_3O_4 nanoparticles targeted delivery as well. The selectivity and effectiveness of these nanoparticles may be increased by functionalization with targeting ligands, antibodies, or peptides that precisely identify bacterial antigens. Such focused strategies would maximize the antimicrobial impact on MDR pathogens while minimizing collateral damage to healthy cells and tissues (Imran et al., 2021).

Although there are still issues with targeted distribution, thorough toxicity assessments, and reproducible synthesis, the research now available provides strong proof that green-synthesized Mn_3O_4 nanoparticles can be extremely helpful in reducing the threat posed by MDR bacteria. They may be successfully integrated into a variety of biomedical and environmental applications, such as wound dressings, coatings for medical devices, drug delivery systems, and water treatment technologies, due to their strong antibacterial, antifungal, and anti-inflammatory qualities (Atif et al., 2019). Future studies that tackle the issues mentioned above will be crucial in converting these encouraging lab results into workable, real-world fixes, thereby offering a new line of defense against the swift spread of bacterial diseases that are resistant to drugs.

According to the literature, combining sophisticated nanoparticle engineering techniques with green synthesis methods is a potent way to create next-generation antimicrobial drugs. The antibacterial range and useful uses of Mn_3O_4 nanoparticles will surely be increased by the ongoing improvement of synthesis parameters, surface functionalization strategies, and composite building procedures (Safaei & Moghadam, 2023). In addition to providing novel approaches to combating drug resistant infections, this fusion of green chemistry and nanotechnology supports the growing focus on environmentally conscious and sustainable scientific innovation.

MATERIALS AND METHODS

The article goes into great detail about the many techniques used to create Mn nanoparticles, including their advantages, disadvantages, and working principles.

1. **Sol-gel method:** A commonly used wet chemical procedure called the sol-gel method transforms a liquid (sol) into a gel-like network, that is then dried and calcinated to produce nanoparticles. It is an important method researches used for better. A precursor molecule with a catalyst for triggering sol gel reaction is essential in this case (Lv et al., 2020). And after the controlled ageing process and drying and calcination the required nano particles has been produced.
2. **Co-precipitation Method:** By precipitating Mn ions from a solution using a precipitating agent, the co-precipitation method is a basic and effective technique to synthesis Mn nanoparticles (Joudeh & Linke, 2022). It is rather than simpler process and cost effective as it needs lesser equipment and produces high yield products.
3. **Chemical Reduction Method:** This process creates Mn nanoparticles by employing a potent reducing agent to reduce manganese salt in a solution (Liu et al., 2020). During the addition of the reducing agents like $NaBH_4$ or N_2H_4, a surfactant like PVP is needed to prevent the further aggregation.
4. **Hydrothermal and Solvothermal Method:** This process encourages the production of nanoparticles with a distinct shape by using high temperature and high-pressure conditions in a sealed autoclave. It needs a controlled temperature around 100^o to 250^o Celsius for several hours and then the sample needs to be collected by centrifugation and drying (Manceau & Steinmann, 2021). On the other-hand the Solvothermal method employs solvents rather than water which is similar to hydrothermal method allows a controlled morphological property.
5. **Green Synthesis:** Green synthesis is an environmentally benign method of producing Mn nanoparticles without the use of hazardous chemicals by using plant extracts, microorganisms, or fungi (Kiwumulo et al., 2022). It is more environmentally friendly approach to nullify the toxic effects of the chemicals.

Other than these methods there are several physical methods like Laser ablation, Ball milling and sputtering which needs high energy ball mills to reduce the particle size and a longer making process, on laser ablation method the target molecule targets a liquid or gas medium and lastly splluttering uses the plasma or electric field vaporization method to produce pure nano particles but these techniques are costly as well as expensive (Sarode & Patil, 2021).

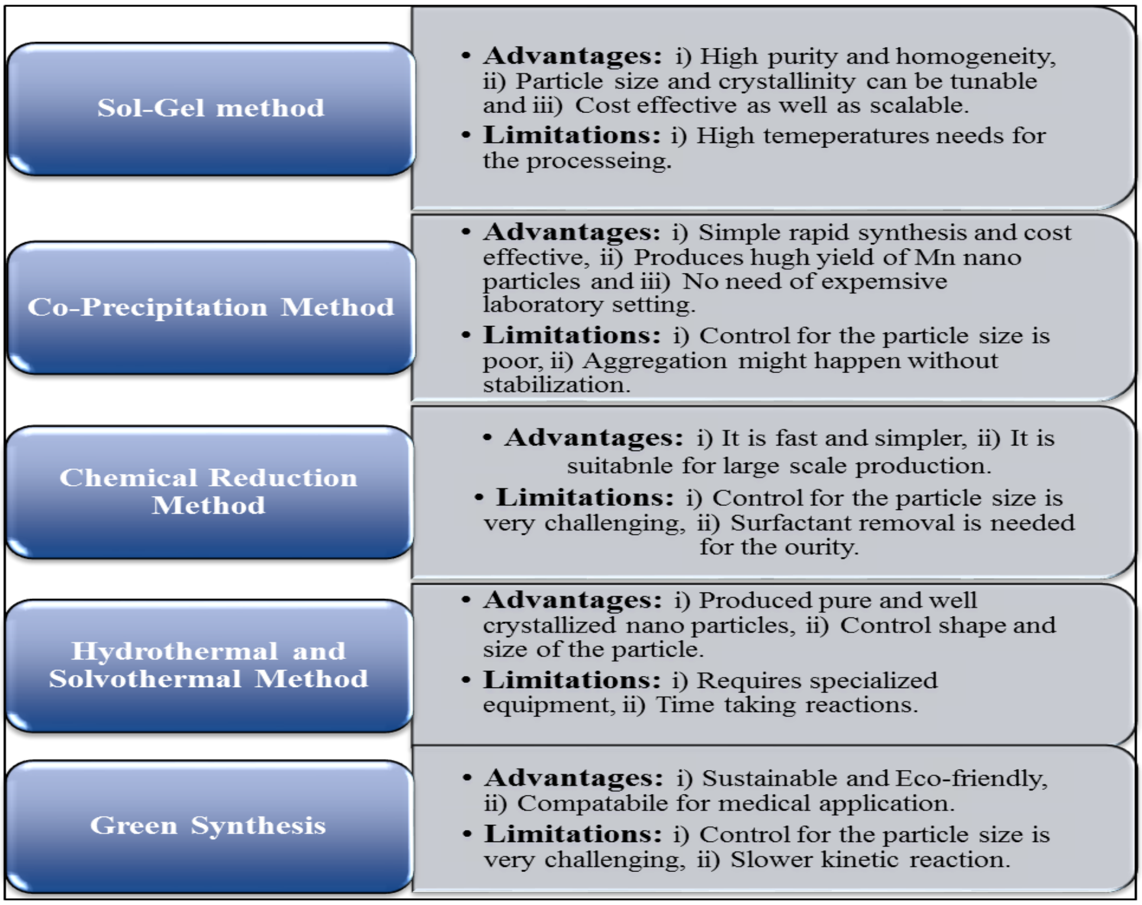

Figure 1: A systematic flowsheet of the Advantages and Limitations of the Mn nanoparticle synthesis methods.

Though the co-precipitation method has its limitations but is easier to perform. To Prepare the preferred Mn_3O_4 nanoparticle we need a Mn precursor whether it may be Manganous sulphate or Manganese II chloride tetrahydrate etc. and a base of Sodium Hydroxide is needed for maintenance of the pH. The schematic presentation of the process is described in a picture format.

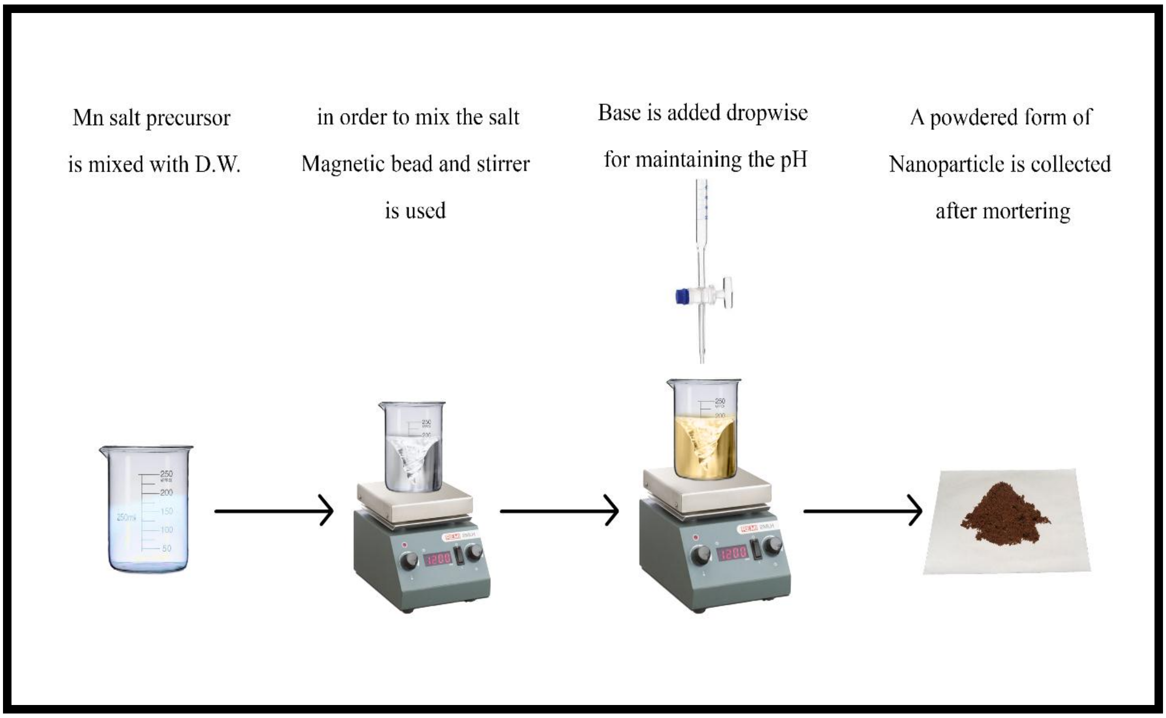

Figure 2: A systematic representation of the co-precipitation process to prepare Mn_3O_4 nanoparticles.

Characterization and Interpretation

There are several data interpretation methods are available that helps to identify the particle size and shapes. X-ray diffraction technique (XRD), Scanning Electron Microscope (SEM), UV spectroscopy, FTIR are helpful to get the proper particle size and shape of the desired nano-particles with different graphical interpretations (Sahoo et al., 2023).

DISCUSSION

The production and analysis of Mn nanoparticles have attached considerable interest because of their distinct characteristics and potentials uses in areas like biomedicine, catalysis, energy storage and environmental achieved, various challenges persist in the production and analysis of Mn nano particles. These challenges are mainly connected to the production techniques, particles characteristics and their biological as well as environmental effects (Patra et al., 2022). Although low-cost and scalable methods, co-precipitation and chemical reduction procedures suffer from poor size control, particle agglomeration, and contaminants. Despite it offers an environmentally benign substitute, the green synthesis method which makes use of biological extracts or bacteria lacks mechanical understanding and repeatability. Furthermore, surface modification and doping techniques to improve biocompatibility, conductivity, and catalytic activity require further refinement (Aboksour et al., 2024). Future research should concentrate on hybrid synthesis approaches, in situ characterization, and computational modeling to improve Mn nanoparticle synthesis while maintaining environmental sustainability and industrial practicality. Regulating the Size Range and Particle Shape Since these characteristics significantly determine the material's surface area, responsiveness, and effectiveness in catalytic and electrical applications, the shape and size of Mn_3O_4 nanoparticles produced by the co-precipitation process are crucial (Joshi et al., 2020). Because of its ease of use, affordability, and environmental friendliness, the co-precipitation approach has several advantages over more intricate synthesis routes. It reduces environmental risks and does away with the need for hazardous organic solvents by using water as a solvent and ordinary reagents like $MnSO_4$ and NaOH (Shaik et al., 2021). Prospects for the Future and Optimization Techniques The goal of ongoing research on co-precipitation synthesis of Mn_3O_4 is to overcome existing obstacles and improve the material's functional performance even more.

CONCLUSION

Manganese (Mn) nanoparticle production has evolved dramatically, with approaches such as sol-gel, co-precipitation, chemical reduction, and hydrothermal synthesis providing distinct advantages in terms of particle size control, crystallinity, and scalability. However, problems like as particle agglomeration, stability issues, and the requirement for high-temperature processing remain significant constraints (Sivakumar & Nelson Prabu, 2021). While green synthesis has emerged as an environmentally acceptable option, its repeatability and mechanistic understanding require additional investigation. Furthermore, surface modification and doping procedures must be adjusted to improve the biocompatibility, catalytic effectiveness, and electrical characteristics of Mn nanoparticles for specific applications (Blinov et al., 2020). Future studies should concentrate on better in-situ characterization for real-time monitoring, computational modeling to optimize synthesis settings, and hybrid synthesis methodologies to combine the benefits of several processes (Dessie et al., 2020). The integration of Mn nanoparticles in biomedical, environmental, and energy-related applications, surface changes for improved biocompatibility and catalytic performance, and economical, scalable production methods should also be the focus of efforts. Filling up these gaps will enable Mn nanoparticles to be widely used and commercialized in advanced technologies. Most importantly Green Synthesis techniques is one of the most important areas of this research to ponder over in future.

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