REVIEW ARTICLE

The Synthesis and Utilization of Nanomaterials for Waste Valorization and Other Frugal Applications

Sarath Poda*

DOI: 10.18811/ijpen.v11i01.01

Abstract

The synthesis of nanostructured materials represents a pivotal advancement in materials science, enabling the precise tailoring of material properties at the nanoscale to address complex technological challenges. This paper explores the integration of nanostructured material synthesis with waste-to-energy conversion, focusing specifically on the role of nano-bio catalysts in transesterification processes. These catalysts are engineered to exhibit enhanced properties such as high catalytic efficiency, selectivity, and reusability by employing diverse synthesis approaches, including bottom-up and top-down techniques such as sol-gel processes, chemical vapor deposition, and self-assembly. Building on the integration of nanotechnology and biotechnology, this study investigates the potential of nano-bio catalysts to improve biodiesel synthesis via transesterification. The critical importance of controlling synthesis parameters to optimize the size, morphology, and composition of nano-bio catalysts is emphasized, alongside an analysis of the challenges associated with scalability, stability, and economic feasibility. By combining the principles of nanotechnology and biotechnology, Nano-bio catalysts improve the efficiency of the transesterification process and contribute to the valorization of waste materials, thus promoting a circular economy. Further, it dives into the larger uses of nanomaterials in catalysis, environmental remediation, and healthcare, emphasizing their various roles in furthering sustainability and providing multifunctional solutions.

Highlights:

- Magnetic nanoparticles hold significant potential for advancing cancer detection, targeted drug delivery, hyperthermia therapies, and improved diagnostic imaging precision.
- Nano-bio catalysts improve biodiesel production efficiency, selectivity, and sustainability via transesterification.
- Zeolites are crystalline materials made of alumina, silica, and metals, used in ion exchange and water purification.
- Nanomaterials face challenges in safety, cost, and environmental impact, including ecosystem accumulation.
- Nanocomposites improve fuel efficiency, nanomaterials enhance automotive systems and coatings, and provide UV protection in sunscreens.

Keywords: Nanotechnology, Bottom-up synthesis, Top-down synthesis, Sol-gel method, transesterification processes, Energy storage applications.

International Journal of Plant and Environment (2025); **ISSN:** 2454-1117 (Print), 2455-202X (Online)

Introduction

Creating nanostructured materials is a cutting-edge area of modern materials science, enabling unprecedented precision in tailoring material properties. As technology advances, so does the demand for materials with refined functionalities and specific features, driving the exploration of nanoscale fabrication techniques. Nanostructured materials, defined by their intricate designs at the nanoscale, exhibit unique physical and chemical properties that distinguish them from bulkier counterparts. Scientists employ various techniques to manipulate matter at the atomic and molecular levels, such as the versatile sol-gel process, the sophisticated chemical vapor deposition technique, and the intricate self-assembly method (Choudhury & Veeraraghavan, 2018). These methodologies allow precise control over the nanoscale construction of materials, unlocking their full potential. The resulting materials possess remarkable attributes such as high surface area, quantum effects, and tunable features, making them ideal for diverse applications. This introduction lays the foundation for a comprehensive exploration of nanostructured material synthesis, unraveling fabrication intricacies and underscoring the transformative impact of nanotechnology on advanced materials. As this journey unfolds, the vast possibilities of nanostructured materials come to light, offering a multidisciplinary platform for innovation and ushering in a new era of materials engineering (Choudhury *et al.*, 2023a; Choudhury *et al.*, 2024a).

It emphasizes the importance of precise synthesis parameter control to shape, compose, and size nanostructures. Additionally, it highlights the role of nanostructured materials in meeting the evolving demands of technological sectors, including renewable energy conversion, thereby fostering transformative discoveries (Choudhury *et al.*, 2023b). This research emphasizes the integration of nanotechnology and biotechnology using nano-bio catalysts to increase biodiesel synthesis by transesterification, with a focus on efficiency, selectivity, and

Department of Petroleum Engineering, Texas Tech University, 2500 Broadway W, Lubbock, TX 79409, USA.

***Corresponding author:** Sarath Poda, Department of Petroleum Engineering, Texas Tech University, 2500 Broadway W, Lubbock, TX 79409, USA, Email: spoda@ttu.edu

How to cite this article: Poda, S. (2025). The Synthesis and Utilization of Nanomaterials for Waste Valorization and Other Frugal Applications. International Journal of Plant and Environment. 11(1), 1-9.

Submitted: 16/12/2024 **Accepted:** 31/01/2025 **Published:** 28/03/2025

Table 1: Comparative Assessment of Various Nanomaterial Synthesis Methods, Their Applications, and Feasibility

S. No.	*Synthesis methods used*	*Key findings of the study*	*Advantages*	*Disadvantages*	*Source*
1	Various methods of fabricating nanomaterials are discussed	Due to the higher surface-to-volume ratio, nano-sized particles are considered extremely efficient as catalysts. However, the limitations include magnetic, electrical, and optical capabilities are vulnerable.	Synthetic methods offer precise size/shape control, uniformity, high purity, scalability, tunable properties, versatility, cost-effectiveness, eco-friendliness, and functionalization options for nanostructured materials.	N.A.	Agarwal *et al.*, 2022
2	Microwave irradiation or Conventional heating process	Nanoparticles exhibit exceptional accuracy in locating target sites. Therefore, considered major a breakthrough in drug delivery.	The paper highlights nanomaterials' benefits in theranostics, including targeted drug delivery, imaging enhancements, and improved treatment efficacy through multifunctional platforms.	Only a limited number of nanoparticles were declared safe for the intended purpose by the Food and Drug Administration due to exhibiting toxicity and incidents of photo-bleaching.	Altammar, 2023
3	Nucleation and growth of metal nanocrystals	Citrate, a salt precursor used in the synthesis of AG nanoparticles is sensitive to light.	Shape-controlled synthesis of metal nanocrystals, highlighting simplicity in chemistry, precise control, and potential for understanding complex physics.	Excessive dependency on factors such as precursor concentration, temperature, time, etc.	Baig *et al.*, 2021
4	Chemical combustion method	1. The nanoparticles can also produce bactericidal effects. 2. In medical applications, the particle size of the nanoparticle has an inversely proportional relation with antibacterial activity	Effective antibacterial properties, potential for biomedical applications due to their size, and ease of synthesis.	Metal oxide-based nanoparticles tend to release reactive oxygen species while interacting with certain environments or biotic systems. This can cause serious oxidative stress and DNA damage.	Dutta *et al.*, 2022
5	Top and bottom-up approach	The author vouched for the application of layered metal-based nanomaterials in electrode manufacturing.	Highlighting diverse synthesis methods, unique properties, recent advancements, and existing challenges, providing a comprehensive understanding of their multifaceted applications.	The process is expensive and synthesis defects can compromise the inherent properties.	El-Said *et al.*, 2018
6	Graphene oxide - zinc oxide nanocomposite adsorbent	Zinc or Graphene oxide nanocomposites depict superior adsorption of fluoride from target samples exceeding 16 mg per gram.	The paper discusses the advantages of adsorption for fluoride removal from water, emphasizing its effectiveness, cost-efficiency, and environmental friendliness compared to other methods.	N.A.	Luanpitpong *et al.*, 2014
7	Transmission electron microscopy (TEM)	The author declared the superiority of TEM as an analytical technique for characterization.	The paper discusses the advantages of using transmission electron microscopy for studying shape-controlled nanocrystals, highlighting its ability to provide detailed insights into their structures, properties, and assembly mechanisms at the nanoscale.	As the electron cannot penetrate beyond a certain thickness, nanomaterials such as carbon nanotubes cannot be analyzed using this technique.	Mauro *et al.*, 2021

8	In-situ and Ex-situ methods	The core properties of nanomaterials primarily depend on factors such as shape, size, and composition.	The paper outlines the advantages of magnetic nanocomposites for environmental remediation, citing their high adsorption capacity, ease of separation, and potential for treating various pollutants efficiently.	N.A.	Mekuye & Abera, 2023
9	Surface-protected etching	The researchers identified surface area, surface charge, and surface functionality as the primary structural factors that influence catalytic activities.	The study depicts an inexpensive and effective synthesis method for Fe_3O_4 nanoparticles found to be efficient for drug delivery due to antibacterial properties.	The study was performed within a limited sample size with negligible discussion on biocompatibility.	Prabhu *et al.*, 2015
10	Laser ablation, arc discharge, and Chemical Vapor Deposition	This process is primarily useful for creating thin film coating with the help of gaseous precursors.	The process consistently yields high-quality nanomaterials and is easily scalable.	The process is expensive and requires detailed monitoring of operation parameters.	Ray & Bandyopadhyay, 2021

sustainability. It takes an interdisciplinary approach, integrating sustainable energy and waste-to-energy conversion, while also developing green synthesis methods to reduce environmental effects. Furthermore, it investigates several nanomaterial applications in catalysis, environmental remediation, and healthcare, demonstrating their multifunctional usefulness and importance in fostering sustainability. Table 1 summarizes the most promising studies in this field.

What Are Nanomaterials?

Nanomaterials are not universally defined, but they are distinguished by their small size, which is measured in nanometers. There are approximately 100,000 times fewer nanometers than the diameter of a single human hair or one millionth of a millimeter (Gawande *et al.*, 2015). Carbon and minerals like silver can be used to create nanoparticles, but they must have a minimum dimension of less than 100 nanometers. The majority of nanoscale substances are too small to be seen under a standard laboratory microscope, let alone with the naked eye.

A nanoscale material called an engineered nanomaterial (ENM) possesses unique optical, magnetic, electrical, and other properties. Electronics, health care, and other industries are likely to be profoundly affected by these new characteristics. In the future, nanotechnology may be used to develop drugs that target particular bodily systems or cells, such as cancer cells, thereby improving therapeutic effectiveness. In materials like cement and linen, nanomaterials can increase their strength and lightness. Their tiny size makes them suitable for electronics and environmental remediation, as they neutralize contaminants. While tiny manufactured particles offer benefits, we understand little about how they could affect people's health and nature. Even well-known materials like silver may cause concern when made very small. Particles are so tiny they're measured in billionths of a meter and may enter the body through the nose, mouth, or skin. Carbon fibers shaped like needles have been found to cause lung irritation in a way like asbestos. Figure 1 showcases the structure of Nano-materials.

How are nanomaterials discovered?

A few nanomaterials occur naturally, for instance, blood-borne proteins necessary for existence and fluids found in the body and fat. Engineered Nanomaterials (ENMs) are particularly appealing to scientists because they have the potential to be applied in a

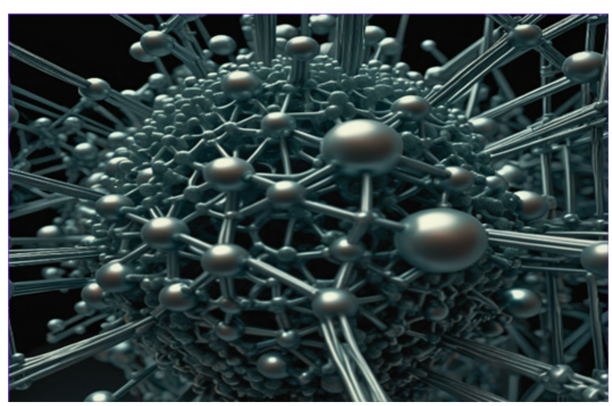

Fig. 1: Visualization of the Intricate Nanostructure of Nano-Materials

wider range of commercial materials, systems, and structures. ENMs are already utilized in hundreds of everyday items, such as sunscreen products, beauty products, sports equipment, stain-resistant clothing, tires, and electronics. They are also involved in medical diagnostics, imaging, and medicine administration, in addition to environmental remediation (Lakavathu *et al.*, 2023).

Mechanisms for Synthesizing of Nano-materials (principles)

The development and production of nanostructured substances is a difficult and intriguing area, with different approaches utilized to make materials with specialized qualities that may be employed in several applications. Here's an overview of the two main techniques:

Top-down approach

This process reduces bulk materials to microscopic bits until they reach the nanoscale. Techniques include: High-energy grinding balls are employed to mechanically grind bulk materials into nanoparticles. Lithography develops nanostructures by etching or depositing materials on a substrate in specific patterns. Template synthesis is the process of creating new nanomaterials by following existing nanostructures. Figure 2 showcases the different methods of synthesis of Nano-materials.

Bottom-up approach

This approach involves building up nanostructures from individual atoms or molecules. Techniques include: Chemical vapor deposition (CVD) is the process of growing nanomaterials from a vapor phase onto a substrate. Sol-gel synthesis has applications of chemical processes to create a gel that can then be dried and treated to produce nanomaterials. Electrochemical deposition is the process of depositing nanoparticles onto a substrate using an electrical current (Paramasivam *et al.*, 2021).

Different methods involved in Nanomaterials

The synthesis of nanostructured materials involves various approaches, each tailored to achieve specific properties and structures at the nanoscale. The prominent approaches include are tabulated in Table 2.

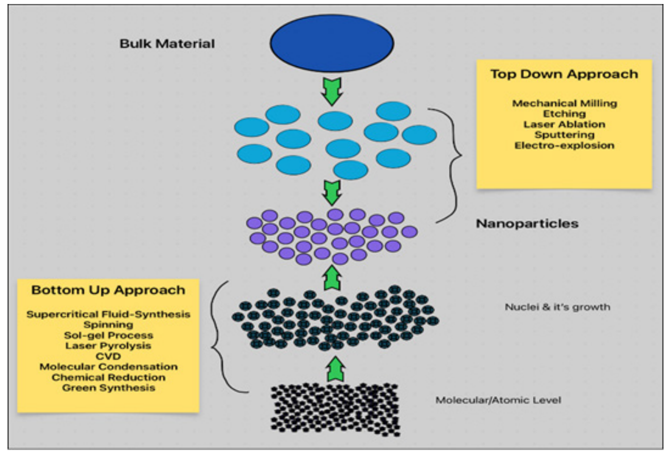

Fig. 2: Illustration of Top-Down and Bottom-Up Approaches in Nanomaterial Synthesis

Unique Nanomaterial features

Nanomaterial production has gained popularity because of its unique optical, magnetic, electrical, mechanical, and chemical capabilities when compared to bulk materials. Manufacturing and processing are important topics in nanotechnology and nanoscience for researching nanomaterials' distinctive features and phenomena, as well as realizing their potential applications in science and engineering. Figure 3 Many technological approaches/methods for creating nanomaterials have been researched. (Wang, 2000).

Semiconductor Nanoparticles

Nanoparticles have received a lot of attention in the materials science community lately. Nanoparticles, which are particles of material with sizes varying between 1 to 20 nm, play an essential role in technological development. Their distinctive physical features make them valuable in a wide range of applications, including nonlinear optics, luminescence, electronic devices, catalysts, solar energy transformation, and optoelectronics. These unique characteristics are driven by two

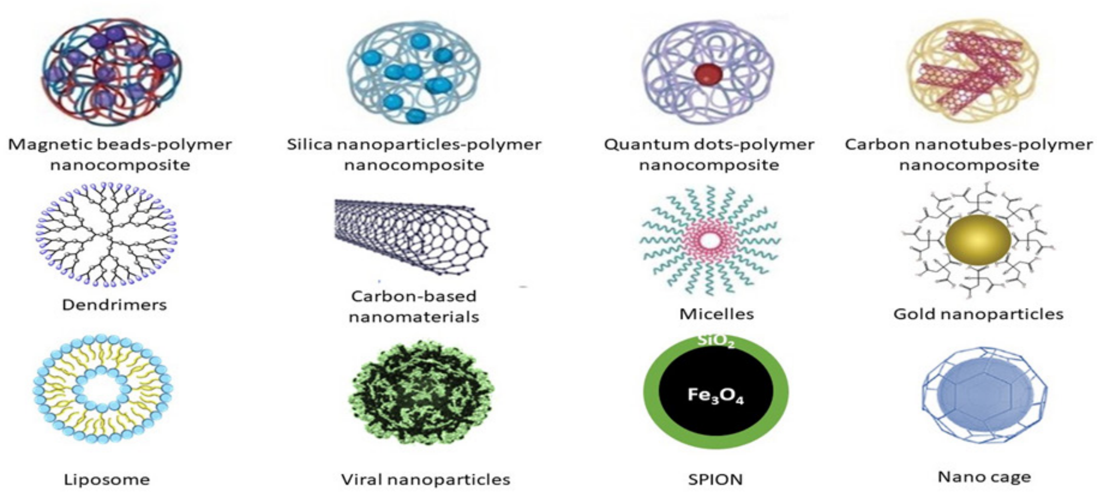

Fig. 3: Various prominent types of nanomaterials based on composition, origin, and structure

Table 2: A comparative overview of the various nanomaterial synthesis methods, showcasing their unique advantages and inherent limitations to aid in selecting appropriate techniques for specific applications (Xia et al., 2009; Prabhu et al., 2015; Baig et al., 2021; Paramasivam et al., 2021; Mekuye & Abera, 2023).

Methods	*Description*	*Benefits*	*Limitations*
Sol-Gel Method	Wet-chemical process converting fluid precursors into metal-oxide-based nanoparticles through sol-to-gel transition.	- Enables production of diverse materials (ceramics, glasses, hybrid compounds). - High control over composition and structure. - Cost-effective for lab-scale synthesis.	- Time-consuming due to multiple processing steps. - Difficulty in large-scale production. - Requires careful handling of precursors.
Chemical Vapor Deposition (CVD)	Uses vapor-phase precursors to deposit thin films or coatings on substrates.	- Precise control over composition and thickness. - Versatile for creating carbon-based nanomaterials and thin films. - High purity and uniformity of products.	- High operational cost. - Complex setup and maintenance. - Potential for toxic by-product formation.
Lithography	Focused light or electron beams create nano-patterns; classified as masked or maskless.	- High precision and resolution for patterning. - Suitable for creating intricate nanostructures. - Wide applicability in electronics and microfabrication.	- Expensive equipment and processes. - Limited scalability for large-scale applications. - Requires highly controlled environments.
Mechanical Milling	Grinding larger materials into nanoscale particles; often involves mechanical alloying.	- Cost-effective and simple. - Useful for creating nanocomposites and alloys. - Effective for large-scale applications in spray coatings and energy materials.	- Limited control over particle size and shape. - Energy-intensive process. - Potential contamination from milling tools.
Electrospinning	Uses an electric field to create nanofibers from polymer solutions or melts.	- Simple and versatile technique. - Produces fibers with large surface area and porosity. - Applications in filtration, sensors, and tissue engineering.	- Limited to polymer-based materials. - Challenges in controlling fiber diameter and uniformity. - Requires optimization for specific applications.
Green Synthesis	Uses natural sources (e.g., plant extracts, and microorganisms) for eco-friendly nanomaterial production.	- Environmentally friendly and sustainable. - Low toxicity and biocompatibility of products. - Utilizes abundant, renewable resources.	- Limited scalability for industrial use. - Variability in material quality due to inconsistencies in natural sources. - Slower reaction rates compared to conventional methods.
Hydrothermal/ Solvothermal Synthesis	High-pressure, high-temperature reactions in aqueous or organic solutions.	- Highly controlled environment for crystal growth. - Suitable for synthesizing metal oxides and semiconductor nanocrystals. - Versatile for various nanostructured materials.	- Requires specialized equipment for high-pressure conditions. - High energy consumption. - Limited scalability for continuous production.

major factors, both of which are related to the size of each of the crystals. The first is a high surface-to-volume ratio, while the second is the consequence of quantum confinement. The present study concentrates on large band gap II-VI transistors. Optoelectronics applications include blue lasers, diodes that emit light, photonic crystals, and nonlinear optical components. The dimension, shape, structure, crystallinity, and geometry all have a great impact on the properties of semiconductor nanoparticles. Synthetic nanotechnologists have major hurdles in precisely managing these parameters. Nanotechnologists face considerable challenges in accurately managing the structures of nanostructures (Xia *et al*., 2009; Choudhury *et al*., 2024b)

Magnetic-Nanoparticles

Nanoparticles' tiny size scale has a major effect on magnetic materials as well. Magnetic particles are being examined for use in cancer detection and therapy. Several technological hurdles must be overcome before nanoparticles may be widely used in medicine. This comprises but is not limited to, creating evenly sized, harmless particles and coating them such that they adhere to specified tissues. Magnetic fields may alter ferromagnetic (superparamagnetic) nanoparticles, making them a potentially useful tool in medicine and pharmacology. Magnetic nanoparticles must fulfill several strict conditions before they may be employed in the body. These requirements include biological compatibility, simple diffusion into a liquid for injection, and, most critically, nontoxicity. (Sun et al., 2008).

Furthermore, the particles' surfaces must be functionalized so that they may bind to and agglomerate in certain, targeted tissues. This would enable magnetic nanoparticles to work in an extensive variety of applications, including drug targeting and greater clarity for magnetic resonance imaging. Recently, it was claimed that nanoparticles may be utilized to cure cancer using a procedure known as thermotherapy or hyperthermia. Iron oxides are a type of magnetic nanoparticle that meets the strict criteria for implantation into the body.

Nano-porous materials

Nanoporous materials are unique substances with a bulk organic or inorganic structure that incorporates a porous architecture. These materials are characterized by pore sizes within the nanometer scale, typically less than 100 nm. Pores are categorized as either open or closed.

Pores that are connected to the surface and allow interactions with external environments, making them vital for applications such as adsorption, catalysis, and molecular separation are called open pores. Closed pores are generally the enclosed voids within the material that play a crucial role in providing thermal insulation and enhancing structural integrity. Nanoporous materials are broadly divided into bulk materials (e.g., activated carbon, zeolites) and membranes (e.g., biological cell membranes).

Size Classification of Nano-materials

The term nanomaterials covers a wide range of resources that have various applications across disciplines. According to the International Union of Pure and Applied Chemistry, porous materials are further divided into three categories: Microporous materials, Mesoporous materials, and Macroporous materials with the material size varying between 0.2–2 nm; 5-50nm; 50–1000 nm respectively. Materials, having pore sizes that correspond to molecule measurement dimensions, have applications in molecular selectivity, such as filtration and separation membranes. Figure 4 represents the chemical synthesis process for nanomaterials.

Network Materials Classification

Based on size, nanoporous materials can be categorized as organic or inorganic network materials. A network material is a structure that 'hosts' the tiny holes and allows the medium (gas or liquid) to interact with the substrate. Nanoporous materials can also be classified into organic and inorganic network materials. These networks employ the nanometer-sized pores and facilitate interactions between gases or liquids and the substrate.

Organic nanoporous membranes

Organic nanoporous materials are typically polymers containing elements like carbon, nitrogen, boron, and oxygen. These materials are predominantly microporous but can exhibit mesoporous or hybrid structures. Common types include:

Fig. 4: Representation of the Chemical Synthesis Process for Nanomaterials

- Covalent Organic Frameworks
- Covalent Triazine Frameworks
- Polymers with Intrinsic Microporosity
- Hyper crosslinked Polymers
- Conjugated Microporous Polymers

Organic nanoporous materials are further categorized into crystalline and amorphous types. Crystalline Networks: These have well-defined, uniform pore sizes that can be tailored by altering the monomer structure. Whereas, Amorphous Networks: Are more irregular, with evenly distributed yet disordered pores. An example is Polymers of Intrinsic Microporosity (PIMs). Both types serve critical roles in applications such as gas sorption and catalysis.

Inorganic nanoporous membranes:

Inorganic nanoporous materials include structures made from oxides, carbon, binary compounds, and pure metals. Some key examples are:

- *Zeolites*

Crystalline to-aluminosilicates composed of alumina, silica hydrates, and alkali/alkaline earth metals. They are widely used in ion exchange and water purification systems.

- *Nanoporous Alumina*

A biocompatible material frequently used in medical implants for dental and orthopedic purposes.

- *Titanium Nanotubes*

Distinguished by their ability to form a protective titanium oxide layer when exposed to oxygen, these materials are highly valued for their biocompatibility and mechanical strength in orthopedic applications.

Nanomaterial applications

Nanomaterials find uses in a wide range of sectors due to their distinctive and controllable nanoscale characteristics. Some prominent uses are:

Electronics and Optoelectronics:

Nanomaterials such as quantum dots and nanowires are used in electronic components and gadgets, resulting in smaller and more efficient electronic circuits. Nanomaterials enhance the performance of LEDs and solar cells. In catalysis, nanocatalysts have a larger surface area, which leads to increased catalytic activity. They are used in a wide range of industrial processes to increase chemical reaction efficiency and selectivity.

Energy Storage and Medicine

Nanomaterials are used in supercapacitors and batteries to increase the capacity for energy storage and charge/discharge rates. Nanomaterials help fuel cells and solar cells operate more efficiently. Nanoparticles are used in systems for drug delivery to provide focused therapy, increase therapeutic effectiveness, and reduce adverse effects. Nanomaterials enable molecular imaging, which aids in the early diagnosis of diseases. Nanocomposite materials are utilized in tissue engineering to create scaffolds and implants.

Textiles and Food Industry

Fabrics with nano-coatings can be stain-resistant, water-resistant, and antimicrobial. Nanofibers are used to make lightweight and durable fabrics. In environmental remediation, nanomaterials are used to remove pollutants and toxins from the air, water, and soil. They can stimulate the breakdown of hazardous chemicals in wastewater treatment systems. Nanomaterials are used in food packaging to enhance barrier properties and increase shelf life. Nano-sensors can detect contaminants or spoilage in food products (RoyChoudhury *et al*., 2017; Mehdizadeh et al., 2024).

Automotive Industry

Nanocomposites are utilized to create lightweight, high-strength components that increase fuel economy. Nanomaterials contribute to the development of better sensors and catalysts for automotive systems. When it comes to consumer goods, nanomaterials are used to create scratch-resistant and durable coatings for devices such as eyeglasses and electronics. Nanoparticles are utilized in sunscreens to provide additional UV protection.

Aerospace

Nanomaterials contribute to the development of lightweight and high-strength materials for aerospace applications. Nanocomposites enhance the structural integrity of aircraft components. The diverse range of applications showcases the versatility of nanomaterials in addressing challenges and advancing technology across various industries. As research continues, new applications and innovations are likely to emerge, further expanding the impact of nanomaterials in different fields.

Transesterification process

Energy recovery from waste materials is a critical area of research aimed at reducing environmental impact and fostering sustainable development. Transesterification, a process for converting triglycerides into biodiesel, has garnered significant attention for its ability to transform waste oils and fats into valuable energy resources. The introduction of nano-bio catalysts into this process has opened new avenues for enhancing reaction rates, selectivity, and overall efficiency. Transesterification involves the reaction of triglycerides with alcohol (commonly methanol) in the presence of a catalyst to produce biodiesel and glycerol as a byproduct. While traditional chemical catalysts (acid or base) have been extensively used, they suffer from drawbacks such as harsh reaction conditions, high energy demands, and limited reusability. This has led to the exploration of advanced catalytic materials.

Nano-bio-Catalyst

Nano-bio catalysts are innovative hybrid materials that integrate the unique properties of nanoparticles with the biocatalytic functionalities of enzymes, such as lipase. The nanoscale dimensions of these materials provide a significantly increased surface area, enhancing their reactivity, while the biocatalytic components deliver high specificity and selectivity in chemical processes. Recent advancements in the field have focused on three key areas. First, the development of nano-functionalized enzymes involves immobilizing lipases on nanoparticles, such as silica or magnetic nanoparticles, to enhance their stability and reusability in catalytic applications. Second, the incorporation of metal oxide nanocatalysts, including materials like titanium dioxide (TiO_2) and zinc oxide (ZnO), has been shown to boost catalytic activity through synergistic interactions between the biocatalyst and the metal oxide components. Finally, sustainable synthesis approaches emphasize the use of renewable and biodegradable materials in the production of nano-bio catalysts, aligning with the principles of green chemistry to minimize environmental impact. Together, these advancements underscore the potential of nano-bio catalysts to drive innovation in catalytic technologies while supporting sustainable development goals.

Advantages, Limitations, and Future Aspects

Nano-bio catalysts offer several key advantages that make them highly effective in catalytic applications. Their high surface area, resulting from their nanoscale structure, significantly accelerates reaction kinetics, thereby reducing both reaction time and energy consumption. Furthermore, these catalysts are often derived from natural or biocompatible sources, making them environmentally friendly and minimizing the hazards associated with traditional chemical catalysts. Another notable benefit is their recyclability, as many nano-bio catalysts can be recovered and reused multiple times with minimal loss of activity, which reduces operational costs and enhances sustainability. Additionally, they exhibit remarkable versatility, being capable of efficiently processing a wide range of feedstocks, including waste cooking oils and non-edible fats, thus broadening their applicability in diverse industrial processes.

Research efforts are increasingly directed toward addressing the challenges associated with the development and application of nano-bio catalysts, with a particular emphasis on cost, scalability, stability, and feedstock variability. High production costs, arising from the synthesis of nanoscale materials and the immobilization of enzymes, remain a significant barrier to widespread adoption. Furthermore, maintaining catalyst efficiency and performance in industrial-scale operations poses additional scalability challenges. Stability is another critical factor, as ensuring the functionality of biocatalysts under harsh reaction conditions is essential for reliable and consistent performance. Moreover, the variability of feedstocks, particularly in waste-to-energy applications, necessitates the development of catalysts capable of adapting to diverse waste streams without compromising yield or quality. To overcome these limitations, research is focused on creating cost-effective and scalable nano-bio catalysts, while simultaneously improving their thermal and chemical stability. Innovations in material science, such as the utilization of bio-inspired nanostructures, offer promising avenues for enhancing catalyst performance and addressing these challenges, paving the way for more sustainable and efficient catalytic technologies.

Challenges

Advantages of Nanomaterials

The distinctive characteristics of nanoparticles, particularly their size, offer numerous advantages compared to bulk materials.

The versatility in customizing nanoparticles to meet specific requirements further amplifies their value. Additionally, their heightened porosity has increased demand for applications across various sectors. In the energy industry, the utilization of nanomaterials proves advantageous by enhancing the efficiency and cost-effectiveness of conventional energy-generating techniques, such as solar panels. This innovation also opens up new avenues for the collection and storage of energy.

Expectations for nanomaterials extend to the electronics and computer industries, where their incorporation promises increased precision in crafting electronic circuits at the atomic level. This technology is expected to boost economic growth and create jobs in the next decades. Scientists predict that nanotechnology will progress in four separate generations. We are now experiencing the first, or maybe second, generation of nanomaterials. The qualities of the first generation of materials are accomplished by adding "passive nanostructures". Coatings and carbon nanotubes/fibers can be used for numerous applications. The second generation uses active nanostructures, such as those that are bioactive, to deliver a medicine to a specific target cell or organ. This can be accomplished by coating the nanoparticle with certain proteins. This advancement is poised to revolutionize the development of diverse electronic devices. Nanomaterials' extraordinarily high surface-to-volume ratio is important in medicine. This distinct feature promotes the connection of cells and active chemicals, providing a significant advantage in the possibility of successfully combating a wide range of ailments.

Disadvantages of Nanomaterials

Despite their advantages, applications of nanomaterials are accompanied by several drawbacks. The common usage of nanomaterials is relatively new, resulting in a limited amount of information on the health and safety implications of exposure to these materials. One prominent concern associated with nanomaterials pertains to inhalation exposure, based on findings from animal studies.

Furthermore, there exist considerable gaps in understanding in the understanding of nanomaterials, contributing to the complexity and difficulty of the manufacturing process. The overall procedure is costly, necessitating optimal results, especially in the realm of consumer goods, to prevent financial losses (Zhu *et al.*, 2013).

Risk assessments related to environmental impacts indicate that nanomaterials present in products like sunscreen may enter aquatic ecosystems after being washed off the skin. Engineered nanomaterials may also accumulate in water bodies, posing risks to freshwater species such as snails, potentially affecting growth and reproduction. Similar concerns are likely to extend to marine ecosystems (Chatzigianni et al., 2022). Additionally, the accumulation of nanomaterials in soils, primarily through sewage sludge, raises further environmental apprehensions, with the potential for increased concentrations over time due to repeated releases.

Conclusion and Future Perspective

In conclusion, this abstract underscore the transformative potential of nanostructured materials across diverse sectors, including electronics, catalysis, medicine, energy storage, and renewable energy applications. The synthesis and optimization of these materials, particularly in the context of waste-to-energy conversion through transesterification processes, represent a critical frontier in scientific exploration. Nano-bio catalysts, as an advanced application of nanostructured materials, demonstrate exceptional potential in enhancing the efficiency and sustainability of biodiesel production, aligning with global efforts toward circular economies and sustainable energy solutions. Advancing our understanding of nanostructured material synthesis, perfecting fabrication techniques, and addressing challenges such as scalability and stability are imperative for realizing their full potential. These materials hold great promise for revolutionizing technological sectors, driving innovation toward tailored properties, and addressing pressing environmental and energy challenges.

The transformative potential of nanostructured materials across a wide range of sectors, including electronics, catalysis, medicine, energy storage, and renewable energy applications. as scalability, cost, and stability must be addressed to enable widespread industrial adoption. Transesterification, a process converting triglycerides into biodiesel using an alcohol and a catalyst, efficiently transforms waste oils into energy. The use of nano-bio catalysts in this process enhances reaction rates, selectivity, and efficiency, addressing limitations of traditional chemical catalysts, such as harsh conditions, high energy demands, and poor reusability. However, challenges such. Advancing our understanding of nanostructured material synthesis, optimizing fabrication techniques, and overcoming inherent limitations are critical for unlocking their full potential. Addressing issues such as reproducibility, surface functionalization, and toxicity concerns, especially in biomedical applications, will unlock the full potential of nanomaterials, driving innovations in renewable energy, healthcare, and environmental management for a more sustainable global society.

Acknowledgements

I am writing to express my deepest gratitude to Dr. Atun Roy Choudhury, Asst. General Manager, Cube Bio Energy Pvt. Ltd, for his invaluable support and guidance throughout the developmental phase.

Reference

Agarwal, A., Singh, N.B., Prajapati, R., Ashraf, I. (2022). Advanced Functional Nanomaterials for Sensing of Pollutants and Water Remediation. In: Ikhmayies, S.J. (eds) Advanced Nanomaterials. Advances in Material Research and Technology. Springer, Cham. https://doi.org/10.1007/978-3-031-11996-5_9

Altammar, K. A. (2023). A review on nanoparticles: characteristics, synthesis, applications, and challenges. Frontiers in microbiology, 14, 1155622. https://doi.org/10.3389/fmicb.2023.1155622

Baig, N., Kammakakam, I., & Falath, W. (2021). Nanomaterials: A review of synthesis methods, properties, recent progress, and challenges. Materials advance, 2(6), 1821-1871. https://doi.org/10.1039/D0MA00807A

Chatzigianni, M., Pavlou, P., Siamidi, A., Vlachou, M., Varvaresou, A., & Papageorgiou, S. (2022). Environmental impacts due to the use of sunscreen products: a mini-review. Ecotoxicology (London, England), 31(9), 1331–1345. https://doi.org/10.1007/s10646-022-

02592-w

Choudhury, A. R., & Veeraraghavan, A. (2018). Treatment of Highly Concentrated Effluent Generated from Intermediate Chemical and Bulk Drug Industries Renovated with Tertiary Removal. International Journal of Environmental Sciences & Natural Resources, 12(2), 29-33.

Choudhury, A. R., Singh, N., Veeraraghavan, A., Gupta, A., Palani, S. G., Mehdizadeh, M., ... & Al-Taey, D. K. (2023a). Ascertaining and optimizing the water footprint and sludge management practice in steel industries. Water, 15(12), 2177. https://doi.org/10.3390/w15122177

Choudhury, A.R., Singh, N., Lalwani, J. *et al.* A comparative assessment of biomethane potential of fresh fecal matter and fecal sludge and its correlation with malodor. Environ Sci Pollut Res 31, 31619–31631 (2024a). https://doi.org/10.1007/s11356-024-33289-8

Choudhury, A.R., Singh, N., Lalwani, J. *et al.* Enhancing biomethanation performance through co-digestion of diverse organic wastes: a comprehensive study on substrate optimization, inoculum selection, and microbial community analysis. Environ Sci Pollut Res 31, 34622–34646 (2024b). https://doi.org/10.1007/s11356-024-33557-7

Choudhury, A.R., Singh, N., Palani, S.G. *et al.* Bioremediation of reverse osmosis concentrate generated from the treatment of landfill leachate. Environ Sci Pollut Res 30, 93934–93951 (2023b). https://doi.org/10.1007/s11356-023-28957-0

Dutta, V., Verma, R., Gopalkrishnan, C., Yuan, M. -H., Batoo, K. M., Jayavel, R., Chauhan, A., Lin, K. -Y. A., Balasubramani, R., & Ghotekar, S. (2022). Bio-Inspired Synthesis of Carbon-Based Nanomaterials and Their Potential Environmental Applications: A State-of-the-Art Review. Inorganics, 10(10), 169. https://doi.org/10.3390/inorganics10100169

El-Said, G. F., El-Sadaawy, M. M., & Aly-Eldeen, M. A. (2018). Adsorption isotherms and kinetic studies for the defluoridation from aqueous solution using eco-friendly raw marine green algae, Ulva lactuca. *Environmental monitoring and assessment*, *190*, 1-15. https://doi.org/10.1016/j.scca.2024.100040

Gawande, M.B., Goswami, A., Asefa, T., Guo, H., Biradar, A.V., Peng, D.L., Zbořil, R., & Varma, R.S. (2015). Core-shell nanoparticles: synthesis and applications in catalysis and electrocatalysis. Chemical Society reviews, 44(21), 7540-90. https://doi.org/10.1039/C5CS00343A

Lakavathu, S., Reddy, V.K., Singh, N. *et al.* Feasibility study of faecal sludge treatment by Geotube and jute tube–based technologies. Environ Sci Pollut Res 30, 124382–124400 (2023). https://doi.org/10.1007/s11356-023-30746-8

Luanpitpong, S., Wang, L., & Rojanasakul, Y. (2014). The effects of carbon nanotubes on lung and dermal cellular behaviors. *Nanomedicine (London, England)*, *9*(6), 895–912. https://doi.org/10.2217/nnm.14.42

Mauro, N., Utzeri, M. A., Varvarà, P., & Cavallaro, G. (2021). Functionalization of Metal and Carbon Nanoparticles with Potential in Cancer Theranostics. Molecules (Basel, Switzerland), 26(11), 3085. https://doi.org/10.3390/molecules26113085

Mehdizadeh, M., Mehdizadeh, Z., Jafarzadeh, E., Choudhury, A. R., Haghi, Z., Matin, A., ... & Omidi, A. (2024). Skin Cancer Prevention by Nutraceuticals. In Nutraceuticals in Cancer Prevention, Management, and Treatment (pp. 191-213). Apple Academic Press.

Mekuye, B., & Abera, B. (2023). Nanomaterials: An overview of synthesis, classification, characterization, and applications. Nano Select, 4(8), 486-501. https://doi.org/10.1002/nano.202300038

Paramasivam, G., Palem, V. V., Sundaram, T., Sundaram, V., Kishore, S. C., & Bellucci, S. (2021). Nanomaterials: Synthesis and Applications in Theranostics. Nanomaterials, 11(12), 3228. https://doi.org/10.3390/nano11123228

Prabhu, Y.T., Rao, K.V., Kumari, B.S. *et al.* Synthesis of Fe3O4 nanoparticles and its antibacterial application. Int Nano Lett 5, 85–92 (2015). https://doi.org/10.1007/s40089-015-0141-z

Ray, S. & Bandyopadhyay, J. (2021). Nanotechnology-enabled biomedical engineering: Current trends, future scopes, and perspectives. Nanotechnology Reviews, 10(1), 728-743. https://doi.org/10.1515/ntrev-2021-0052

RoyChoudhury, A., Ashok, K. N., & Arutchelvan, V. (2017). A review on anaerobic treatment in decentralized and source-separation-based sanitation concepts: applicability in developing countries. International Journal of Trend in Scientific Research and Development, 1, 553-559.

Sun, C., Lee, J. S., & Zhang, M. (2008). Magnetic nanoparticles in MR imaging and drug delivery. Advanced drug delivery reviews, 60(11), 1252-1265. https://doi.org/10.1016/j.addr.2008.03.018

Wang, Z. L. (2000). Transmission electron microscopy of shape-controlled nanocrystals and their assemblies. The Journal of Physical Chemistry B, 104(6), 1153-1175. https://doi.org/10.1021/jp993593c

Xia, Y., Xiong, Y., Lim, B., & Skrabalak, S. E. (2009). Shape-controlled synthesis of metal nanocrystals: simple chemistry meets complex physics?. Angewandte Chemie International Edition, 48(1), 60-103. https://doi.org/10.1002/anie.200802248

Zhu, J., Wei, S., Chen, M., Gu, H., Rapole, S. B., Pallavkar, S., ... & Guo, Z. (2013). Magnetic nanocomposites for environmental remediation. Advanced Powder Technology, 24(2), 459-467. http://dx.doi.org/10.1016/j.apt.2012.10.012.