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APPLICATION OF ENGINEERED NANOPARTICLES IN THE DEGRADATION OF BIOMEDICAL WASTE: A REVIEW

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Abstract: Biomedical waste (BMW) is a critical global concern due to its infectious, hazardous, and non-biodegradable nature. Traditional disposal methods like incineration and landfilling have proven inadequate due to their environmental and health hazards. In recent years, nanotechnology—particularly engineered nanoparticles (ENPs)—has emerged as a promising tool for the efficient degradation and detoxification of biomedical waste. This review explores the applications of various ENPs in biomedical waste degradation, focusing on their mechanisms, efficiency, challenges, and future directions.

Key Words: Biomedical waste, Engineered nanoparticle (ENP), Photocatalytic degradation

Introduction: The exponential growth of biomedical waste (BMW), especially during global health crises such as the COVID-19 pandemic, has raised significant concerns about environmental pollution, public health hazards, and waste management infrastructure.[1] Biomedical waste encompasses a wide range of hazardous materials including infectious substances, pharmaceuticals, sharps, pathological waste, and synthetic polymers such as plastics and latex. Inappropriate disposal and insufficient treatment of such waste can lead to the propagation of antibiotic-resistant microorganisms, contamination of soil and water bodies, and increased burden on ecosystems and human health.[2,3]

Conventional BMW management methods—such as

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incineration, landfilling, autoclaving, and chemical disinfection—are widely practiced but remain limited in their ability to completely neutralize persistent organic pollutants (POPs), heavy metals, and synthetic polymers. Incineration, for instance, is effective in reducing waste volume but releases toxic gases such as dioxins, furans, and volatile metals.[4] Landfilling leads to long-term leaching of contaminants into groundwater and soil. As a result, there is a growing need for alternative, environmentally sustainable, and technologically advanced solutions for the degradation and detoxification of biomedical waste.

Nanotechnology, particularly in the form of engineered nanoparticles (ENPs), has emerged as a transformative tool in environmental remediation, including waste degradation. ENPs are defined as particles with at least one dimension below 100 nanometers and are engineered to exhibit specific physical, chemical, or biological properties.[5] Due to their high surface area-to-volume ratio, enhanced reactivity, and tunable surface functionalities, ENPs offer significant advantages in degrading organic, inorganic, and microbial contaminants present in BMW.[6]

Various classes of ENPs—such as metal nanoparticles (e.g., silver, copper), metal oxides

(e.g., titanium dioxide, zinc oxide, iron oxide), carbon-based nanomaterials (e.g., graphene oxide, carbon nanotubes), and polymeric nanoparticles—have been extensively studied for their role in environmental applications.[7] These nanoparticles exhibit multiple mechanisms for BMW treatment, including photocatalytic degradation of organic pollutants, antimicrobial activity against pathogenic microorganisms, redox-based transformation of heavy metals, and adsorption of pharmaceuticals and dyes.[8,9]

Among these, titanium dioxide (TiO_2) and zinc oxide (ZnO) nanoparticles are particularly well-known for their photocatalytic properties, enabling the decomposition of complex organic molecules under light irradiation.[10] Likewise, zero-valent iron nanoparticles (nZVI) are widely used for the reduction of heavy metals and chlorinated compounds in contaminated media.[11] Carbon-based nanomaterials, due to their large π-conjugated systems and high adsorption capacity, have also been employed to sequester pharmaceutical residues and viral particles from hospital effluents.[12]

However, the application of ENPs in BMW degradation is not without challenges. Issues such as nanoparticle toxicity, environmental persistence, cost-effectiveness, and regulatory uncertainties require thorough assessment and sustainable engineering solutions.[13] Despite these concerns, the integration of nanotechnology with waste management practices holds immense promise. This review aims to explore the diverse roles of engineered nanoparticles in the degradation of biomedical waste, discussing their mechanisms, efficacy, current applications, limitations, and future potential.

Engineered Nanoparticles (ENPs): An Overview

Engineered nanoparticles (ENPs) are synthetically designed nanomaterials with at least one dimension ranging between 1 and 100 nanometers. Due to their tunable physicochemical properties—such as high surface area-to-volume ratio, shape anisotropy, surface charge, and enhanced reactivity—ENPs have become a transformative tool in diverse fields, including biomedicine, environmental remediation,

and waste management.[5] In the context of biomedical waste (BMW) degradation, ENPs offer unique advantages over traditional materials due to their catalytic activity, antimicrobial efficacy, and ability to degrade persistent organic pollutants under mild environmental conditions.

ENPs can be broadly categorized into several types based on their chemical composition and functional properties:

Metal and Metal Oxide Nanoparticles: Metallic nanoparticles—such as silver (Ag), gold (Au), and copper (Cu)—and metal oxides like titanium dioxide (TiO_2), zinc oxide (ZnO), and iron oxides (Fe_2O_3, Fe_3O_4) are among the most commonly used ENPs for waste treatment. These nanoparticles exhibit strong photocatalytic, oxidative, and antimicrobial properties. For instance, TiO_2 and ZnO nanoparticles are known to generate reactive oxygen species (ROS) under UV or visible light, leading to the degradation of complex organic molecules present in biomedical effluents.[10] Silver nanoparticles have demonstrated potent antimicrobial activity, making them ideal for the inactivation of pathogens in infectious medical waste.[9]

Carbon-Based Nanomaterials: Carbon nanomaterials such as graphene oxide (GO), carbon nanotubes (CNTs), fullerenes, and activated carbon derivatives exhibit high sorption capacity, structural stability, and chemical inertness. These materials are particularly useful for the adsorption of pharmaceutical residues, dyes, and heavy metals from BMW.[12] The π-conjugated structure and functionalizable surface of GO and CNTs enable efficient interaction with organic molecules, which enhances their applicability in waste treatment technologies.

Polymeric and Biopolymer-Based Nanoparticles: Polymeric ENPs, including dendrimers, micelles, and nanogels, are designed for controlled release and biocompatibility. Their ability to encapsulate and degrade pharmaceutical compounds makes them suitable for detoxifying chemical components in hospital waste. These materials can also serve as

carriers for enzymes or catalysts that facilitate biotransformation reactions.[14]

Composite and Hybrid Nanoparticles: Hybrid ENPs are synthesized by combining two or more nanomaterials to achieve multifunctionality. For example, Fe_2O_3-TiO_2 composites integrate magnetic recovery with photocatalytic degradation, making them highly efficient and recyclable in continuous treatment systems.[15] Similarly, Ag-ZnO hybrids combine antimicrobial and oxidative properties for treating infectious and pharmaceutical waste simultaneously.

The application of ENPs in biomedical waste management is guided by factors such as reactivity, selectivity, environmental stability, ease of recovery, and low toxicity. Recent advances in green synthesis methods—using plant extracts, microbial systems, or biopolymers—aim to minimize environmental risks associated with nanoparticle release and accumulation.[16]

While ENPs hold substantial promise, challenges such as nanoparticle aggregation, cytotoxicity, cost of production, and regulatory gaps must be addressed before their large-scale application. Nevertheless, with continuous research and innovation, engineered nanoparticles represent a highly adaptable and sustainable platform for the degradation and detoxification of hazardous biomedical waste.

Mechanisms of Biomedical Waste Degradation by ENPs: Engineered nanoparticles (ENPs) offer a range of physicochemical mechanisms to degrade, detoxify, or immobilize contaminants commonly found in biomedical waste (BMW). These mechanisms vary depending on the type of nanoparticle, the chemical nature of the waste, and the treatment conditions. Biomedical waste typically contains pharmaceuticals, biological pathogens, synthetic polymers, and toxic metals, which require multi-pronged strategies for complete neutralization. ENPs are especially valuable in this context due to their catalytic, adsorptive, oxidative, and antimicrobial properties.[5]

Photocatalytic Degradation: Photocatalysis is among the most studied and effective mechanisms by which ENPs degrade persistent organic pollutants in biomedical waste. Metal oxide nanoparticles, particularly titanium dioxide (TiO_2) and zinc oxide (ZnO), generate reactive oxygen species (ROS) such as hydroxyl radicals ($\bullet OH$) and superoxide anions ($O_2\bullet-$) under UV or visible light exposure. These ROS attack the molecular structure of organic pollutants—such as drug residues, dyes, and proteins—leading to their mineralization into harmless end products like CO_2 and H_2O.[10,17] This approach is especially useful for degrading antibiotics and cytotoxic drugs in hospital wastewater.

Adsorption and Sequestration: Carbon-based ENPs such as graphene oxide (GO), carbon nanotubes (CNTs), and activated carbon nanoparticles are widely utilized for their exceptional adsorptive capacity. The high surface area, π-π interactions, and abundant surface functional groups enable these materials to adsorb pharmaceutical compounds, endocrine-disrupting chemicals (EDCs), and pathogens from liquid biomedical waste.[12] This non-destructive process is reversible and can be optimized for selective removal of contaminants using surface modifications.

Redox-Based Chemical Transformation: Zero-valent iron nanoparticles (nZVI) and other redox-active metal nanoparticles facilitate electron transfer reactions that break down toxic compounds or convert them into less harmful species. For instance, nZVI can dechlorinate persistent organic compounds or reduce hexavalent chromium (Cr^{6+}) to the less toxic trivalent form (Cr^{3+}).[11] This redox mechanism is particularly effective for the detoxification of heavy metals and chlorinated pharmaceutical by-products in biomedical effluents.

Antimicrobial and Antiviral Activity: Biomedical waste often contains pathogenic microorganisms including bacteria, viruses, and fungi. Metallic ENPs—especially silver (Ag), copper (Cu), and their oxides—exert broad-spectrum antimicrobial effects. These nanoparticles disrupt microbial membranes, generate intracellular oxidative stress, and interfere with protein and DNA replication

processes, ultimately leading to cell death.[9] This mechanism makes ENPs highly effective in disinfecting surgical waste, PPE residues, and other infectious components.

Enzyme-Mimetic (Nanozyme) Activity: Some ENPs, particularly cerium oxide (CeO_2), iron oxide (Fe_2O_3), and platinum nanoparticles, mimic the activity of natural enzymes such as peroxidases and oxidases. These "nanozymes" catalyze oxidative reactions under ambient conditions and can be applied to degrade organic toxins and biofilm-forming pathogens in biomedical waste.[18] Nanozymes present a promising, low-energy alternative to harsh chemical disinfectants.

Conclusion: The degradation of biomedical waste via ENPs is governed by diverse and tunable mechanisms, each suitable for specific classes of waste materials. Photocatalytic degradation is best for persistent organics; redox processes target heavy metals and chlorinated compounds; while antimicrobial nanoparticles ensure disinfection of infectious waste. Integrating these mechanisms into a unified treatment system could lead to a highly efficient, modular approach to biomedical waste management.

Specific Applications

Degradation of Pharmaceutical Waste: Engineered TiO_2 and ZnO nanoparticles have been effectively used to photodegrade persistent pharmaceutical residues such as antibiotics and hormones from hospital wastewater. [12, 13]

Treatment of Infectious Waste: Silver and copper nanoparticles, known for their antimicrobial properties, have been incorporated into polymer matrices for coating PPE and surgical tools, enabling self-disinfection.[7]

Plastic and Polymer Waste Management: Nanocatalysts such as cerium oxide (CeO_2) and nano-clays can accelerate the breakdown of plastic polymers like polyethylene and polystyrene in medical disposables.[19]

Heavy Metal Detoxification: nZVI and Fe_2O_3 nanoparticles have been employed in removing toxic metals such as mercury, cadmium, and lead from biomedical effluents.[4]

Challenges and Limitations: Despite their advantages, several challenges persist:

- **Toxicity and Environmental Persistence**: Uncontrolled release of ENPs can pose new environmental risks.
- **Cost and Scalability**: Large-scale production and deployment remain expensive.
- **Regulatory Frameworks**: Lack of standardized guidelines for nanoparticle use in waste treatment hinders practical implementation.

Future Perspectives: Advancements in green synthesis methods, bio-inspired ENPs, and hybrid nanocomposites may enhance the applicability and safety of these materials. Integrated approaches combining ENPs with biological or physicochemical methods (e.g., photocatalysis + biodegradation) may offer synergistic effects.[20]

Machine learning and AI can also aid in optimizing nanoparticle design for target-specific BMW degradation.[21]

Conclusion: Engineered nanoparticles offer a promising alternative to traditional biomedical waste treatment methods due to their efficiency, specificity, and versatility. With ongoing innovations in nanomaterials science, their application can significantly mitigate the risks associated with biomedical waste, provided the challenges around safety and scalability are addressed.

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