NOVEL ADVANCEMENTS IN THE FIELD OF NANOSTRUCTURED MATERIALS: ZERO-, ONE-, TWO- AND THREE-DIMENSIONAL MATERIALS

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SUMMARY

Energy generation and preservation are significant difficulties that can be met using fuel cells, solar cells, and batteries. Micro- and nanomaterials with exciting chemical and physical characteristics offer a new avenue for addressing these issues. Nanostructured materials (NSMs) have attracted more attention due to their excellent electrical, optical, and thermal properties. In this paper, the innovative research on the synthesis, development, and classification of NSMs for various applications has been reviewed comprehensively. Furthermore, highlights the most recent research status on the structure and properties of NSMs and concludes the prospects and future difficulties in this area.

KEYWORDS

Nanostructured materials, Dimensionality, Scanning electron microscopy, Applications

1. INTRODUCTION

Carbon-based nanostructured materials (NSMs) have been extensively used in widespread domains like energy conversion and storage, production of hydrogen fuel, substitute for antibiotics, treatment of wastewater, and many more (Li et al., 2023). These materials have a size of 1 to 100 nm and have different characteristics depending on their atomic level (Kumar et al., 2020b). The NSMs have unique physical and chemical properties compared to their bulk materials due to the smaller size and large ratio of surface to volume. Recent advancements in NSMs have gone beyond the solitary instead of combining more than two or more compatible individual materials in order to form better performance (Liang and Cheng, 2018). This alteration in the behaviour of NSMs is more advantageous in potential applications. The exceptional properties of carbon-based materials make them ideal for strengthening polymers, leading to the development and manufacture of carbon-based polymer composites (Kumar et al., 2020a, Manoj Kumar and Kamal, 2019).

Nowadays, nanotechnology is an emerging and fast-growing field that deals with the synthesis, characterization, and processing of such NSMs. Researchers in this field are focused on developing and improving technologies and manufacturing processes. Additionally, it involves discovering new scientific methods for creating materials with specific microstructural characteristics and utilizing these methods to produce bulk materials with engineered properties and technological functions (Gleiter, 2000, Jouini et al., 2022). NSMs are often generated in one of two ways: bottom-up or top-down. These can be achieved through chemical or physical methods. The top-down technique is used to manipulate materials to nanoscale dimensions by the application of an external force, while the bottom-up strategy involves the assembly or formation of materials to a nanometer size by the bonding of liquids and gases through atomic transformation. Recently, the synthesis of NSMs via chemical vapor deposition (Sun et al., 2021), physical vapor deposition (Yap, 2012), sol-gel method (Bokov et al., 2021), hydrothermal synthesis (Gan et al., 2020), liquid-phase exfoliation (Li et al., 2020), and micro-emulsion has gained relevance, and it is combined with other methods to increase the synthesis efficiency. The advancement of technology has facilitated the creation and analysis of new materials with unique characteristics at a small scale. Nanomaterials are created by arranging atoms in regular patterns at the nanoscale scale. This has led to the development of unique materials such as fullerenes, carbon nanotubes (CNTs), nanoporous materials, aerogels, dendrimers, and core-shell structures, etc.

Carbon-based NSMs, with their strong reversible cycle, good thermal and electrical stability, and low cost, are critical components in energy storage and conversion

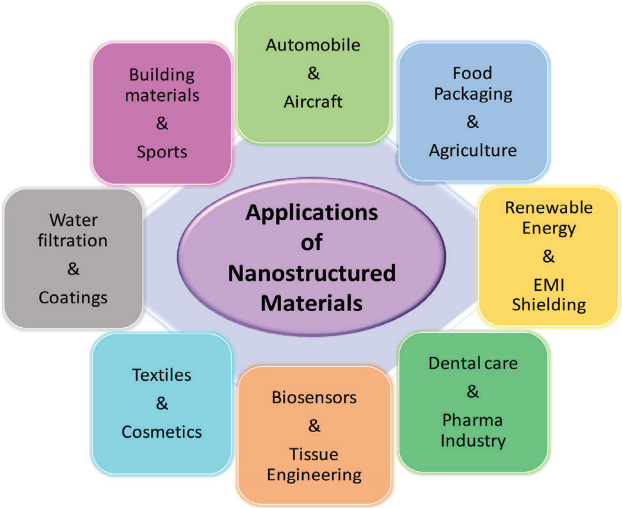

Figure 1. Common applications of NSMs

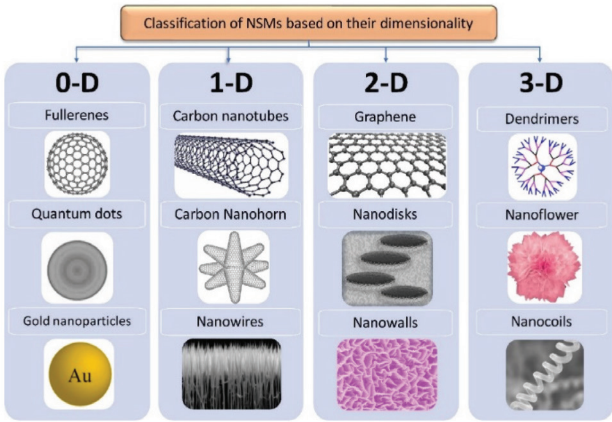

Figure 2. Classification of NSMs based on their dimensionality

management. Many works have already been approached to enhance the performance of NSMs, as well as tuning their structure and dimension. Carbon can be modified into different NSMs such as 0-D fullerenes (buckyballs); 1-D CNTs, nanohorns, nanaorods; 2-D nanosheets; and 3-D nanospheres (Kumar et al., 2019). The construction of 2-D graphene and 1-D CNTs shows that it is possible to create carbon materials with improved electrical properties. CNTs are known for their remarkable features, such as a large surface area, better conductivity, and excellent mechanical and thermal stability (Terrones et al., 2004). These properties make CNTs highly desirable for a variety of uses, including nanoelectronics (Khan et al., 2023), energy storage (Chitriv et al., 2024), and composite materials (Ali et al., 2023). On the other side, graphene is the most promising material for batteries, given its large surface area, flexibility, fast electronic and ionic transport, defect-rich pores, and functional groups in the oxide form (Qiu et al., 2023). These outstanding features explain why NSMs are the perfect candidates in the various sectors to produce energy storage devices, biomedical appliances, water filtration, and tissue engineering. Figure 1 illustrates several different applications of NSMs. This paper reviewed the brief classification and unique features of NSMs and summarized their benefits and limitations across various domains, considering their growing application in recent decades.

2. CLASSIFICATON OF NSMs

NSMs are defined as solids having micro-structural features in the range of 1-100 nm in at least 1-D. These materials have extraordinary thermal, electrical, and mechanical properties due to their fine particle size and high-volume fraction of grain boundary. NSMs demonstrate properties that are reasonably different from their bulk properties. These materials contain a controlled morphology with at least one nanoscale dimension. An NSM can be nano-sized along only one, two, and all three dimensions (Hou et al., 2009), in the form of a rod, film, or a dot (Li et al., 2005), gave the first classification scheme of NSMs based on crystallinity and chemical composition and further extended by (Liang et al., 2014). However, this classification was not fully described because of low dimensional structures such as nanoflakes, nanotubes, and nanowires, which were not taken into consideration. Figure 2 displays the classification of NSMs according to their dimensionality.

2.1 ZERO-DIMENSIONAL NSMs

In the past years, noteworthy progress has been made in the field of 0-D NSMs. A variety of chemical and physical methods has been developed for manufacturing 0-D NSMs with controlled dimensions. Recently, 0-D NSMs quantum dots, onion, nanolenses, hollow spheres, and heterogeneous particle arrays have been synthesized by many research groups (Zhang and Wang, 2009a, Liu et al., 2017, Guo et al., 2009, Dhas and Suslick, 2005), and different types of 0-D NSMs are shown in Figure 3. Furthermore, 0-D quantum dots have been extensively considered in lasers (Ledentsov, 2002), light-emitting diode (LEDs) (Stouwdam and Janssen, 2008), solar cells (Lee et al., 2009), and single-electron transistors (Mokerov et al., 2001).

2.2 ONE-DIMENSIONAL NSMs

Over the past few years, significant study and progress have been made in the field of 1-D NSMs. The last few years have seen the synthesis and characterization of 1-D NSMs made of inorganic materials, including nanowires, nanocrystals, nanoribbons, nanotubes, and nanobelts. Quantum confinement and nanoscale effects related to surface area are more prominent in 1-D than in 2-D NSMs. However, unlike 0-D, 1-D NSMs possess a single bulk-like dimension, which allows them to be integrated and connected to device architectures. After the discovery of

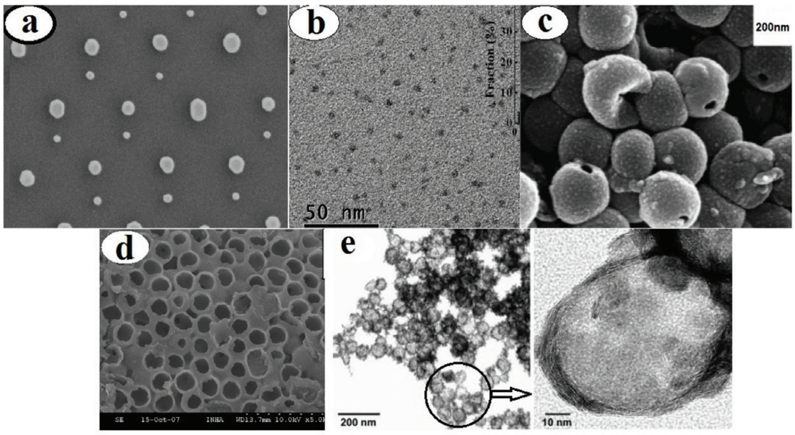

Figure 3. Electron microscope image of various 0-D NSMs synthesized by several research groups (a) nanoparticles binary arrays (Zhang and Wang, 2009b) (b) Quantum dots (Liu et al., 2017) (c) hollow core–shell nanoparticles (Guo et al., 2009) and (d) Hollow MoS_2 nanospheres (Dhas and Suslick, 2005)

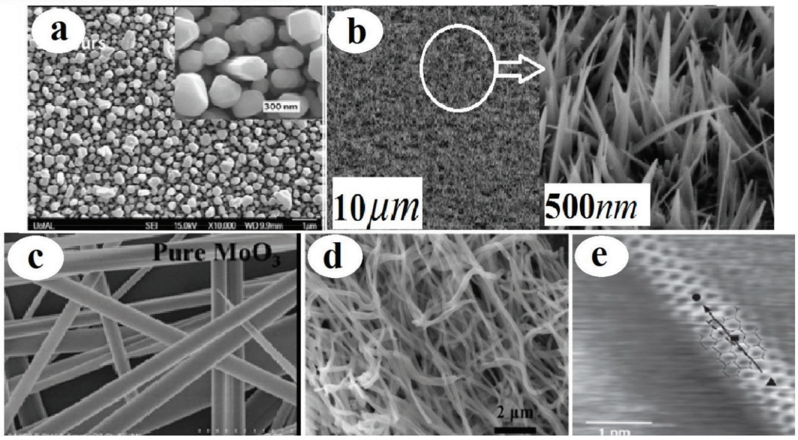

Figure 4. Electron microscope image of various 1-D NSMs, prepared by several research groups (a) nanorods (Qiu et al., 2023) (b) nanowires (Budiman et al., 2016) (c) nanobelts (Yang et al., 2017) (d) Nanoribbons (Li et al., 2017) and (e) nanotubes (Qiu and Yang, 2017)

nanotubes by Iijima (Iijima, 1991), the field of 1-D NSM has attained significant attention and a great impact on nanodevices, nanoelectronics, nanocomposite materials, and alternative energy resources. Figure 4 showcases various synthesized NSMs, such as nanorods, nanowires, nanobelts, nanoribbons, and nanotubes.

2.3 TWO-DIMENSIONAL NSMs

In recent years, the synthesis of 2-D NSMs has become an important area in materials development, owing to their low-dimensional characteristics that are different from the bulk properties. 2-D nanomaterial is also used for developing innovative applications in the field of sensors, nanocontainers, photocatalysts, and nanoreactors (Pradhan and Leung, 2008). Different types of 2-D NSM images are shown in Figure 5.

Zhou et al. (Zhou et al., 2014) synthesized high-quality 2-D gallium selenide (GaSe) crystal on a flexible mica substrate using the facile van der Walls epitaxy method. They produced single and few-layer GaSe nanoplates with lateral size up to tens of micrometers. On the other hand, Wang et al. (Wang et al., 2013) prepared layered materials using liquid-phase exfoliation by the dispersions of molybdenum disulfide (MoS_2) with large populations of single and few layers. Pradhan et al. (Pradhan and Leung, 2008) demonstrated the vertical growth of 2-D NSMs of thickness 40-100 nm and length up to several micrometers on indium-tin oxide-coated glass substrate using an electrochemical deposition in the temperature range of 22-90 ^oC.

2.4 THREE-DIMENSIONAL NSMs

3-D NSMs have concerned significant attention in recent years due to their high surface area and high absorption

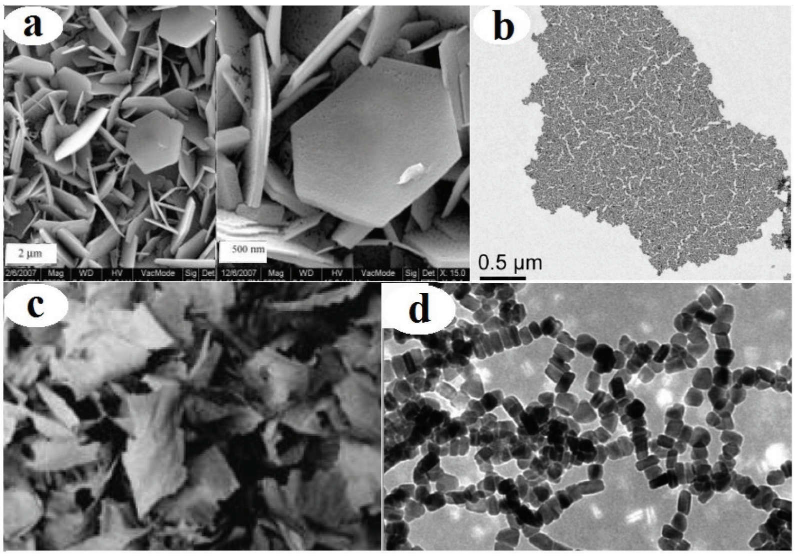

Figure 5. Electron microscope image of various 2-D NSMs (a) nanodisks (Deng et al., 2008) (b) nanosheets (Kim et al., 2014) (c) nanowalls (Akhavan and Ghaderi, 2010) and (d) nanoplates (Lu et al., 2009)

Table 1. Properties of carbon-based NSMs

NSMs	Properties of NSMs
Fullerenes (Buckyballs)	Semiconductor, conductor, and superconductor are all safe and inert materials that transfer light based on intensity.
CNTs	High thermal and electrical conductivity; High tensile strength (100 times stronger than steel) with better elasticity and flexibility.
Graphene	Good electrical, and thermal conductivity, as well as light absorption; High tensile strength and modulus.
Carbon Black	High strength and surface area; UV-resistant.
Carbon Nanofiber	Show good electrical, thermal, mechanical, and acoustic properties.

capacity. The performances of these NSMs mostly depend on the size, shape, dimensionality, and morphologies, which are considered in their quality execution and applications. Thus, many researchers are attracted to prepare 3-D NSMs with a well-ordered structure and morphology. These structures are used in different applications such as magnetic materials, catalysis, and electrode materials for batteries (Balach et al., 2018). Microscope images of typical 3-D NSMs such as nanoflowers, nanocones, nanocoils, and nanoballs are shown in Figure 6.

Yuan et al. (Yuan et al., 2015) demonstrated the fabrication of three-dimensionally ordered arrays of core-shell microspheres and magnetic mesoporous carbon shells. The obtained 3-D ordered arrays possess two sets of periodic structures at both sub-micrometer scale and mesoscale with a large mesopore size of 19 nm and a high surface area of 326 m^2/g. Song et al. (Song et al., 2010) fabricated 3-D radial ZnO nanowire/silicon microrod hybrid architectures by combining bottom-up and top-down methods. They reported that the ultra-large surface areas of the 3-D architectures are promising for diverse applications in catalysts, sensing, and photovoltaics. Table 1 listed the properties of carbon-based NSMs. The benefits and limitations of NSMs for energy storage systems have been summarized in Table 2.

3. APPLICATIONS OF NSMs

Ove the last few years, experimental findings revealed that the new era of polymeric composite materials have been developed by infusing different NSMs and their hybrids into polymer matrices. Therefore, the NSMs-based polymeric composites have unfolded several ways to industrial areas mainly energy, automotives, and electronic sectors. High performance NSMs-based composites can be produced by opting appropriate fabrication/design methodologies (Kamal et al., 2021). To explore the structure-processing-property relationships of NSMs, both computational and experimental studies have been conducted in recent years. However, compared to various NSMs -reinforced composites, CNTs- and graphene-reinforced composites have been widely studied due to their abundant applications (Mittal et al., 2015, Islam et al., 2022). Table 3 listed the various applications of NSMs and their effects on the properties improvement of composites.

Huang and co-authors (Huang et al., 2018) have developed a ground breaking solution - graphene-based polyvinyl butyral composites to encapsulate solar cells. This revolutionary technology has shown promising results in enhancing the conversion efficiency of solar cells. On the other side, the surface of solar cells can be coated with nanocomposite materials to improve performance due

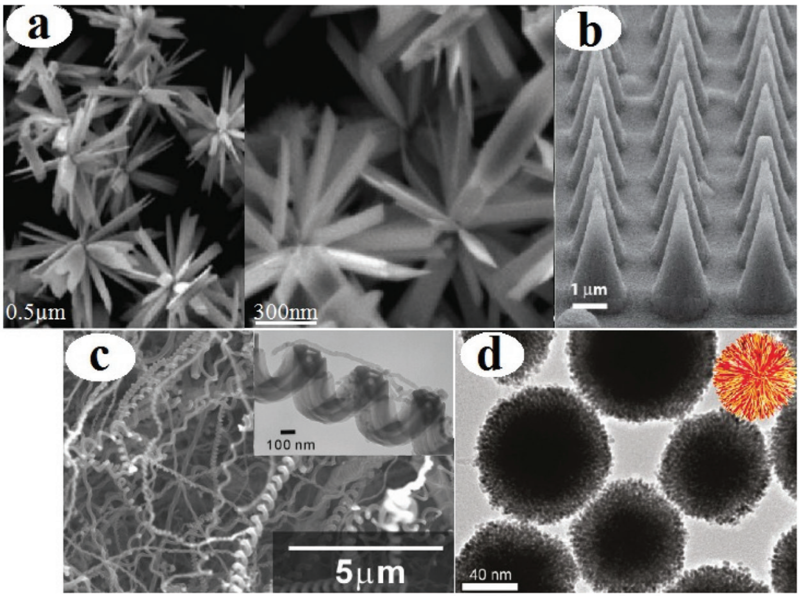

Figure 6. Electron microscope image of various 3-D NSMs (a) nanoflowers (Yu and Cao, 2008) (b) nanocones (Dutto et al., 2013) (c) nanocoils (Okazaki et al., 2005) and (d) nanoballs (Wang and Yamauchi, 2009)

Table 2. Advantages and limitations of using each type of NSMs in energy storage systems (Xu et al., 2021)

0-D	1-D	2-D	3-D
Benefits			
No large-scale solid-state diffusion	Efficient electron transport along and across the 1-D configuration	A significant number of available electrochemically active sites	Greater surface-to-volume ratio
Improved mechanical strength	Flexible freestanding structure	More surface area	Enhanced metal ion accessibility
Shorter alkali ion diffusion length	High aspect ratio	Good electrical conductivity	Reduced diffusion constraints and enhanced electrolyte penetration
Easy electrolyte accessibility	Facile strain relaxation	Surface and interlayer storage of large-sized metal ions	Effective absorption of electrode strain
Limitations			
Low dimensionality/surface area	The tightly interconnected configuration could impede Li ion diffusion and strain relaxation	Consumption of large amounts of electrolyte	Side reactions may occur due to the huge surface area
Agglomeration	Low coulombic efficiencies caused by continuous formation of the SEI film	Restacking and aggregation	Thicker electrode often leads to increased resistance
Low tap density/limited active sites	Poor mechanical property	Parasitic reactions related to electrolyte decomposition	Complicated synthesis method
Poor chemical stability	Low tap density	Irreversible capacity reduction in the first cycle caused by SEI development	Excessive electrolyte intake results in electrode flooding

to their passivity, antireflection, and bandgap properties (Law et al., 2023). In marine applications, graphene-based polymer composites provide corrosion resistance while also being lightweight and easy to fabricate. Graphene-induced fibrous composite is utilized in various ship components such as spars, hull, till, rudder, keels, masts, and long upright and parallel (deck) poles. The complete structure, particularly the chassis, of high-powered racing boats, is now composed of hybrid nanocomposites, which maintain their great performance and safety.

Table 3. Summary of various applications of NSMs and their effects on the properties of composites

Refs.	Matrix type	Carbon-based NSMs	Applications	Results
(Hu et al., 2017)	Polyimide	CNT	Aerospace	CNT/PI composites' modulus and strength were increased to 182 GPa and 3.9 GPa, respectively.
(Marriam et al., 2018)	Epoxy resin	CNT	Military automotive and defence	The fabricated composites showed improved tensile strength and peeling of 164.76% and 74.38%, respectively.
(Li et al., 2019)	Carbon	CNT	Electrical	Composite fibers' breaking load 320% ↑, strength 354% ↑ (2.3 GPa), and modulus 667% ↑ (60 GPa).
(Lee et al., 2019)	Polyvinyl alcohol	SWCNT	Military automotive and defence	PVOH grafting improved the stability of the SWCNT content (45 wt%), leading to higher stiffness (38.5 GPa) and strength (1100 MPa).
(Allheily et al., 2016)	Epoxy	Graphite	Aeronautic materials	Carbon fiber composite laminates exposed to laser irradiation experience thermo-mechanical weakening
(Yan et al., 2012)	Polystyrene	Graphene	EMI	The lightweight composite's particular shielding efficacy was as high as 64.4 dB cm3/g.
(Cheng et al., 2018)	Chitosan (CS)/Cu	GO	Electrical	Improved tensile strength to 868.6 MPa, ~5 times higher compared to the pure film.
(Al-Saleh and Sundararaj, 2013)	Polypropylene	Carbon black	EMI	Absorption loss contributes to the overall attenuation

4. CONCLUSIONS

Nanomaterials are intriguing materials because they have superior and tunable chemical, physical, and biological characteristics compared to bulk materials. NSMs can be categorized based on their structure, dimensionality, origin, and content. Researchers harnessed NSM properties by grafting various groups onto them, resulting in nanoparticles appropriate for energy generation and preservation. Researchers demonstrated the use of NSMs in water purification, cosmetics, biosensors, construction, drug delivery systems, aircraft, energy storage, and the food and agriculture industries. Different types of NSMs have been explored based on their dimensionality, such as zero, one, two, and three-dimensional, for their potential use in energy conversion applications. Thanks to their large surface area, higher mechanical strength, and thermal stability, that can be obtained via cost-effective synthesis method. However, more research is needed to determine how to create multifunctional nanomaterials with specific functions by coupling nanoscale structures to macroscopic functional qualities that can tolerate harsh operating conditions.

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