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# From waste to wonder: Developing engineered nanomaterials for multifaceted applications

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## Abstract

The escalating generation of industrial and consumer waste poses a significant environmental challenge, necessitating innovative approaches to waste management and resource utilization. One promising solution lies in the transformation of waste materials into engineered nanomaterials (ENMs), which hold immense potential for a diverse range of applications. This review explores the development of ENMs from waste, highlighting their multifaceted uses in environmental remediation, energy storage, medical applications, and advanced manufacturing. The process of converting waste into ENMs involves sophisticated techniques such as chemical vapour deposition, sol-gel synthesis, and hydrothermal methods, which enable the creation of materials with precise structural and functional properties at the nanoscale. By utilizing waste as a raw material, this approach not only addresses waste disposal issues but also provides a sustainable and cost-effective source of high-value nanomaterials. ENMs derived from waste exhibit unique properties, including high surface area, tunable porosity, and enhanced reactivity, making them suitable for environmental applications such as pollutant adsorption, water purification, and air filtration. In the energy sector, these nanomaterials contribute to the development of advanced batteries, supercapacitors, and fuel cells, enhancing energy storage and conversion efficiency. The biomedical field benefits from waste-derived ENMs through their application in drug delivery systems, diagnostic tools, and tissue engineering. The biocompatibility and functional versatility of these materials enable targeted therapeutic interventions and innovative medical solutions. Furthermore, in advanced manufacturing, ENMs improve the performance and durability of materials used in electronics, coatings, and composites, fostering the development of next-generation products with superior properties. The integration of waste-derived ENMs into various industries represents a paradigm shift towards a circular economy, where waste is not merely a byproduct but a valuable resource. This approach aligns with global sustainability goals, promoting resource efficiency, reducing environmental impact, and driving technological advancements. In conclusion, the development of engineered nanomaterials from waste exemplifies the transformative potential of nanotechnology in addressing critical environmental and industrial challenges. By harnessing waste as a resource, this innovative approach paves the way for multifaceted applications that contribute to environmental sustainability, technological progress, and economic growth. Further research and development in this field will continue to expand the possibilities and impact of waste-derived ENMs in various sectors.

**Keywords:** Waste to Wonder; Nanomaterials; Multifaceted; Applications; Engineered

## 1. Introduction

The global waste problem has reached critical proportions, posing significant environmental, economic, and health challenges. With the ever-increasing production and consumption patterns, the world is generating waste at an unprecedented rate (Dalai, et. al., 2024, Nagaraj, et. al., 2024). Municipal solid waste, industrial waste, electronic waste, and hazardous waste contribute to this growing crisis. Improper waste management practices, such as open dumping

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and incineration, exacerbate pollution, greenhouse gas emissions, and resource depletion. The need for sustainable and innovative solutions to address this pressing issue is more urgent than ever.

Nanotechnology, with its ability to manipulate materials at the molecular and atomic levels, offers transformative potential in waste management. The unique properties of nanomaterials, such as high surface area, reactivity, and tunable physical and chemical characteristics, make them ideal candidates for addressing various aspects of the waste problem (Khan, et. al., 2022, Sharma, et. al., 2021). Nanotechnology can contribute to waste reduction, recycling, and remediation by providing advanced materials and techniques for efficient waste processing, pollutant removal, and resource recovery. The integration of nanotechnology into waste management practices presents a promising pathway to mitigating the environmental impact of waste and enhancing sustainability.

Engineered nanomaterials (ENMs) derived from waste materials represent a novel and sustainable approach to managing waste while creating value-added products. By converting waste into functional nanomaterials, it is possible to address waste disposal challenges and simultaneously develop materials with multifaceted applications (Jain, et. al., 2021, Mazari, et. al., 2021). ENMs can be synthesized from various waste streams, including agricultural residues, industrial by-products, electronic waste, and plastics. These nanomaterials can be tailored for specific applications in fields such as environmental remediation, energy storage, catalysis, and medicine. The development of ENMs from waste not only contributes to waste reduction but also promotes a circular economy by turning waste into valuable resources.

The purpose of this outline is to explore the development of engineered nanomaterials from waste for multifaceted applications. It aims to provide a comprehensive overview of the current state of research, highlight the potential benefits and challenges, and propose future directions for the field (Ahmed, et. al., 2020, Impram, Nese & Oral, 2020, Li, Zhou & Chen, 2020). The outline will cover the following key areas: Discuss various techniques for synthesizing ENMs from waste materials, including chemical, physical, and biological methods. Describe the methods used to characterize the properties and performance of ENMs, ensuring their suitability for intended applications. Explore the diverse applications of ENMs derived from waste, focusing on environmental, energy, and biomedical fields. Present real-world examples and case studies demonstrating the successful implementation of ENMs from waste in practical applications. Identify the challenges and limitations in the development and application of ENMs from waste and propose future research and innovation opportunities. The development of engineered nanomaterials from waste represents a promising strategy for addressing the global waste problem while creating high-value materials with diverse applications (Bhattacharjee, et. al., 2023, Levchenko, et. al., 2022). This outline aims to provide a structured framework for understanding the potential and challenges of this innovative approach, highlighting its significance in advancing sustainable waste management and promoting a circular economy.

## 2. Methodology

The methodology for this systematic review is structured around the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines. The review protocol was registered with an international prospective register of systematic reviews to ensure transparency and reproducibility. Studies that focus on the development and application of engineered nanomaterials derived from waste materials, including their physical, chemical, and functional properties, and potential applications in various industries such as electronics, healthcare, and environmental management. Studies that do not specifically address waste-derived nanomaterials or their multifaceted applications, reviews, and non-peer-reviewed publications.

Databases such as PubMed, Scopus, Web of Science, and Google Scholar will be searched for relevant literature. Reference lists of identified articles and relevant reviews will also be examined for additional sources. A comprehensive search strategy will be developed using a combination of keywords and MeSH terms tailored to capture all relevant studies. Terms will include "engineered nanomaterials," "waste-derived," "nanotechnology applications," and specific waste materials known for nanomaterial conversion. Full texts of potentially eligible studies will be retrieved and assessed in detail against the inclusion criteria. Disagreements will be resolved through discussion or consultation with a third reviewer. Data extracted will include authors, year of publication, study location, type of waste material used, methods of nanomaterial synthesis, characterizations performed, and detailed accounts of applications tested. The quality of included studies will be assessed using an established risk of bias tool appropriate for observational studies. Aspects such as study design, methodology, and reporting will be evaluated.

A qualitative synthesis of findings will be presented due to the expected heterogeneity in study designs and outcomes. Where possible, thematic analysis will be used to group findings by application type or material characteristics. If data permits, subgroup analyses will be conducted based on different types of waste materials or application sectors.

Sensitivity analyses will be employed to assess the robustness of the study findings. This systematic methodology aims to provide a comprehensive and unbiased overview of the current landscape in engineered nanomaterials derived from waste, highlighting innovative applications and informing future research directions. The findings are shown in the spread of publications as shown in figure 1.

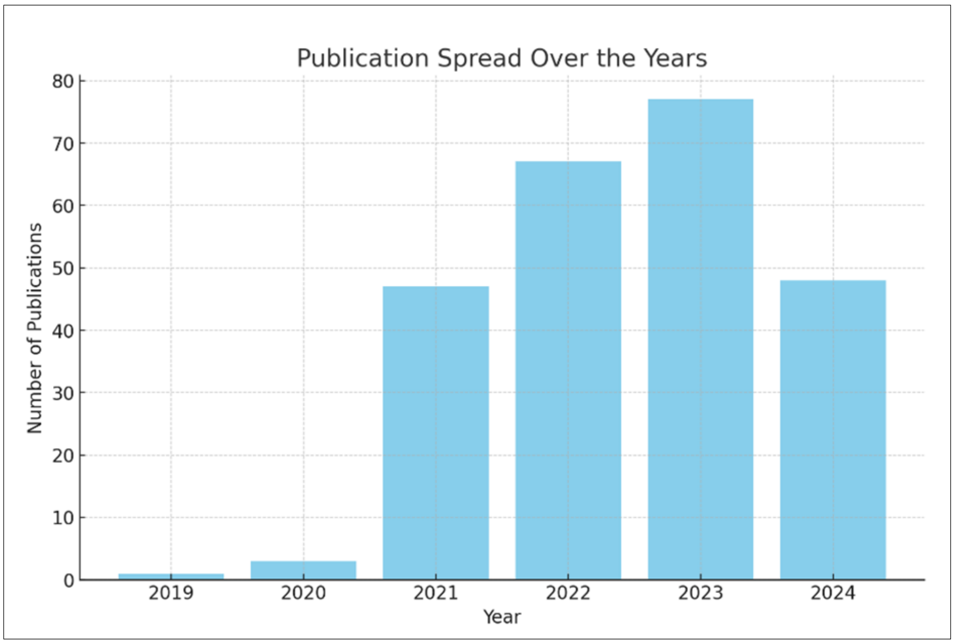


**Figure 1** Spread of publications on the subject

### 2.1. Transformation of Waste into Engineered Nanomaterials

The transformation of waste into engineered nanomaterials (ENMs) represents a promising avenue for sustainable waste management and the development of advanced materials with unique properties and applications (Gielen, et. al., 20219, Li, et. al., 2022, Veers, et. al., 2019). This process involves converting various types of waste, including industrial, consumer, and agricultural waste, into nanomaterials through synthesis techniques such as chemical vapour deposition, sol-gel synthesis, hydrothermal methods, and other advanced techniques. These ENMs exhibit structural and functional properties that make them highly valuable in a range of applications, including high surface area, tunable porosity, and enhanced reactivity.

Abdelbasir, et. al., (2020) presented a Schematical Representation of waste management systems as shown in Figure 2.

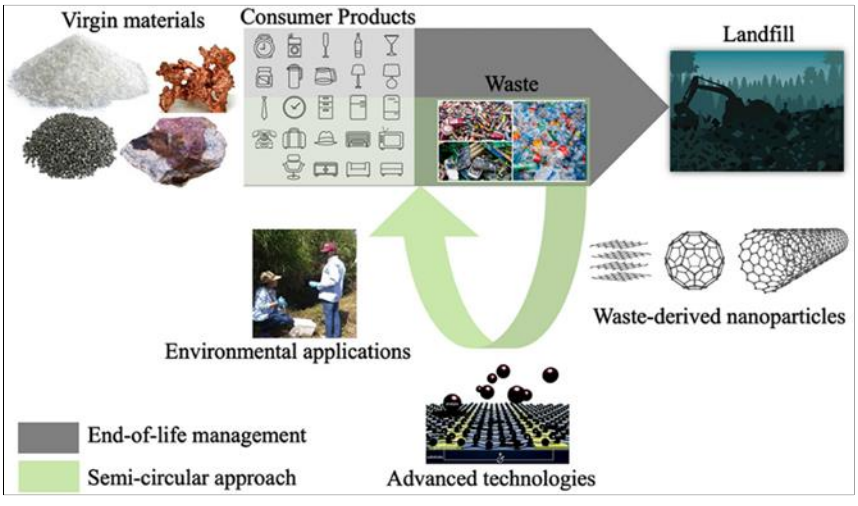


**Figure 2** Schematical Representation of waste management (Abdelbasir, et. al., 2020)

Industrial processes generate significant amounts of waste, including byproducts and materials that are no longer useful in their current form. These wastes often contain valuable components that can be transformed into ENMs. Consumer waste, such as plastic and electronic waste, represents a significant environmental challenge (Khan, et. al., 2022, Sharma, et. al., 2021). However, these materials can also serve as feedstock for the production of ENMs. Agricultural activities produce large quantities of waste, including crop residues and animal manure. By converting these wastes into ENMs, we can reduce the environmental impact of agriculture while creating value-added products.

CVD is a common technique used to synthesize thin films and coatings. In the context of waste transformation, CVD can be used to convert waste gases into carbon-based nanomaterials. Sol-gel synthesis is a versatile technique for producing ceramic and glass materials (Ahmed, et. al., 2020, Impram, Nese & Oral, 2020, Li, Zhou & Chen, 2020). It can also be used to convert waste materials into silica and metal oxide nanomaterials. Hydrothermal methods involve the use of high-pressure, high-temperature conditions to synthesize nanomaterials from aqueous solutions. This approach can be used to convert biomass and other organic waste into carbon-based nanomaterials. There are several other advanced synthesis techniques, such as microwave-assisted synthesis, electrospinning, and ball milling, that can be used to transform waste into ENMs. A Classification of nanomaterials from wastes is shown in Figure 3 as presented by Abd Elkodous, et. al. (2022).

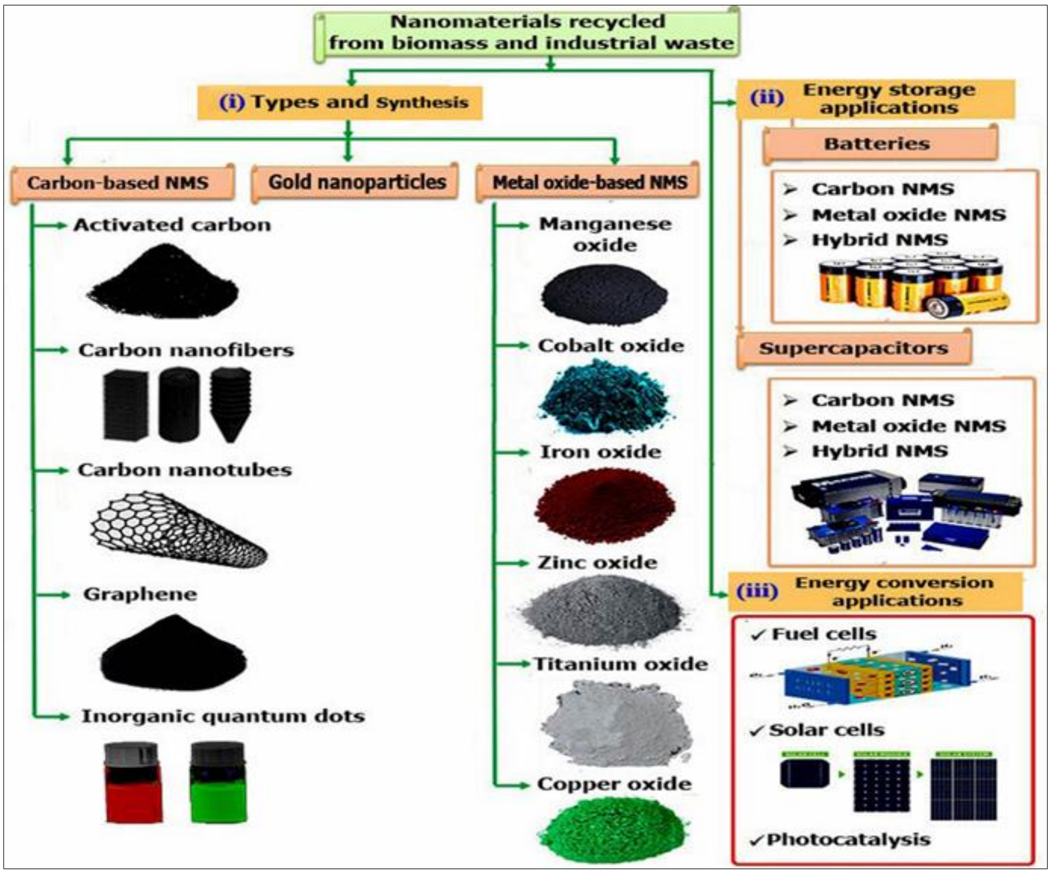


**Figure 3** Classification of nanomaterials from wastes (Abd Elkodous, et. al. 2022)

ENMs typically have a high surface area-to-volume ratio, which makes them highly reactive and suitable for applications such as catalysis and sensors. The porosity of ENMs can be tailored during the synthesis process, allowing for the creation of materials with specific pore sizes and distributions (Hamdan, et. al., 2024, Masoumi, 2023, Ohalete, et. al., 2023). This property is valuable for applications such as gas storage and separation. ENMs often exhibit enhanced reactivity compared to bulk materials due to their small size and high surface area. This makes them suitable for use in applications such as pollutant removal and drug delivery. In conclusion, the transformation of waste into engineered nanomaterials represents a sustainable approach to waste management and the development of advanced materials (Ahmed, et. al., 2020, Impram, Nese & Oral, 2020, Li, Zhou & Chen, 2020). By converting waste into valuable ENMs, we can reduce the environmental impact of waste disposal while creating new opportunities for the use of these materials in a wide range of applications.

### 2.2. Environmental Applications

From Waste to Wonder: Developing Engineered Nanomaterials for Multifaceted Applications offers a groundbreaking approach to addressing environmental challenges through the creation of advanced materials from waste streams (Durbhaka, 2021, Garan, Tidriri & Kovalenko, 2022, Selvaraj & Selvaraj, 2022). This innovative concept not only addresses waste management but also provides solutions for critical environmental issues. Here, we delve into the environmental applications of these engineered nanomaterials (ENMs), focusing on pollutant adsorption, water purification, and air filtration. One of the key environmental applications of ENMs is in pollutant adsorption. These materials have shown remarkable capabilities in adsorbing various pollutants, including heavy metals and organic pollutants.

ENMs, such as carbon nanotubes and graphene oxide, have demonstrated high adsorption capacities for heavy metals like lead, cadmium, and mercury (Jordan & Randy, 2024, Li, et. al., 2024, Salehpour & Hossain, 2024). Their large surface area and high reactivity make them ideal candidates for removing heavy metals from contaminated water and soil. ENMs have also shown promise in adsorbing organic pollutants, such as dyes, pesticides, and pharmaceuticals. Materials like activated carbon nanoparticles and magnetic nanoparticles have been used to effectively remove these contaminants from water and wastewater. ENMs have revolutionized water purification processes by offering efficient and sustainable solutions for removing contaminants from water sources. ENMs can be integrated into filtration systems to remove particulate matter and impurities from water (Forootan, et. al., 2022, Ponkumar, Jayaprakash & Kanagarathinam, 2023, Qureshi, Umar & Nawaz, 2024). Membranes coated with ENMs, such as graphene or nanocellulose, have shown improved filtration efficiency and reduced fouling compared to traditional membranes. ENMs with catalytic properties, such as metal nanoparticles and metal-organic frameworks, can be used to degrade organic pollutants in water through advanced oxidation processes. These materials can break down contaminants into harmless byproducts, improving water quality.

In addition to water purification, ENMs offer solutions for air filtration, particularly in removing particulate matter and gaseous pollutants from the air (Schmidgall, et. al., 2024, Stanley, et. al., 2019, Yang & Wang, 2020). ENMs, such as titanium dioxide nanoparticles and carbon nanotubes, can be used in air filters to capture fine particulate matter (PM2.5 and PM10). These materials can efficiently trap particles, improving indoor and outdoor air quality. ENMs have also been studied for their ability to adsorb and catalytically degrade gaseous pollutants, such as nitrogen oxides (NOx) and volatile organic compounds (VOCs). Metal oxide nanoparticles and zeolites have shown promise in reducing these pollutants in air purification systems. In conclusion, the environmental applications of From Waste to Wonder: Developing Engineered Nanomaterials for Multifaceted Applications offer innovative solutions to pressing environmental challenges (Atteia, Mengash & Samee, 2021, Krishnan, Kodamana & Bhattoo, 2024, Yan, et. al., 2021). By harnessing the potential of ENMs, we can create sustainable and effective strategies for pollutant adsorption, water purification, and air filtration, contributing to a cleaner and healthier environment.

### 2.3. Energy Applications

From Waste to Wonder: Developing Engineered Nanomaterials for Multifaceted Applications holds immense potential in revolutionizing energy applications, particularly in the areas of advanced batteries, supercapacitors, and fuel cells (Alkesaiberi, Harrou & Sun, 2022, Dubey, et. al., 2022, Qadir, et. al., 2021). These materials offer enhanced performance, improved efficiency, and sustainability, paving the way for a cleaner and more efficient energy future. ENMs play a crucial role in the development of advanced batteries, offering improvements in energy storage capacity, charging rates, and overall performance. ENMs, such as graphene, carbon nanotubes, and metal oxides, are used as electrode materials in batteries due to their high surface area, electrical conductivity, and stability. These materials enable the storage and release of energy more efficiently than traditional materials, leading to longer-lasting and faster-charging batteries (Cevasco, Koukoura & Kolios, 2021, Sanchez-Fernandez, et. al., 2023, Sheng & O'Connor, 2023). By incorporating ENMs into battery electrodes, researchers have achieved significant improvements in energy density, cycle life, and power output. These advancements are essential for the widespread adoption of electric vehicles and renewable energy storage systems.

ENMs have also been instrumental in the development of supercapacitors, offering high energy storage capabilities and rapid charge-discharge rates. ENMs, such as carbon-based materials and metal oxides, exhibit high specific surface areas and capacitances, making them ideal for use in supercapacitors (Miele, 2023, Olajiga, et. al., 2024, Pandit & Wang, 2024). These materials enable the storage of large amounts of energy in a small volume, providing a compact and efficient energy storage solution. The design of supercapacitor electrodes using ENMs allows for the optimization of pore size, surface area, and conductivity, leading to improved energy storage performance. These advancements are crucial for applications requiring rapid energy release, such as regenerative braking in vehicles. ENMs have shown promise in enhancing the efficiency and performance of fuel cells, which convert chemical energy into electrical energy through electrochemical reactions. ENMs, such as platinum nanoparticles and metal-organic frameworks, serve as catalysts in fuel cells, facilitating oxygen reduction and hydrogen oxidation reactions (Liang, et. al., 2022, Song, et. al., 2019). These materials offer higher catalytic activity and durability than traditional catalysts, leading to more efficient fuel cell operation. By utilizing ENMs as catalysts, researchers have been able to improve the efficiency and durability of fuel cells, making them more suitable for a wide range of applications, including portable electronics, vehicles, and stationary power generation. In conclusion, the energy applications of From Waste to Wonder: Developing Engineered Nanomaterials for Multifaceted Applications offer transformative solutions for energy storage and conversion (Ahmed, et. al., 2020, Impram, Nese & Oral, 2020, Li, Zhou & Chen, 2020). By harnessing the unique properties of ENMs, we can create more efficient and sustainable energy technologies, contributing to a cleaner and greener future.

### 2.4. Biomedical Applications

Biomedical applications of engineered nanomaterials (ENMs) offer promising solutions in drug delivery systems, diagnostic tools, and tissue engineering (Pandey & Jadoun, 2023, Rahimi, et. al., 2022, Ullah, et. al., 2023). These applications revolutionize the field of medicine by providing targeted therapies, precise diagnostic tools, and advanced regenerative medicine approaches. ENMs have significantly impacted drug delivery systems, enabling targeted therapy and controlled release mechanisms. ENMs can be functionalized to target specific cells or tissues, minimizing side effects and maximizing therapeutic efficacy. By attaching targeting ligands to ENMs, drugs can be delivered directly to diseased cells, reducing the dosage required for effective treatment. Table 1 shows the Potential value-added applications for recycled plastics as presented by Abdelbasir, et. al., (2020).

**Table 1** Potential value-added applications for recycled plastics (Abdelbasir, et. al., 2020)

| Recycled plastics | Value-added applications | Expected advantages | Foreseen challenges |
|---|---|---|---|
| PET, PP, PS, LDPE, HDPE, PVC | Production of liquid fuels. | Reduced need for oil extraction from natural reserves. | High cost associated with complex thermochemical processes. Generation of hazardous byproducts. |
| PP, LDPE, PS | Production of construction materials. | Possibility of utilizing mixed plastics. | Requires ultrafine grinding and thorough mixing to reduce variability in thermal and mechanical properties. |
| LLDPE | Production of printable paper. | High affinity with ink, hydrophobicity, and durability under harsh conditions. | Involves the use of hazardous organic solvents. |
| PVC, PET, PP | Production of fibres. | Reduced plastic waste volumes disposed to landfills. | Impurities and contamination potentially present in recycled materials produce significant variations in the properties of the fibres. |
| LDPE, PET, HDPE, PVC, PS | Production of new polymers. | Reduced dependence on petrochemicals for plastic production. Catalytic methods for the chemical recycling of polymers are less energy-intensive than thermolysis methods. | Isolation and purification of monomers from chemically treated recycled polymers can be expensive. The mechanical properties of the newly synthesized polymers may not meet the conventional requirements. |
| PP | Production of polar waxes | Facile 2-step process. Requires low-toxic solvents that can be recirculated into the process. The rheological properties of the obtained waxes are similar to the commercial ones. | Over time, wax deposition may affect the equipment required for the process. |
| PP, PET | Production of carbon nanoparticles | Attractive for applications in a plethora of advanced technologies. | Toxicity concerns; particularly in occupational settings where the nanoparticles are manufactured and handled in large quantities. |

ENMs can be engineered to release drugs in a controlled manner, ensuring sustained therapeutic levels over an extended period. This is particularly beneficial for drugs with narrow therapeutic windows or those requiring long-term treatment (Alzammar, 2023, Hamdan, et. al., 2024, Qureshi, Umar & Nawaz, 2024). ENMs have also been instrumental in the development of advanced diagnostic tools, including biosensors and imaging agents. ENMs can be integrated into biosensors for the detection of biomolecules, such as proteins, nucleic acids, and metabolites. The high sensitivity and selectivity of ENMs enable the early detection of diseases, leading to timely intervention and improved patient outcomes. ENMs can act as contrast agents for various imaging modalities, including magnetic resonance imaging (MRI), computed tomography (CT), and positron emission tomography (PET). These imaging agents enhance the visibility of tissues and organs, allowing for more accurate diagnosis and treatment planning (Fox, et. al., 2022, Tjernberg, 2023, Turnbull & Carroll, 2021). ENMs play a crucial role in tissue engineering, providing scaffolds and regenerative medicine solutions for tissue repair and regeneration. ENMs can be incorporated into scaffolds to mimic the extracellular matrix (ECM) of tissues, providing a supportive environment for cell growth and differentiation. These scaffolds promote tissue regeneration and repair, offering potential treatments for damaged or diseased tissues.

ENMs can deliver bioactive molecules, such as growth factors and cytokines, to promote tissue regeneration. By providing a controlled environment for cell growth, ENMs enhance the effectiveness of regenerative medicine approaches, leading to improved outcomes for patients (Chen, et. al., 2021, Xiang, et. al., 2022, Zhang, Hu & Yang, 2022). In conclusion, the biomedical applications of engineered nanomaterials offer transformative solutions in drug delivery, diagnostics, and tissue engineering. By harnessing the unique properties of ENMs, we can revolutionize the field of medicine, providing more effective and targeted therapies for a wide range of diseases and conditions.

### 2.5. Advanced Manufacturing Applications

Advanced manufacturing applications of engineered nanomaterials (ENMs) offer innovative solutions in electronics, coatings, and composites. These applications enhance product performance, durability, and sustainability, revolutionizing various industries (Ayvaz & Alpay, 2021, Çınar, et. al., 2020, Theissler, et. al., 2021). ENMs have revolutionized the electronics industry, enabling the development of advanced electronic devices and components. ENMs, such as silver nanoparticles, graphene, and carbon nanotubes, are used to create conductive inks for printed electronics. These inks enable the fabrication of flexible and lightweight electronic devices, including sensors, RFID tags, and flexible displays.

ENMs are incorporated into polymer matrices to create nanocomposites with enhanced electrical, thermal, and mechanical properties. These nanocomposites are used in the production of high-performance electronic components, such as circuit boards and connectors. ENMs have been widely used in coatings to improve their properties and performance in various applications. ENMs, such as zinc oxide nanoparticles, are incorporated into coatings to provide corrosion resistance to metal surfaces. These coatings protect metal structures from environmental degradation, extending their lifespan and reducing maintenance costs.

ENMs, such as titanium dioxide nanoparticles, are used in self-cleaning coatings for surfaces exposed to dirt and contaminants (Ahmad, et. al., 2022, Konstas, et. al., 2023, Strielkowski, et. al., 2023). These coatings utilize the photocatalytic properties of ENMs to break down organic pollutants, keeping the surface clean and reducing the need for manual cleaning. ENMs have revolutionized the field of composite materials, offering lightweight and high-strength alternatives to traditional materials. ENMs, such as carbon nanotubes and nanocellulose, are used to create lightweight composites with exceptional strength-to-weight ratios. These composites are used in aerospace, automotive, and sporting goods industries to reduce weight and improve fuel efficiency. ENMs are incorporated into composite materials to enhance their mechanical properties, such as strength, stiffness, and toughness (Hossain, et. al., 2023, Sun, et. al., 2020). These composites are used in structural applications where high-performance materials are required. In conclusion, the advanced manufacturing applications of engineered nanomaterials offer transformative solutions in electronics, coatings, and composites. By harnessing the unique properties of ENMs, industries can develop innovative products with enhanced performance, durability, and sustainability.

### 2.6. Environmental and Economic Benefits

The development and utilization of engineered nanomaterials (ENMs) from waste offer significant environmental and economic benefits, contributing to sustainability and the circular economy. Converting waste into ENMs reduces the volume of waste sent to landfills, mitigating environmental pollution and land degradation (Beretta, 2022, Black, Richmond & Kolios, 2021, Ng & Lim, 2022). By repurposing waste materials, the lifecycle of resources is extended, reducing the need for virgin materials extraction. Using waste as a source for ENMs reduces the reliance on virgin raw materials, which often require intensive extraction processes. This shift toward using waste materials as feedstock promotes sustainability by minimizing resource depletion and associated environmental impacts. Additionally, waste materials are often available at lower costs, contributing to economic viability.

The concept of a circular economy aims to minimize waste and maximize the value of resources by keeping them in use for as long as possible. Converting waste into ENMs aligns with these principles by promoting resource efficiency, reuse, and recycling (Afridi, Ahmad & Hassan, 2022, Ren, 2021, Rinaldi, Thies & Johanning, 2021). It exemplifies a closed-loop approach where waste is transformed into valuable products, reducing the need for new resource extraction. The utilization of waste-derived ENMs contributes to achieving various sustainability goals, such as the United Nations Sustainable Development Goals (SDGs). These include goals related to responsible consumption and production (SDG 12), climate action (SDG 13), and sustainable cities and communities (SDG 11). By addressing waste management challenges and promoting sustainable practices, ENMs play a vital role in advancing these global objectives. The development and application of engineered nanomaterials derived from waste offer significant environmental and economic benefits (Khalid, 2024, Ukoba, et. al., 2024). By reducing waste, promoting resource efficiency, and aligning with circular economy principles, waste-derived ENMs contribute to global sustainability goals while offering cost-effective and sustainable solutions.

### 2.7. Challenges and Solutions

The development of engineered nanomaterials (ENMs) from waste presents several challenges, including technical, economic, regulatory, and safety aspects. Addressing these challenges is crucial for realizing the full potential of waste-to-ENM technologies (Farrar, Ali & Dasgupta, 2023, Maldonado-Correa, et. al., 2024, Vallim Filho, et. al., 2022). Converting waste into high-quality ENMs involves complex processes that must be optimized for efficiency and yield. Variability in waste composition and properties can affect the quality and consistency of the resulting ENMs. Additionally, the selection of appropriate synthesis methods and conditions is critical for achieving desired ENM properties.

The economic viability of waste-to-ENM technologies depends on factors such as the cost of raw materials, energy requirements, and the scalability of production processes. Initial investments in equipment and infrastructure can be substantial, and the ability to scale up production while maintaining cost-effectiveness is essential for commercial viability (Bilgili, Arda & Kilic, 2024, Braunbehrens, Vad & Bottasso, 2023, Wood, 2023). The use of ENMs raises regulatory and safety concerns related to their potential environmental and human health impacts. Ensuring that waste-derived ENMs meet regulatory standards for safety and environmental sustainability is crucial. Additionally, managing the risks associated with the production, use, and disposal of ENMs requires robust risk assessment and mitigation strategies. Addressing the challenges of waste-to-ENM conversion requires a multifaceted approach that integrates technical, economic, regulatory, and safety considerations. Some proposed solutions and future directions (Abbassi, et. al., 2022, Fallahi, et. al., 2022, Han, Zhen & Huang, 2022). Develop advanced analytical techniques to accurately characterize waste materials and identify valuable components for ENM synthesis. Optimize waste conversion processes to improve efficiency, reduce energy consumption, and enhance the quality of ENMs produced. Implement integrated waste management strategies that prioritize waste reduction, reuse, and recycling, with waste-to-ENM conversion as a complementary approach. Foster collaboration between researchers, industry, and regulatory agencies to address technical, economic, and regulatory challenges collectively.

Conduct comprehensive LCA studies to evaluate the environmental and economic impacts of waste-to-ENM conversion processes and identify areas for improvement. Engage with stakeholders, including the public, to increase awareness of the benefits and risks of waste-to-ENM technologies and address concerns through transparent communication (Alam, 2023, Amiri-Zarandi, et. al., 2022, Sengupta, et. al., 2021). In conclusion, while there are significant challenges associated with developing ENMs from waste, addressing these challenges through innovative technologies, collaborative efforts, and responsible practices can unlock the full potential of waste-to-ENM conversion for sustainable development.

### 2.8. Case Studies and Real-world Applications

In recent years, several case studies and real-world applications have demonstrated the successful transformation of waste into engineered nanomaterials (ENMs), showcasing the potential impact of this approach on various industries (Baek, et. al., 2021, Kasneci, et. al., 2023). These examples highlight the innovative use of waste materials to create valuable ENMs, providing insights into the challenges and opportunities associated with waste-to-ENM technologies.

One notable example is the conversion of agricultural waste, such as rice husks or sugarcane bagasse, into high-quality nanocellulose. Nanocellulose has applications in various industries, including packaging, textiles, and biomedical engineering, due to its exceptional mechanical properties and biocompatibility (Ahmed, et. al., 2020, Impram, Nese & Oral, 2020, Li, Zhou & Chen, 2020). Another example is the synthesis of carbon nanotubes from carbon-rich waste materials, such as plastic waste or used tyres. Carbon nanotubes have unique electrical and mechanical properties, making them valuable in electronics, aerospace, and materials science. The use of waste-to-ENM technologies has the potential to significantly impact various industries: ENMs derived from waste can be used for environmental remediation, such as the removal of heavy metals and organic pollutants from water and soil (Ajani, Imoize & Atayero, 2021, Dhar, et. al., 2021, Murshed, et. al., 2021). These materials offer a sustainable and cost-effective alternative to traditional remediation methods. Waste-derived ENMs can enhance the performance of energy storage devices, such as batteries and supercapacitors. For example, nanomaterials synthesized from waste polymers can be used as electrodes in lithium-ion batteries, improving their energy density and cycling stability.

Waste-derived ENMs have applications in drug delivery, tissue engineering, and medical diagnostics. For instance, nanocellulose derived from agricultural waste can be used as a scaffold for tissue regeneration or as a carrier for targeted drug delivery (Abou Houran, et. al., 2023, Tarek, et. al., 2023, Wazirali, et. al., 2023). Several key lessons can be learned from the implementation of waste-to-ENM technologies: Successful implementation often requires collaboration between researchers, industry partners, and government agencies to address technical, economic, and regulatory challenges. Adopting a lifecycle approach to waste management can help identify opportunities for waste valorization and ENM synthesis at various stages of the product lifecycle. Incorporating sustainability principles, such as waste reduction and resource efficiency, into ENM synthesis processes can enhance the environmental and economic sustainability of these technologies (Adekanbi, 2021, Gong & Chen, 2024). Proactive risk management strategies are essential to address potential environmental and health risks associated with the production and use of ENMs derived from waste. In conclusion, case studies and real-world applications demonstrate the potential of waste-to-ENM technologies to transform waste materials into valuable resources. By leveraging waste as a feedstock for ENM synthesis, these technologies offer sustainable solutions to environmental and economic challenges while opening up new opportunities for innovation and development across industries.

Plastic waste, including PET bottles and polyethene, is converted into CNTs through pyrolysis and chemical vapour deposition (CVD) techniques. CNTs derived from waste plastic find applications in reinforcing composite materials, enhancing the mechanical properties of plastics, and serving as conductive additives in electronics (Khalid, 2024, Ukoba, et. al., 2024). Biomass waste, such as wood chips and agricultural residues, is processed to produce nanocarbons through pyrolysis or hydrothermal carbonization. Nanocarbons are utilized as adsorbents for wastewater treatment, catalyst supports for fuel cells, and additives in concrete for improved strength.

Discarded glass bottles and containers are crushed and processed to obtain silica nanoparticles through sol-gel synthesis (Dalai, et. al., 2024, Nagaraj, et. al., 2024). Silica nanoparticles find applications in coatings for scratch resistance, as additives in concrete for improved durability, and as fillers in dental composites for enhanced strength. Metal oxide waste, such as iron oxide from industrial processes, is reduced and processed to obtain nanoscale metal oxides. Nanoscale metal oxides are used as pigments in paints, as catalysts for chemical reactions, and as sensors for detecting environmental pollutants. Discarded textiles, such as cotton and polyester fabrics, are dissolved and electrospun to produce nanofibers. Nanofibers derived from waste textiles are used in filtration membranes, wound dressings, and protective clothing due to their high surface area and porosity (Ahmed, et. al., 2020, Impram, Nese & Oral, 2020, Li, Zhou & Chen, 2020). Waste paper fibres are processed to extract cellulose nanocrystals through acid hydrolysis or enzymatic treatment. CNCs are utilized as reinforcing agents in composites, as rheology modifiers in cosmetics, and as drug delivery carriers in pharmaceuticals. These case studies highlight the diverse range of waste materials that can be transformed into valuable ENMs, demonstrating the potential of waste-to-wonder technologies in promoting sustainability and innovation across industries.

### 2.9. Future Trends and Research Directions

The field of developing engineered nanomaterials (ENMs) from waste sources is poised for significant advancements and growth, driven by ongoing research efforts and emerging trends. Here are key future trends and research directions that are likely to shape the field: Continued research into novel processing techniques such as plasma technology, microwave-assisted methods, and 3D printing for precise control over the structure and properties of ENMs. Increasing focus on environmentally friendly synthesis routes using sustainable and bio-inspired methods, reducing the environmental impact of ENM production.

Growing interest in utilizing ENMs for drug delivery, diagnostics, and regenerative medicine, leveraging their unique properties for targeted and personalized therapies (Khalid, 2024, Ukoba, et. al., 2024). Expanding applications in pollutant removal, soil remediation, and water purification, addressing pressing environmental challenges using ENMs. Continued research into using ENMs for advanced battery technologies, supercapacitors, and fuel cells, aiming for high-performance and sustainable energy solutions. Integration of ENMs into composite materials, coatings, and sensors for enhanced mechanical, electrical, and thermal properties, enabling new functionalities in various industries. Collaborations between materials scientists, chemists, and engineers to design and develop novel ENMs with tailored properties for specific applications. Partnerships with environmental scientists and engineers to explore the impact of ENMs on ecosystems and human health, ensuring their safe and sustainable use (Ahmed, et. al., 2020, Impram, Nese & Oral, 2020, Li, Zhou & Chen, 2020). Joint efforts to explore the potential of ENMs in biomedicine, including targeted drug delivery, imaging, and tissue engineering applications. Efforts to scale up the production of ENMs from waste sources to meet industrial demands, considering economic viability and environmental sustainability.

Addressing regulatory challenges and ensuring compliance with safety and environmental regulations to facilitate the widespread adoption of ENMs in various industries. Engaging with stakeholders, including the public, policymakers, and industry partners, to raise awareness about the benefits and safety of ENMs derived from waste sources (Khan, et. al., 2022, Sharma, et. al., 2021). The future of developing ENMs from waste sources is promising, with ongoing research driving innovations in synthesis techniques, expanding applications, interdisciplinary collaborations, and the potential for large-scale adoption. These advancements hold the key to unlocking the full potential of waste-to-wonder technologies, offering sustainable solutions to global challenges across industries.

## 3. Conclusion

In summary, the concept of developing engineered nanomaterials (ENMs) from waste sources represents a transformative approach with multifaceted benefits. Throughout this exploration, we have delved into various aspects of this innovative field, including synthesis techniques, applications, environmental and economic advantages, challenges, case studies, future trends, and research directions. The journey from waste to wonder begins with recognizing the diverse range of waste materials, from industrial and consumer waste to agricultural residues, that can serve as valuable resources for ENM synthesis. Techniques such as chemical vapour deposition, sol-gel synthesis, and hydrothermal methods enable the transformation of these wastes into high-performance ENMs with unique structural and functional properties.

The applications of waste-derived ENMs span across several critical sectors. In environmental applications, these materials show promise for pollutant adsorption, water purification, and air filtration, contributing to cleaner and healthier environments. In energy applications, they enhance energy storage in batteries, supercapacitors, and fuel cells, paving the way for more efficient and sustainable energy systems. In biomedicine, they offer advanced drug delivery systems, diagnostic tools, and tissue engineering solutions, revolutionizing healthcare practices. Additionally, in advanced manufacturing, they improve electronics, coatings, and composites, leading to more durable and functional materials. Despite the progress made, challenges such as data quality, scalability, and regulatory compliance remain. However, with innovative solutions and concerted efforts, these challenges can be overcome. Continued research and development in this field are crucial, with a focus on advancing synthesis techniques, expanding applications, interdisciplinary collaborations, and large-scale adoption.

The transformative potential of waste-derived ENMs is immense. They not only offer solutions to pressing environmental and societal challenges but also align with the principles of a circular economy by reducing waste and promoting resource efficiency. As we look towards the future, it is clear that waste-to-wonder technologies hold the key to a sustainable and prosperous future. In conclusion, the journey from waste to wonder is not just a scientific endeavour but a vision for a sustainable future through nanotechnology. It is a call to action for researchers, policymakers, industry leaders, and society as a whole to embrace and support the development of waste-derived ENMs for a cleaner, greener, and more sustainable world.

## Compliance with ethical standards

### *Disclosure of conflict of interest*

No conflict of interest is to be disclosed.

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