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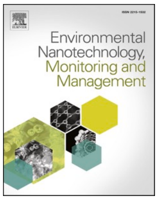

A review of nanoparticle synthesis methods, classifications, applications, and characterization

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ABSTRACT

Nanoparticles, at the convergence of science and technology, have rapidly evolved and continue to revolutionize numerous fields. Research areas that make use of contemporary advances in nanotechnology include wastewater treatment, such as the recent use of nanocomposites in membrane surfaces. However, membrane fouling associated with its surface hydrophobic properties is a major setback bedeviling effective removal of carcinogenic and non-biodegradable chemicals presents in wastewater discharges. Nanoparticles with controlled morphologies when incorporated into membrane surfaces impart hydrophilicity and enable efficient membrane-water interactions. There are many synthesis methods of nanoparticles, ranging from physical to chemical to green synthesis, rendering the selection of suitable methods that enable control over the morphological structure of the synthesized material highly challenging. Herein, we provide a comprehensive review of nanoparticles, synthesis methods, characterization techniques, and their multifaceted applications. The choice of suitable methods depends on their ability to produce nanoparticles with controlled morphologies, perspicuous technology, and low energy requirements compared to other methods. Factors such as pH concentration and calcination temperature are found to influence morphological structure. The article also discusses the synthesis of nano oxides like titanium dioxide (TiO_2), silicon dioxide (SiO_2), and their composites. The review is designed to facilitate informed decisions and to serve as a beneficial reference for researchers as well as professionals, fostering the transfer of knowledge, multidisciplinary collaboration, and novel advances in the dynamic and evolving domain of nanoparticles.

1. Introduction

The word “nanotechnology” refers to manipulating matter at scales between 1 and 100 nm (Baig, 2023; Gupta et al., 2023; Papolu and Bhogi, 2023). Particles of sizes characterized within the above range are referred to as nanoparticles (Altammar, 2023). It was coined by Taniguchi in 1974; however, the notion was made known in 1959 by Richard Bayda et al., (2020). Feynman proposed that it was possible to tune matter at both atomic and molecular stages, and he envisioned the development of machines that could be built at this scale (Bayda et al., 2020). The development of new tools and techniques in the 1980s made it possible to begin exploring nanotechnology in earnest, and the field has since grown rapidly (Bayda et al., 2020). The precedencies are as follows:

1. The invention of the STM “scanning tunneling microscope” was in 1981 by Gerd Binnig and colleagues The STM is a device that can be used to image individual atoms on a surface. This was a breakthrough for nanotechnology, as it allowed, for the first time in history, researchers to visualize and tune single atoms.
2. The discovery of fullerenes by Robert and colleagues four years later Fullerenes are a class of molecules that consist of atomic carbon arranged in spherical or ellipsoidal shapes. Fullerenes are extraordinarily strong and lightweight, and they have a variety of potential applications in nanotechnology.
3. Drexler published a book titled “Book of Engines of Creation” in 1986. This outlined the potential of nanotechnology to revolutionize many fields, including materials science, medicine, and electronics.

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Drexler's book was very influential, and it helped to popularize the concept of nanotechnology (Altammar, 2023; Bayda et al., 2020).

Intertwining of these experimental advances and a wide understanding of analytical methods for nanotechnology goals in the 1980s led to the emergence of nanotechnology as a research area. Nanotechnology is relatively evolving (Al-Awsi et al., 2024; Hsu et al., 2023; Huang,Zhu,and Kianfar, 2021), and has the potential to revolutionize many industries and improve our lives in many ways. Several types and classifications of nanoparticles exist depending upon their properties, such as size (Chung et al., 2015), shape (El-Khatib et al., 2018; Guzenko et al., 2014), and chemical characteristics (Altammar, 2023). Tables 1 and 2 show several types and classifications of nanoparticles. Nanomaterials have been used for centuries (Bayda et al., 2020). Some examples of ancient uses of nanomaterials include asbestos, nanofibers to reinforce ceramic mixtures, and the use of PbS nanoparticles in ancient hair-dye formulas (Bayda et al., 2020). Nanomaterials are today applied to use in several areas (L. Chen et al., 2023; Gokul et al., 2023b; Hsu et al., 2023; Jaiswal et al., 2023; Mata,Nakkala,and Sadras, 2023; Nzilu et al., 2023) among the most recent of which is their application in drug delivery and to impart hydrophilic properties on hydrophobic membrane surfaces through membrane coating for wastewater treatment (J. Zeng et al., 2023a; Zhu et al., 2023). Despite these evolving prospects, contemporary challenges in synthesizing scalable nanomaterials with controlled sizes and morphologies for modern applications are still the greatest bottleneck since each synthesis method (Fig. 7) produces nanoparticles with distinct sizes and morphological structures. Basically, there are two approaches of nanoparticle synthesis, viz., top-down and bottom-up, which are further classified into physical methods as the top-down approach and chemical and green synthesis methods as the bottom-up approach (Fig. 7). In physical approach such as the work of Çuvalcı et al., 2023; Kovalev et al., 2021; Ratso et al., 2021; and P. Wang et al., 2023, for example, it is difficult to have control over the size and morphological structure of the synthesized materials. While green synthesis methods seem promising, they involve the use of sophisticated technology and are immensely demanding (Gupta et al., 2023b), even though research advances are increasingly making the procedure more perspicuous. It is therefore undeniable that the choice of a suitable, cost-effective, and less energy-intensive method is highly crucial. To address this challenge, a plethora of arduous research and review papers were presented, most of which focused on either specific synthesis methods or comparing the suitability of one method over another. However, the aggregation of these numerous articles, joined with recent advances confounded the issues. This article provides a comprehensive and apposite review elucidating both physical, chemical, and green synthesis methods coupled with characterization techniques and identify sustainable synthesis methods that allow control over nanoparticle morphological structure. The paper also aims to provide a quick outline of the concepts and progress in nanotechnology and nanomaterial classifications. This review is not exhaustive research in literature, but it does examine some of the most imperative work in the subject and aspires to give researchers a comprehensive and fundamental understanding of nanomaterials, suitable synthesis methods, their potential applications, and future perspectives. The article is structured into four parts. Part one includes an overview of the nanomaterials, classifications, and properties. Part two examines the different methods of synthesizing nanomaterials, capturing all the synthesis methods listed in Fig. 7, plus other chemical methods not listed therein. The third section explains the detailed procedure for the identified method and factors influencing this method and provides procedural examples of the synthesis of silicon oxide (SiO2), zinc oxide (ZnO), titanium oxide (TiO_2), tin oxide (SnO_2), graphene carbon nitride (g-C3N4) and their composites. It closes with the advantages and applications of nano oxides synthesized. The fourth section examines nanoparticle characterization techniques and the prospective applications of nanomaterials. As our understanding of nanotechnology continues to expand, we may expect to see even more innovative and groundbreaking applications of nanomaterials in the future.

Table 1
Types of nanoparticles, properties, and selected applications.

Types	Definitions and examples	Unique properties	Applications	Reference
Zero-dimensional nanomaterials (0D)	Materials with all their dimensions are within 1–100 nm (<100 nm). Nanoparticles are a type of 0D nanomaterial. Examples Quantum dots,	a) "High surface area to volume ratio" 'Quantum confinement effects Enhanced optical and electronic properties. Good biocompatibility	a) Biosensors Drug delivery Photonics Electronics Catalysis	(Guo et al., 2021; Huang et al., 2021; Tiwari,Tiwari,and Kim, 2012; Wang et al., 2020; Zhou et al., 2021)
One Dimensional nanomaterials (1D Nanomaterial)	Materials with one dimension in the nanoscale range (less than 100 nm). e.g., Nanowires, nanotubes, and nanofibers. Nanowires are typically cylindrical. Nanotubes are typically tubular, and Nanofibers are typically long, thin fibers.	a) High aspect ratio One-dimensional confinement effects Enhanced optical and electronic properties. Good mechanical properties	a) Electronics Sensors Catalysis Energy storage Biomaterials	(Gao et al., 2021; Kolahalam et al., 2019a; Zeng et al., 2022; Zhao et al., 2013a)
2Dimensional nanomaterials (2D-Nanomaterial)	nanomaterials with 2 dimensions within 1–100 (<100 nm), while the third dimension is much larger. Examples of 2D- nanomaterial include Graphene, hexagonal boron nitride, and molybdenum disulfide.	a) Ultrathin structures High surface area to volume ratio Strong in-plane bonding "Weak Vander waal forces between layers" Enhanced optical & and electronic properties.	a) Electronics Sensors Catalysis Energy storage Biomaterials	(Baig, 2023; Huang et al., 2020; Wang et al., 2021; Yang, Wang, and Xu 2020)
3Dimensional nanomaterials (3-D Nanomaterial)	Nanomaterial whose dimension is not defined by nanoscale. They are classified as bulk nanoparticles, nano bundles, nanowires, dispersion nanoparticles, bundles multi nanolayers, and 3-D printed structures.	a) Large surface area Complex internal structure High mechanical strength Good biocompatibility	a) Biomaterials Drug delivery Tissue engineering Energy storage Catalysis	(Kolahalam et al., 2019a; Pang et al., 2020)