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Exploring the application of the carbon and boron nitride nanotubes: a review

D. Deshwal[1,2]*, A. K. Narwal[1]

[1]*Department of Mechanical Engineering, Deenbandhu Chhotu Ram University of Science and Technology, Murthal, Sonipat - 131039, Haryana, India*
[2]*Department of Mechanical Engineering, Shree Guru Gobind Singh Tricentenary University Gurgaon - 122505, Haryana, India*

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This article comprehensively examines the various applications of carbon nanotubes (CNTs) and boron nitride nanotubes (BNNTs) in multiple scientific and technological fields. Carbon nanotubes (CNTs) and boron nitride nanotubes (BNNTs) possess distinctive mechanical, thermal, and electrical characteristics, rendering them viable options for various applications. The article examines the present state of research in this field, emphasizing recent advancements in synthesizing and characterizing these nanotubes. The study is expanded to investigate the applications of BNNTs and CNTs in the biomedical domain. Notable properties allow cancer treatment, gene therapy, and tissue regeneration. The prospective uses of CNTs and BNNTs in energy storage, electronics, sensors, and materials science are examined comprehensively. Owing to the piezoelectric properties of BNNT, it is suitable for use as a sensor and has diverse applications in robotics. This review offers significant insights into nanotube synthesis techniques, applications, and a case study, advancing nanotechnology and emphasizing the necessity for additional research to fully exploit its potential.

Keywords: Nanotubes, biomedical applications, BNNT, CNT

INTRODUCTION

Boron nitride nanotubes (BNNTs) and carbon nanotubes (CNTs) are two types of nanotubes that have gained significant interest in materials science and nanotechnology. Despite their structural similarities, BNNTs and CNTs exhibit distinct properties that make them suitable for different applications. While CNTs are well known for their superior electrical conductivity, BNNTs stand out due to their excellent thermal stability and chemical resistance. Understanding these differences is crucial for optimizing their use in advanced technologies. BNNTs and CNTs are both members of the family of nanotubes, which are tiny cylindrical structures made of nanomaterials with diameters on the order of a few nanometers (10^{-9} meters) and lengths up to several microns (10^{-6} meters).

BNNTs are formed by boron and nitrogen atoms arranged in a hexagonal lattice, resembling the structure of CNTs. Their structural representation is illustrated in Figure 1. BNNTs exhibit remarkable thermal and mechanical properties, including high thermal stability, excellent thermal conductivity, and superior tensile strength. Additionally, their unique electrical characteristics make them highly suitable for applications in electronic devices.

Carbon nanotubes consist of carbon atoms organized in a cylindrical shape with a honeycomb lattice configuration.

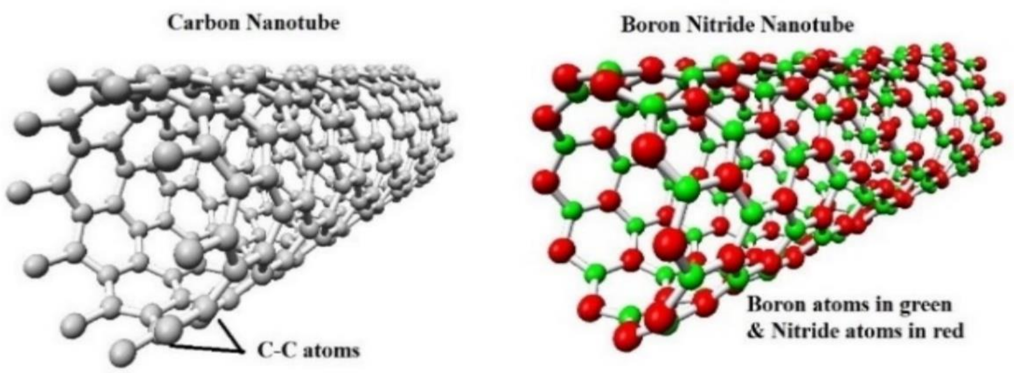

Figure 1. Structure of CNT and BNNT

* To whom all correspondence should be sent:
E-mail: deshudinesh@gmail.com

They can exist as single-walled or multi-walled structures, exhibiting exceptional mechanical, electrical, and thermal characteristics. On the other hand, boron nitride nanotubes are made of boron and nitrogen atoms arranged in a similar cylindrical structure. Due to their biocompatibility, they are being studied for similar applications as carbon nanotubes and biomedical applications. While both nanotubes have similar structures and properties, BNNTs have some advantages over CNTs in specific applications. For example, they are more oxidation-resistant and have better thermal stability at high temperatures. However, carbon nanotubes are more commonly studied and have a wider range of applications due to their lower cost and higher availability. As a result, their unique properties have created many opportunities for use in various areas, including electronics, energy storage, biomedicine, and environmental cleanup. However, more research is required to fully explore their capabilities and applications.

This review explores the latest research on CNTs and BNNTs, focusing on their unique properties and real-world applications. By comparing their strengths and examining their impact across different fields, we highlight their potential to drive innovation and inspire further advancements in nanotechnology. The outstanding mechanical strength of CNTs, high aspect ratio, and lightweight nature make them excellent choices for strengthening composite materials. They have found applications in aerospace, automotive, and construction industries, where their inclusion has improved strength, stiffness, and durability of various structural components. Additionally, the extraordinary electrical conductivity and thermal properties of CNTs have sparked interest in their incorporation into next-generation electronic devices, interconnects, and sensors, thereby revolutionizing the field of nanoelectronics.

On the other hand, boron nitride nanotubes, often referred to as "white graphene," possess remarkable thermal stability, high thermal conductivity, and excellent dielectric properties. These characteristics make BNNTs highly desirable in thermal management, high-temperature electronics, and optoelectronic devices. Furthermore, their unique biocompatibility and chemical inertness have led to extensive exploration in biomedicine, including drug delivery systems, tissue engineering scaffolds, and biosensors.

Throughout this review, we will focus on the individual applications of CNTs and BNNTs and explore their synergistic potential when combined in hybrid structures. By harnessing the complementary properties of these nanomaterials, researchers have developed novel materials with enhanced performance, offering exciting opportunities for breakthroughs in various fields.

BNNTs and CNTs are nanotubes that have various biomedical applications. The BNNTs basic blocks originated from the CNTs but have better physical and chemical properties compared to its counter CNT [1]. In the early 90s, various studies were carried out exploring CNT to understand the field of nanostructures [2]. Extreme material properties have been found to grow when the structure is brought down to the nanoscale [3].

In recent years, significant progress has been made in synthesizing, characterization, and functionalizing carbon and boron nitride nanotubes, expanding their potential applications even further. Researchers have explored various fabrication techniques to tailor the properties of these nanotubes, such as diameter, chirality, and surface functionalization, to meet specific application requirements.

Carbon nanotubes possess considerable energy storage potential due to their extensive surface area, superior electrical conductivity, and mechanical robustness. They are extensively utilized in supercapacitors and lithium-ion batteries as effective conductive additives, establishing a conductive network that enhances charge transport. Moreover, their distinctive architecture facilitates the encapsulation of active substances, improving battery stability and cycling efficacy. These innovations can potentially revolutionize portable electronics, electric vehicles, and renewable energy technologies.

BNNTs are distinguished by their remarkable thermal and chemical stability, rendering them suitable for high-temperature applications. In thermal management, BNNTs have been investigated as additives in polymer composites and coatings to enhance heat dissipation in electronic devices. Their superior thermal conductivity and resistance to extreme temperatures can improve the performance and reliability of advanced electronic systems. Furthermore, BNNTs exhibit promise in optoelectronics owing to their distinctive optical characteristics, including a broad bandgap and significant light absorption, facilitating applications in photovoltaics, light-emitting diodes (LEDs), and photodetectors.

The biomedical sector has observed an increasing interest in the application of carbon and boron nitride nanotubes. Carbon nanotubes (CNTs) have been examined for drug delivery systems, as their extensive surface area and capacity to encapsulate therapeutic agents, facilitate targeted and controlled release. The biocompatibility and unique optical characteristics of BNNTs render them exceptionally appropriate for bioimaging and biosensing applications. Moreover, their potential in biomedical applications is significant, especially in tissue engineering, where their biocompatibility and mechanical properties, similar to those of natural tissues, render them suitable for scaffolding purposes. Moreover, their chemical inertness renders them optimal for biosensors and diagnostic platforms, providing high sensitivity and selectivity in disease detection.

As we move forward, this review will look closer at these applications, their challenges, and the innovative solutions researchers are developing. This study also explores future trends, including hybrid structures, functionalization techniques, and scalable production methods, shaping the next phase of advancements in this field. The applications of carbon and boron nitride nanotubes are vast and diverse, spanning industries such as electronics, energy, biomedicine, and more. Their exceptional properties and continuous advancements in fabrication techniques hold immense potential for transforming various fields and driving technological advancements. By understanding the capabilities and limitations of these nanotubes, researchers can explore innovative approaches and further unlock the remarkable applications of carbon and boron nitride nanotubes. In summary, this review aims to provide a comprehensive understanding of the applications of carbon and boron nitride nanotubes, showcasing their remarkable properties and highlighting their potential for transforming a wide range of industries. By delving into the latest research findings and advancements, we hope to inspire further exploration and innovation in utilizing these nanotubes, thus driving the advancement of nanotechnology and its impact on society.

Synthesis of nanotubes

The integration of nanotubes with different strategies has been discussed here. Spearheading and rapid formation of BNNTs was largely enlivened due to CNT synthesis processes, including arc extraction, laser heating, and vaporization, boron Nitride replacement strategy from CNT structures, chemical vapor deposition method (CVD) uses borazine, the induction heating of boron oxide with CVD (BOCVD) and high ball processing [4]. Some commonly used synthesis methods for nanotubes are shown in Figure 2.

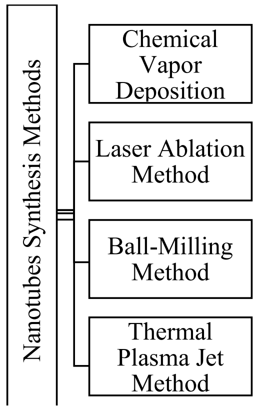

Figure 2. Nanotubes synthesis methods

- *Chemical vapor deposition method (CVD)*

It is the best standard method, generally used to obtain carbon nanomaterials on a large-scale, and was recently adopted to obtain boron nitride nanotubes. In contrast with different methodologies, this procedure offers better controllability of development boundaries concerning development parameters related to the development process, temperature, catalysts, stirring and test planning to ensure purity and the highest obtained quality of nanomaterials [5].

In comparison with the large-scale production, nearly 100 grams of CNT being nhhobtained in the CVD method, BNNT's has significantly lower production rate - nearly 100 mg [6]. Therefore, an approach for delivering a BN proclamation of BNNTs mergers is called BOCVD (boron oxide chemical vapor deposition) [7].

In BOCVD, MgO powder and boron were used as reactants to produce B_2O_2. At high temperatures (about 1000 ^{0}C – 1700 ^{0}C), a reaction was carried out between B_2O_2 and NH_3 gas to produce BNNTs. As a result of the discovery of these BOCVD BNNTs, the authors have also embarked on other related activities, such as refining, distribution, operation, doping, polymeric compounds, etc. However, the commercialization and actual use of BNNTs in the industry is hampered by the generally low level of creativity and the need to redesign the exhibition room presented and tested [8].

- *Laser ablation method*

Enlivened by CNT's development, new technologies like the laser removal or laser dissipation procedure have been utilized for the development of BNNTs since 1996. Mainly, the advantages associated with using this laser ablation method are that it produces high-quality nanotubes of high crystallinity and high aspect ratio [9]. In this method due to laser heating at a temperature of around 2000 ^{0}C, phase transformation of boron or boron nitride takes place from solid to liquid in an N_2 atmosphere. Because of the presence of N_2 atmosphere, a direct reaction takes place between boron and nitrogen, which stimulates the growth of BNNTs [10]. Goldberg *et al*. was the one who for the first time succeeded in BNNT synthesizing.

Multi-walled BNNT nanotubes were also synthesized by the laser ablation method, in this process nitrogen gas at very high pressure approx. 5GPa to 15GPa is injected in a diamond anvil cell simultaneously at a very high temperature approx. 5000K laser heating the hexagonal and cubic boron nitride (BN) in the cell [11].

Langley Research Center, NASA, also synthesized BNNT's accordingly. By CO_2 laser at very high temperature ~ 4000K, they continuously heated boron metal fiber in a chamber filled with nitrogen gas at a pressure ~ 14 bar. BNNTs obtained from this method were small in diameter (generally < 5nm) but with high purity. The production rate of this method was ~0.2 g per hour [12].

- *Ball milling method*

Grinding by a ball (ball milling) is utilized to develop BNNTs which are of industrial grade with minimal effort and low cost. In pervasive conditions, the direct reaction was carried out between boron and nitrogen that can be stimulated by presenting an indistinct structure in boron powder. This change is made effortlessly using a sufficient amount of mechanical energy, controlled and monitored by a few parameters, for example, operating time, and power (rotation every minute) [13].

As a result, the amount of BNNT can be made by running normally. This cycle is less than the processing time that can be reached in several hours and the emerging heat in the annealing of boron powder plays an important role in the BNNT formation. According to the study published by Chen *et al*., in NH_3 gas atmosphere, boron powder was processed for 150 hours, afterward in the N_2 atmosphere, the isothermal tempering was carried out at 1000^0 C to 1200° C. In a subsequent study, the authors suggested that extending the milling process plays a crucial role in maximizing BNNT production. A longer milling duration enhances the nitration cycle between boron and NH_3, thereby accelerating the formation of nucleation structures that facilitate BNNT synthesis [14].

- *Thermal plasma jet (TPJ) method*

Even though BNNTs produced by laser removal strategy had very high quality, the production rate is very low, i.e. 1 mg/h. Therefore, the plasma jet method is a perfect solution to this problem. Thermal plasma has the capacity to apply thermal energy over a wide range of volumes, expanding the growth area up to 100 cm^2. TPJ method comprises two concentric electrode terminals - one is anode and the second is cathode. When a gas mixture of inert gases like Ar, N_2 and H_2 passes through a nozzle between the two concentric electrodes a wide range of arc–plasma regions forms [15].

Literature review

CNTs and BNNTs have attracted considerable attention in the scientific community because of their unique properties and broad range of potential applications. This literature review aims to provide a thorough overview of the current research on CNTs and BNNTs, focusing on key studies that demonstrate their potential in diverse fields.

CNTs possess exceptional mechanical properties, including high tensile strength and stiffness. These properties have led to their extensive use as reinforcing agents in composite materials. In a study, CNT-reinforced composites have shown improved mechanical properties, including increased tensile strength and fracture toughness. These results emphasize the potential of CNTs to enhance the performance of structural materials in industries like aerospace and automotive [16].

The excellent electrical conductivity of CNTs has opened up avenues for their use in nanoelectronic devices. The application of CNTs as interconnects in integrated circuits showcases their high conductivity and reliability. Furthermore, CNTs have demonstrated potential in energy storage devices, including supercapacitors and lithium-ion batteries [17]. The study reported enhanced energy storage performance when CNTs have been used as electrode materials due to their high surface area and exceptional electrical [18].

CNTs have demonstrated potential in a range of biomedical applications, such as drug delivery, tissue engineering, and biosensing. The use of CNTs as drug carriers highlights their capability to encapsulate therapeutic agents and facilitate targeted delivery [19]. Additionally, CNT-based scaffolds have been investigated for tissue engineering applications due to their biocompatibility and ability to mimic the structure of natural tissues [20]. Moreover, CNTs have been explored in biosensors for sensitive and selective detection of biological analytes [21].

BNNTs possess excellent thermal conductivity and stability, making them ideal for thermal management applications. A study demonstrated the incorporation of BNNTs into polymer composites, resulting in enhanced thermal conductivity and improved heat dissipation properties. This finding has implications for thermal management in electronics, where the efficient removal of heat is critical for device performance and reliability [22].

The unique optical properties of BNNTs, including a wide bandgap and high light absorption, have opened up opportunities in optoelectronic devices. The use of BNNTs as promising materials for photovoltaics demonstrates their potential in efficient solar energy conversion [23]. Furthermore, BNNTs have been explored in the development of LEDs and photodetectors due to their high thermal stability and excellent electrical insulation properties [24].

The biocompatibility and chemical inertness of BNNTs make them attractive for biomedical applications. BNNTs have a potential as carriers for drug delivery, noting their stability and ability to protect encapsulated drugs [25]. BNNTs have also been explored in biosensing applications, offering high sensitivity and selectivity in disease detection [26].

Researchers have also explored the combination of CNTs and BNNTs to harness their complementary properties and create hybrid structures. The use of CNT/BNNT hybrid materials in energy storage devices highlights their improved performance compared to individual nanotubes [27]. Additionally, CNT/BNNT hybrids have shown promise in thermal management, sensing, and catalysis applications [28].

The development of reliable and scalable fabrication techniques for CNTs and BNNTs is crucial for their widespread application. Several methods have been explored for the synthesis of CNTs and BNNTs, including CVD, arc discharge, and laser ablation. CVD has become a widely used technique for the controlled production of both CNTs and BNNTs, enabling the creation of nanotubes with specific properties [29]. Additionally, functionalization techniques have been investigated to modify the surface properties of nanotubes, enabling enhanced compatibility with different matrices and targeted applications. For instance, the surface functionalization of CNTs with functional groups or polymers has been explored to improve their dispersion in composites and facilitate better interfacial bonding [30]. Similarly, surface modification of BNNTs has been studied to enhance their dispersion in solvents and compatibility with polymeric matrices [31].

Despite the significant progress in understanding the properties and applications of CNTs and BNNTs, several challenges and areas for further exploration remain. One challenge lies in the large-scale production of nanotubes with consistent properties at a lower cost. Efforts are underway to optimize synthesis methods and develop scalable fabrication techniques to meet the growing demand. Moreover, the toxicity and biocompatibility of nanotubes need to be thoroughly investigated for safe biomedical applications. Understanding the potential health and environmental impacts is crucial for the responsible development and application of these nanomaterials.

Future research will focus on exploring new applications and integrating nanotubes into emerging technologies. For example, incorporating CNTs and BNNTs in 3D printing technologies holds promise for the fabrication of complex structures with tailored properties. Additionally, combining nanotubes with other nanomaterials, such as graphene and transition metal dichalcogenides, holds promise for enhancing their properties and expanding their applications. It can lead to the development of multifunctional nanocomposites with enhanced performance in various applications. The comparative analysis of the properties of CNTs and BNNTs with the corresponding applications are presented in Table 1.

The literature review emphasizes the significant research on the applications of CNTs and BNNTs, demonstrating their potential in reinforcing materials, nanoelectronics, energy storage, thermal management, and biomedicine. The advancement of fabrication methods and functionalisation strategies has been crucial in customising the properties of nanotubes for particular applications. Despite the persisting challenges, ongoing research initiatives and interdisciplinary collaborations are anticipated to propel further progress in utilizing the unique characteristics of CNTs and BNNTs for innovative technological applications.

Table 1. Comparison of CNTs and BNNTs properties with their respective applications

Nanotube Properties	CNTs	CNT Applications	BNNTs	BNNT Applications
Structure	Cylindrical tubes of carbon atoms in a honeycomb lattice [32]	Nanoelectronics, structural reinforcements [33]	Cylindrical tubes of boron and nitrogen atoms [34]	High-temperature electronics, biomedicine [35]
Density	Low density (~1.3-1.4 g/cm³) [36]	Lightweight aerospace materials [37]	Low density (~2 g/cm³) [38]	Lightweight, high-strength materials [39]
Elasticity	Highly flexible, excellent bending properties	Flexible electronics, nanocomposites [40]	Rigid and stable under extreme conditions [41]	Radiation shielding, high-stress applications [42]
Mechanical Strength	High tensile strength (~50-100 GPa) [43]	Aerospace composites, automotive materials [44]	Comparable or superior tensile strength (~30-100 GPa) [45]	Structural reinforcements, impact-resistant coatings [46]
Thermal Conductivity	High (~3000 W/m·K) [47]	Heat sinks, thermal coatings, energy devices [48]	Very high (~2000-3000 W/m·K) [49]	Thermal management, aerospace applications [50
Thermal Expansion	Low thermal expansion [51]	Thermal coatings, heat-resistant composites [52]	Very low thermal expansion [53]	Aerospace, extreme environment applications [54]
Corrosion Resistance	Moderate resistance [55]	Anti-corrosion coatings [56]	Highly resistant to corrosion [57]	Protective coatings, marine applications [58]
Energy Storage	High surface area, good for batteries & supercapacitors [59]	Lithium-ion batteries, supercapacitors, hydrogen storage [60	Limited charge storage capability [61]	Thermal stability in energy systems [62]
Electrical Conductivity	Excellent conductor (metallic/semi-metallic behavior) [63]	Transistors, flexible electronics, interconnects [64]	Insulating or semi-conducting (~wide bandgap of ~5.5 eV) [65]	High-performance dielectric materials, optoelectronics [66]
Optical Properties	Fluorescent, tunable bandgap [67]	Photodetectors, LEDs, infrared emitters [68]	Wide bandgap (~5.5 eV), optically transparent [69]	UV shielding, optoelectronic devices
Oxidation Resistance	Prone to oxidation at high temperatures [70]	Limited high-temperature applications [71]	Highly resistant to oxidation [72]	High-temperature structural applications [73]
Chemical Stability	Reactive in certain environments [74]	Chemical sensors, catalysis [75]	Chemically inert [76]	Corrosion-resistant coatings, extreme conditions [77]
Biocompatibility	Some toxicity concerns [78]	Limited biomedical use (drug carriers, biosensors) [79]	High biocompatibility [80]	Implants, biosensors, tissue scaffolds [81]
Cost and Availability	Lower cost, widely available [82]	Mass production applications [83]	Expensive, limited commercial production [36]	High-end applications, research-focused fields [84]

Applications of nanotubes

CNTs applications

CNTs have a number of unique properties that make them potentially useful for a variety of applications. One potential application of carbon nanotubes is in electronics. Because they are very small, they could be used to create tiny transistors and other electronic components that are much smaller and more efficient than current technology. They could also be used to create flexible, transparent displays. The most promising application is in the development of nanoscale electronic devices, such as transistors and interconnects. Carbon nanotubes are ideal for this application because they have very high electrical conductivity, are very small and have excellent thermal properties [85-86]. Carbon nanotubes could be used to create smaller, faster, and more energy-efficient transistors than those currently used in silicon-based electronics. They have the potential to replace silicon transistors in future electronics because they are capable of operating at higher frequencies, dissipating heat more efficiently, and consuming less power. Carbon nanotube field-effect transistors (CNFETs) have been identified as a promising nanotechnology for developing energy-efficient computing systems. The primary challenge in translating this technology to commercial manufacturing is developing a method for uniformly depositing nanotubes onto large-area substrates. This method must be manufacturable, compatible with existing silicon-based technologies, and offer energy efficiency advantages over silicon. Bishop *et al*. demonstrated that submerging the substrate in a nanotube solution is a viable deposition technique that can address these challenges and enable the fabrication of CNFETs in industrial facilities [87]. In addition to transistors, carbon nanotubes could also be used to create other electronic components, such as diodes, resistors, and capacitors [88]. CNT diodes have intrinsic cut-off frequency exceeding 100 GHz, with measured bandwidths reaching at least 50 GHz or higher [89]. They could also play a key role in the development of flexible and transparent electronics, with potential applications in flexible displays, wearable electronics, and smart packaging [90]. By improving the uniformity of CNT films and introducing a new pretreatment technique for flexible substrates, CNT thin-film transistors (TFTs) have been successfully used to drive a flexible 64 × 64-pixel active-matrix light-emitting diode (AMOLED) display. The resulting AMOLED features uniform brightness across all 4096 pixels, and a high yield of 99.93% [91].

Carbon nanotubes offer significant potential for energy storage applications because of their unique features, such as a large surface area, strong mechanical strength, and outstanding electrical conductivity. Below are some of the possible applications of carbon nanotubes in energy storage [92-93].

- *Batteries:* Carbon nanotubes can be used as electrode materials in batteries to enhance their performance. They have been shown to improve the capacity, energy density, and cycle life of batteries. Carbon nanotubes can also improve the rate of charge and discharge, leading to faster charging times [94]. The increasing demand for portable and wearable electronics has fueled the interest in developing flexible batteries that can maintain their functionality even under various mechanical deformations. Significant efforts have been made in material synthesis and structural design to achieve this goal. Carbon nanotubes (CNTs), with their unique one-dimensional (1D) nanostructure, can be easily formed into various macroscopic structures, including 1D fibers, 2D films, and 3D sponges or aerogels. Due to their remarkable mechanical and electrical properties, CNTs and CNT-based hybrid materials are considered excellent materials for building components in flexible batteries [95].
- *Supercapacitors:* Carbon nanotubes can serve as electrode materials in supercapacitors, enhancing their energy storage capacity. Their high surface area and excellent electrical conductivity enable them to rapidly store and release energy. Carbon nanotube-based supercapacitors have the potential to provide high power density and long cycle life [96-97]. Three symmetric paper supercapacitor designs were created using CNTs, graphite nanoparticles (GNPs), and graphene electrodes. These supercapacitors utilized a gel electrolyte made of polyvinyl alcohol (PVA) and phosphoric acid (H_3PO_4), with a separator film composed of $BaTiO_3$. The surface of the carbon nanomaterials, electrode films, and gel electrolyte was examined using scanning electron microscopy and transmission electron microscopy [98].
- *Hydrogen storage:* CNTs can also be used for hydrogen storage, which is an important component of hydrogen fuel cells. Carbon nanotubes can adsorb hydrogen molecules on their surface, increasing the amount of hydrogen that can be stored in a small space [99]. The study explored the potential of Li-doped carbon nanotubes as a viable storage medium for hydrogen. A computational model was used to study the impact of CNT size on its structural and energetic properties, focusing specifically on the adsorption of an isolated lithium atom on the CNT wall as a site for hydrogen adsorption [100]. It was found that the capacity for H_2 adsorption is strongly affected by the specific surface area, as well as the morphological and structural characteristics of the CNTs [101].
- *Solar cells:* CNTs can improve the performance of solar cells by boosting their energy conversion efficiency. They can act as electron acceptors in organic solar cells, helping to enhance their power conversion efficiency [102]. Over the past few years, there has been a surge of interest in carbon-based materials, specifically CNTs, for their exceptional physicochemical properties, cost-effectiveness, eco-friendliness, and abundance. These attributes make CNTs an ideal material for use in the production of organic solar cells (OSCs).

Moreover, CNTs' low sheet resistance and high optical transmittance render them an excellent candidate for an alternative anode to the conventional indium tin oxide (ITO) which is not only expensive but also toxic and scarce [103].

Carbon nanotubes also have potential applications in materials science. They could be used to create stronger, lighter materials for use in construction and aerospace applications. They could also be used to create new types of sensors and actuators, as well as for drug delivery and other medical applications.

CNTs have several medical applications, such as carrying drugs and biomolecules for efficient delivery to body cells and organs. They can also be used in tissue regeneration and have application in diagnostics and analysis as they can be used as biosensors [104]. The various applications of CNTs are illustrated in Figure 3.

The studies of CNTs are advanced because their exemplary contribution has been found in regenerative medicine and tissue engineering which is sustainable too [105]. CNTs are the best among the various available materials because of their biocompatible nature and resistance to biodegradability. They also have better functionality with biomolecules to improve organ regeneration [106].

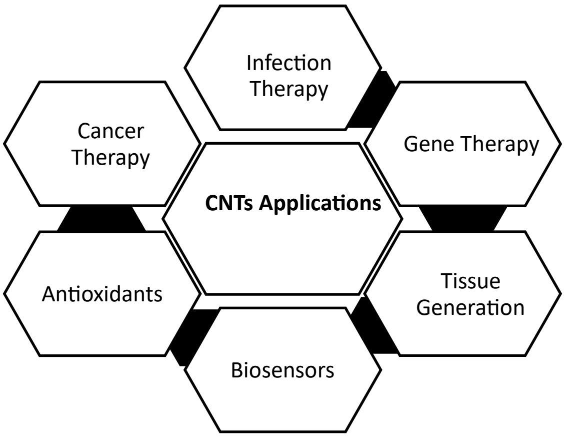

Figure 3. CNTs biomedical applications

CNTs also act as drug carriers to diagnose cancer. CNTs are having improved cellular uptake of potent drugs which makes them efficient delivery systems. It has been found that due to the high aspect ratio and high surface area of the CNTs they have an advantage over various existing delivery carriers [107]. CNTs are resistive in nature to the infectious agents, as a result they resolve problems associated with antibacterial, antiviral drugs and vaccine inefficacy in the body [108]. CNTs were recently found to carry the DNA molecule and insert it into the cell nucleus to cure the defective gene by using the gene therapy approach [109].

Despite their potential, however, there are still many challenges associated with the use of carbon nanotubes. For example, they are difficult to be produced in large quantities and at low cost. They can be toxic if not handled properly, raising concerns about their safety in consumer products.

BNNTs applications

BNNT (boron nitride nanotubes) are a type of nanomaterial that has unique properties, such as high strength, high thermal stability, and excellent electrical insulation. These properties make BNNTs attractive for a wide range of applications, including:

- *Biomedical:* BNNTs offer potential in biomedicine, with applications in drug delivery, tissue engineering, and medical imaging. Their low toxicity makes them suitable for enhancing the targeting and delivery of drugs to specific cells or tissues [110].

Like CNTs, BNNTs have various biomedical applications, but are chemically and physically more stable. BNNTs are used for the treatment of cancer by electroporation-based oncology [111]. They have also found applications in nerve & bone tissue regeneration [112]. A new bioink for tissue engineering was created using a hydrogel-based ink made of alginate (Alg) strengthened with functionalized boron nitride nanotubes (f-BNNTs). The ink's printability, physiochemical properties, and biocompatibility were quantitatively characterized to verify its suitability. The findings imply that the Alg reinforced with f-BNNTs, which is 3D printable, has the potential to serve as a bioink for tissue engineering [113]. The various applications of BNNTs are illustrated in Figure 4.

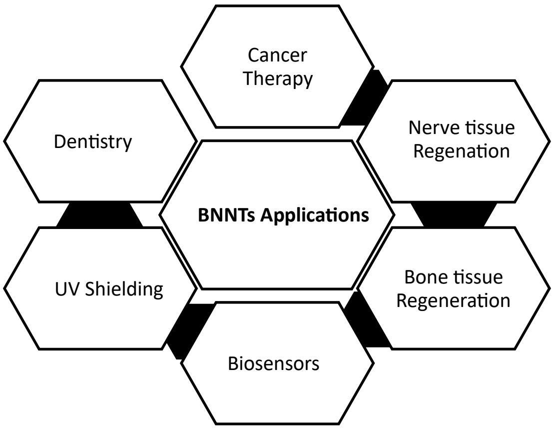

Figure 4. BNNTs biomedical applications

The BNNTs have applications in ceramic composites, e.g., lightweight ceramic composites. BNNTs are used in low-temperature applications like dentistry and also in high-temperature applications like jet engines [114]. The study aimed to investigate how the properties of resin-based light-curing dental sealants (RBSs) are affected by the addition of BNNTs at varying concentrations. The RBSs were formulated using methacrylate monomers, consisting of 90 wt.% of triethylene glycol dimethacrylate and 10 wt.% of bisphenol A-glycidyl methacrylate. Two concentrations of BNNTs (0.1 wt.% and 0.2 wt.%) were incorporated into the resin, with a control group containing no filler. The study evaluated several properties of the RBSs, including the degree of conversion, ultimate tensile strength, contact angle, surface free energy, surface roughness, and color. The results suggest that adding BNNTs to RBSs may introduce bioactivity and decrease their surface free energy [115]. Due to BNNTs anti radiant property, it is used for ultraviolet (UV) shielding applications [116].

- *Electronics:* BNNTs have excellent electrical insulation properties, making them ideal for applications in electronics. They can be used as insulators in high-temperature environments, which can improve the performance and reliability of electronic devices [117]. BNNTs are resistant to fire, which allows them to be used in fire-retardant cabling to manufacture flame-resistant high-strength cables. Also, used for creating high-strength and lightweight conductive cables [118]. BNNTs are electric insulators used in strong composites and electrically insulating components. They are applied in manufacturing lightweight and strong wiring of aerospace components [119]. The study reported a composite paper with excellent thermal conductivity, prepared through the synergistic combination of one-dimensional aramid nanofibers (ANFs), one-dimensional edge-hydroxylated BNNTs, and polyethyleneimine (PEI). The resulting composite paper demonstrates a high level of thermal conductivity, measuring 9.91 $Wm^{-1}K^{-1}$, as well as low dielectric loss (<0.01) and an exceptional heat resistance performance. Furthermore, the composite paper exhibits an ultrahigh electrical breakdown strength, measuring approximately 334 kV/mm [120]. By forming an oriented, percolative network, the boron nitride platelets with high-loading provided exceptional in-plane thermal conductivity, ranging from 77.1 to 214.2 W m^{-1} K^{-1}, comparable to certain metals like aluminum alloys (108–230 W m^{-1} K^{-1}). Through the utilization of the BN-based paper as an electrically insulating and flexible substrate, the study reveals its potential for reducing the temperature of electronic devices [121].
- *Energy:* BNNTs can be used in energy storage devices such as lithium-ion batteries and supercapacitors. BNNTs can improve the performance and safety of these devices by enhancing their energy density, cycle life, and thermal stability [116].

Ensuring the safety of lithium-ion batteries is a critical issue, affecting both large-scale energy storage and everyday use of mobile devices. A primary cause of safety concerns is the overheating of the cell, which can result from short circuits in environments with high temperatures and currents. The separator is a key component in preventing such short circuits and thus, the thermal stability of the separator is critical in ensuring battery safety. BNNTs, a promising new nanomaterial, can enhance the thermal stability of polyolefin separators by preventing thermal shrinkage during high-temperature and high-current operation, which helps avoid battery short circuits [122].

Using a simple and cost-effective hydrothermal method, zinc oxide nanoparticles are synthesized on both cellulose nanofibers (CNF) and BNNT surfaces, producing a ternary nanostructure. Upon investigating the electrochemical and piezoelectric properties of this structure, it was found that the BNNT–CNF/ZnO ternary nanostructure delivers impressive performance, achieving a specific capacitance of 300 F g^{-1}, along with high energy (37.5 W h kg^{-1}) and power density (0.9 kW kg^{-1}) at a current density of 1 A g^{-1} [123].

BNNTs are used in transparent armor, batteries and aerospace as a polymer. Because of their piezoelectric nature, the BNNTs can enhance sensors and robotics applications [124].

- *Aerospace and defense**:*** BNNTs can be used to reinforce composite materials, which are used in aerospace and defense applications such as aircraft, spacecraft, and armor. BNNTs have a higher strength-to-weight ratio than other reinforcement materials, making them ideal for these applications [125]. The study explored the use of BNNTs to strengthen aluminum in aircraft wing plates, focusing on their impact on the dynamic characteristics. The reinforcement was applied in two ways: uniformly and functionally graded throughout the plate's thickness. The plate was modelled as a rectangle, with edges shaped by linear, circular, or hyperbolic functions. The study examined various factors, including thermal environment, BNNT volume, reinforcement distribution, and geometric parameters. The results showed that BNNTs significantly improve the reinforcement properties of aircraft wings [126].

- *Environmental:* BNNTs can be used in environmental applications such as water treatment and air purification. BNNTs can remove pollutants from water and air by adsorbing or catalyzing them, and they have high thermal stability, which can enable them to be used in high-temperature environments [127]. Due to their large surface area and high-temperature resistance, BNNTs have been studied as reusable adsorbents for water purification. The material showed around 94% efficiency in capturing methylene blue particles from water, even after being used for three cycles, highlighting its potential for use in the filtration industry [6]. A cost-effective template made from electrospun polyacrylonitrile fibers was used to create a stable mat of BNNTs through atomic layer deposition (ALD) of BN at low temperatures. Using polymer-derived ceramics chemistry, this ALD process produces high-quality BNNTs with excellent properties, including superhydrophobicity, stability for a month in different pH conditions and air, and remarkable performance in water treatment [128].
- *Case study*

The investigation into boron nitride nanotubes (BNNTs) has revealed intriguing possibilities in enhancing mass sensing capabilities for biomolecule detection. The conventional perception of BNNTs as straight structures has been challenged by considering their wavy surfaces, significantly affecting their mass sensing abilities. The utilization of a nonlinear mathematical model, grounded in continuum mechanics, elucidates the nonlinear deformations induced by waviness, leading to oscillations of significant amplitude within the nanostructures [129].

Table 2. Shift in resonance frequency for different Waviness Factor (h/L) (Deshwal and Narwal 2023a)

Waviness Factor (h/L)	Resonance Frequency (BNNT having 20 nm length)	Resonance Frequency (BNNT having 60 nm length)
0	3.71E+05	1.24E+05
0.05	4.32E+05	2.54E+05
0.075	4.99E+05	3.55E+05
0.1	5.78E+05	4.60E+05

The resonance frequency analysis conducted on wavy single-walled BNNTs, using sophisticated computational simulations, underscores the potential of these structures in bio-mass sensing. The waviness factor plays a pivotal role in modulating sensitivity, selectivity, and resonance frequency shifts of BNNT-based biomolecule sensors, as presented in Table 2. Moreover, the study suggests that variations in waviness patterns, sizes, and amplitudes could substantially optimize BNNTs for superior biomolecule detection capabilities, as depicted in Figure 5. Understanding the effects of different geometrical parameters on sensor performance opens avenues for tailored design approaches and promising advancements in biomolecular sensing technologies.

The findings emphasize the necessity of considering realistic waviness in BNNTs for accurate and sensitive biomolecule sensing applications. Further research aimed at optimizing waviness structures and exploring diverse parameters will undoubtedly contribute to refining BNNT-based biomolecule sensors for enhanced sensitivity and selectivity in future biosensing technologies.

This study underscores the importance of embracing waviness in BNNTs, paving the way for the development of highly efficient and tailored biomolecule detection platforms [130].

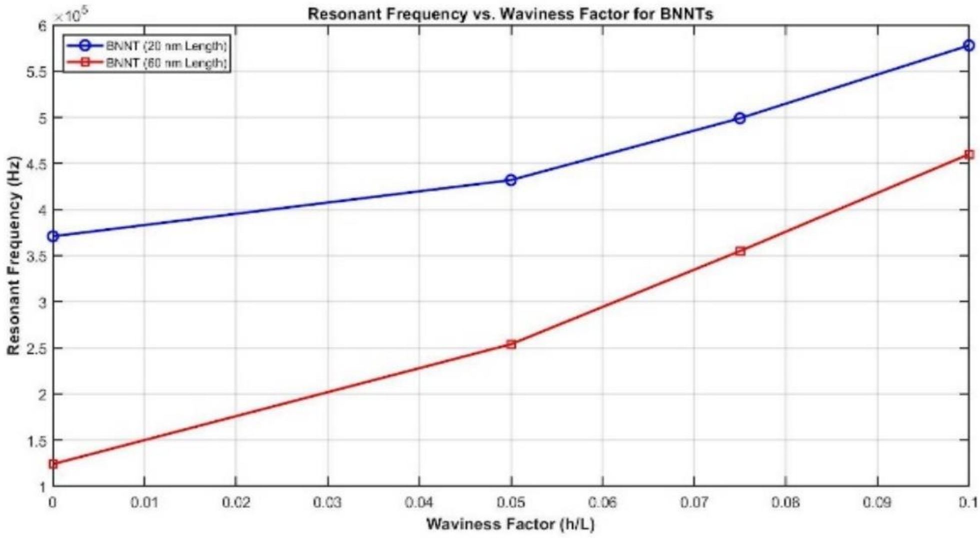

Figure 5. Comparison of the resonance frequency of the different waviness for the 20 nm and 60 nm BNNTs length

Future perspective

CNTs and BNNTs have demonstrated significant potential in various scientific and technological fields. CNTs, in particular, have been widely researched and are used in electronics, energy, sensors, and materials science, thanks to their exceptional mechanical, thermal, and electrical properties, which make them ideal for nanoscale devices and components.

In contrast, BNNTs are less studied but possess unique properties, including high thermal conductivity, exceptional mechanical strength, and strong resistance to oxidation. These characteristics make them promising candidates for use in aerospace, thermal management, and nanoelectronics applications.

Some of the potential applications of CNTs and BNNTs include high-performance composites, field emission devices, energy storage devices, nanosensors, drug delivery systems, and nanoelectronics, among others. The use of these nanotubes is expected to revolutionize various fields by offering enhanced performance, improved efficiency, and reduced costs.

The BNNTs and CNTs are found to be with great potential to be used in the biomedical field. Both of them are used as drug carriers to cure cancer. BNNTs have superior electrical properties which make them be used as sensors and in various applications in the field of robotics too. Both nanotubes are also used in tissue regeneration, gene therapy and dentistry but due to their varied applications, they can be analyzed for different geometric configurations to check their mechanical and physical stability. The nanotubes have various applications in biosensing, e.g., the use as a mechanical resonator to sense the biomass. For biomass sensing, the nanotubes should be mechanically, chemically and physically stable.

The successful implementation of commercial and industrial applications remains limited by various difficulties encountered when working with CNTs and BNNTs. High-quality nanotubes stay out of reach due to limited synthesis methods that cannot produce uniform-sized and structured nanotubes of defined chirality. The current production techniques, including CVD and arc discharge and laser ablation produce varying nanotubes that need complicated and expensive post-processing steps to reach pure specifications. How CNTs and BNNTs should be characterized is problematic because the standard techniques including TEM, Raman spectroscopy, and XRD fulfill their objectives yet they take too long to operate effectively in industrial settings. Accurate examination of nanotube structural features and purity standards and electronic functionality remains challenging because it hinders designers from developing applications-specific nanotube solutions.

The ability to scale up CNT production with BNNT production remains problematic because of high energy requirements, catalyst degradation and unstable growth environments. Researchers persistently address the scaling challenge which involves maintaining high-quality production output with excellent yield at cost-effective rates. Mass-production does not exist commercially at reasonable costs which prevents extensive industrial use especially in electronics, aerospace and biomedicine applications. Their use in composites and semiconductors combined with energy storage applications becomes challenging because of problems related to incorporation, as well as issues regarding poor dispersion and weak interfacial bonding and tendency toward agglomeration. Several techniques exist to improve compatibility yet these techniques change intrinsic nanotube properties thus creating efficiency limitations.

REFERENCES

1. Lahiri, D.; Rouzaud, F.; Richard, T.; Keshri, A. K.; Bakshi, S. R.; Kos, L.; Agarwal, A. Boron Nitride Nanotube Reinforced Polylactide–Polycaprolactone Copolymer Composite: Mechanical Properties and Cytocompatibility with Osteoblasts and Macrophages in Vitro. *Acta Biomater.* (2010), **6** (9), 3524–3533. https://doi.org/10.1016/j.actbio.2010.02.044.
2. Wildgoose, G. G.; Banks, C. E.; Compton, R. G. Metal Nanoparticles and Related Materials Supported on Carbon Nanotubes: Methods and Applications. *Small* (2006), **2** (2), 182–193. https://doi.org/10.1002/smll.200500324.
3. Bagherifard, S.; Hickey, D. J.; de Luca, A. C.; Malheiro, V. N.; Markaki, A. E.; Guagliano, M.; Webster, T. J. The Influence of Nanostructured Features on Bacterial Adhesion and Bone Cell Functions on Severely Shot Peened 316L Stainless Steel. *Biomaterials* (2015), **73**, 185–197. https://doi.org/10.1016/j.biomaterials.2015.09.019.
4. Zhi, C.; Bando, Y.; Tang, C.; Golberg, D. Boron Nitride Nanotubes. *Mater. Sci. Eng. R Reports* (2010), **70** (3–6), 92–111. https://doi.org/10.1016/j.mser.2010.06.004.
5. Su, D. S.; Perathoner, S.; Centi, G. Nanocarbons for the Development of Advanced Catalysts. *Chem. Rev.* (2013), **113** (8), 5782–5816. https://doi.org/10.1021/cr300367d.
6. Cho, H.; Kim, J. H.; Hwang, J. H.; Kim, C. S.; Jang, S. G.; Park, C.; Lee, H.; Kim, M. J. Single- and Double-Walled Boron Nitride Nanotubes: Controlled Synthesis and Application for Water Purification. *Sci. Rep.* (2020), **10** (1), 7416. https://doi.org/10.1038/s41598-020-64096-z.
7. Antonio, J.; Acapulco, I. Synthesis of Low Dimensional Boron Nitride Nanomaterials for Thermal Management Applications. (2020), No. January.
8. Tanur, A. E. Structure and Properties of Nanomaterials : From Inorganic Boron Nitride Nanotubes to the Calcareous Biomineralized Tubes of H . Dianthus. (2012).
9. Kumar Jagadeesan, A.; Thangavelu, K.; Dhananjeyan, V. Carbon Nanotubes: Synthesis, Properties and Applications. In *21st Century Surface Science - a Handbook*; IntechOpen, (2020). https://doi.org/10.5772/intechopen.92995.
10. Kim, K. S.; Couillard, M.; Shin, H.; Plunkett, M.; Ruth, D.; Kingston, C. T.; Simard, B. Role of Hydrogen in High-Yield Growth of Boron Nitride Nanotubes at Atmospheric Pressure by Induction Thermal Plasma. *ACS Nano* (2018), **12** (1), 884–893. https://doi.org/10.1021/acsnano.7b08708.
11. Liermann, H.-P.; Konôpková, Z.; Morgenroth, W.; Glazyrin, K.; Bednarčik, J.; McBride, E. E.; Petitgirard, S.; Delitz, J. T.; Wendt, M.; Bican, Y.; Ehnes, A.; Schwark, I.; Rothkirch, A.; Tischer, M.; Heuer, J.; Schulte-Schrepping, H.; Kracht, T.; Franz, H. The Extreme Conditions Beamline P02.2 and the Extreme Conditions Science Infrastructure at PETRA III. *J. Synchrotron Radiat.* (2015), **22** (4), 908–924. https://doi.org/10.1107/S1600577515005937.
12. Remund, J.; Wald, L.; Lefevre, M.; Ranchin, T.; Page, J.; Remund, J.; Wald, L.; Lefevre, M.; Ranchin, T.; Page, J.; Linke, W. Worldwide Linke Turbidity Information To Cite This Version : *Proc. ISES Sol. World Congr.* (2003).
13. Prabha S. Kundur and Om P. Malik. *Power System Stability and Control*, 2nd ed.; McGraw Hill Education: New York, (2022).
14. Sudagar, J.; Lian, J.; Sha, W. Electroless Nickel, Alloy, Composite and Nano Coatings – A Critical Review. *J. Alloys Compd.* (2013), **571**, 183–204. https://doi.org/10.1016/j.jallcom.2013.03.107.
15. Journet, C.; Bernier, P. Production of Carbon Nanotubes. *Appl. Phys. A Mater. Sci. Process.* (1998), **67** (1), 1–9. https://doi.org/10.1007/s003390050731.
16. Guzman de Villoria, R.; Hallander, P.; Ydrefors, L.; Nordin, P.; Wardle, B. L. In-Plane Strength Enhancement of Laminated Composites via Aligned Carbon Nanotube Interlaminar Reinforcement. *Compos. Sci. Technol.* (2016), **133**, 33–39. https://doi.org/10.1016/j.compscitech.2016.07.006.
17. Liu, W.; Song, M.; Kong, B.; Cui, Y. Flexible and Stretchable Energy Storage: Recent Advances and Future Perspectives. *Adv. Mater.* (2017), **29** (1). https://doi.org/10.1002/adma.201603436.
18. Khalafallah, D.; Miao, J.; Zhi, M.; Hong, Z. Confining Self-Standing CoSe2 Nanostructures and Fe3C Wrapped N-Doped Carbon Frameworks with Enhanced Energy Storage Performances. *Appl. Surf. Sci.* (2021), **564**, 150449. https://doi.org/10.1016/j.apsusc.2021.150449.
19. Raphey, V. R.; Henna, T. K.; Nivitha, K. P.; Mufeedha, P.; Sabu, C.; Pramod, K. Advanced Biomedical Applications of Carbon Nanotube. *Mater. Sci. Eng. C* (2019), **100**, 616–630. https://doi.org/10.1016/j.msec.2019.03.043.
20. Zhao, H.; Liu, M.; Zhang, Y.; Yin, J.; Pei, R. Nanocomposite Hydrogels for Tissue Engineering Applications. *Nanoscale* (2020), **12** (28), 14976–14995. https://doi.org/10.1039/D0NR03785K.
21. Maduraiveeran, G.; Sasidharan, M.; Ganesan, V. Electrochemical Sensor and Biosensor Platforms Based on Advanced Nanomaterials for Biological and Biomedical Applications. *Biosens. Bioelectron.* (2018), **103**, 113–129. https://doi.org/10.1016/j.bios.2017.12.031.
22. Quiles-Díaz, S.; Martínez-Rubí, Y.; Guan, J.; Kim, K. S.; Couillard, M.; Salavagione, H. J.; Gómez-

Fatou, M. A.; Simard, B. Enhanced Thermal Conductivity in Polymer Nanocomposites via Covalent Functionalization of Boron Nitride Nanotubes with Short Polyethylene Chains for Heat-Transfer Applications. *ACS Appl. Nano Mater.* (2019), **2** (1), 440–451. https://doi.org/10.1021/acsanm.8b01992.

23. Gómez-Villarejo, R.; Estellé, P.; Navas, J. Boron Nitride Nanotubes-Based Nanofluids with Enhanced Thermal Properties for Use as Heat Transfer Fluids in Solar Thermal Applications. *Sol. Energy Mater. Sol. Cells* (2020), **205**, 110266. https://doi.org/10.1016/j.solmat.2019.110266.
24. Xu, T.; Zhang, K.; Cai, Q.; Wang, N.; Wu, L.; He, Q.; Wang, H.; Zhang, Y.; Xie, Y.; Yao, Y.; Chen, Y. Advances in Synthesis and Applications of Boron Nitride Nanotubes: A Review. *Chem. Eng. J.* (2022), **431**, 134118. https://doi.org/10.1016/j.cej.2021.134118.
25. Sargazi-Avval, H.; Yoosefian, M.; Ghaffari-Moghaddam, M.; Khajeh, M.; Bohlooli, M. Potential Applications of Armchair, Zigzag, and Chiral Boron Nitride Nanotubes as a Drug Delivery System: Letrozole Anticancer Drug Encapsulation. *Appl. Phys. A* (2021), **127** (4), 257. https://doi.org/10.1007/s00339-021-04402-2.
26. Johnson, A. P.; Sabu, C.; Swamy, N. K.; Anto, A.; Gangadharappa, H. V.; Pramod, K. Graphene Nanoribbon: An Emerging and Efficient Flat Molecular Platform for Advanced Biosensing. *Biosens. Bioelectron.* (2021), **184**, 113245. https://doi.org/10.1016/j.bios.2021.113245.
27. Vedaei, S. S.; Nadimi, E. Gas Sensing Properties of CNT-BNNT-CNT Nanostructures: A First Principles Study. *Appl. Surf. Sci.* (2019), **470**, 933–942. https://doi.org/10.1016/j.apsusc.2018.11.220.
28. Jakubinek, M. B.; Ashrafi, B.; Martinez-Rubi, Y.; Guan, J.; Rahmat, M.; Kim, K. S.; Dénommée, S.; Kingston, C. T.; Simard, B. Boron Nitride Nanotube Composites and Applications. In *Nanotube Superfiber Materials*; Elsevier, (2019); pp 91–111. https://doi.org/10.1016/B978-0-12-812667-7.00005-7.
29. Liu, C.; Fang, Q.; Wang, D.; Yan, C.; Liu, F.; Wang, N.; Guo, Z.; Jiang, Q. Http://Www.Espublisher.Com/Journals/Articledetails/115/. *ES Mater. Manuf.* (2019). https://doi.org/10.30919/esmm5f199.
30. Park, S. H.; Bandaru, P. R. Improved Mechanical Properties of Carbon Nanotube/Polymer Composites through the Use of Carboxyl-Epoxide Functional Group Linkages. *Polymer (Guildf).* (2010), **51** (22), 5071–5077. https://doi.org/10.1016/j.polymer.2010.08.063.
31. Smith, K. K.; Redeker, N. D.; Rios, J. C.; Mecklenburg, M. H.; Marcischak, J. C.; Guenthner, A. J.; Ghiassi, K. B. Surface Modification and Functionalization of Boron Nitride Nanotubes via Condensation with Saturated and Unsaturated Alcohols for High Performance Polymer Composites. *ACS Appl. Nano Mater.* (2019), **2** (7), 4053–4060. https://doi.org/10.1021/acsanm.8b02192.
32. Dhanaselvam, P. S.; Karthikeyan, B.; Vanitha, P. Principle and Application of C-Based Nanomaterials: Graphite, Graphene, and Carbon Nanotube (CNT). In *Handbook of Emerging Materials for Semiconductor Industry*; Springer Nature Singapore: Singapore, (2024); pp 49–64. https://doi.org/10.1007/978-981-99-6649-3_4.
33. Shariatinia, Z. Applications of Carbon Nanotubes. In *Handbook of Carbon-Based Nanomaterials*; Elsevier, (2021); pp 321–364. https://doi.org/10.1016/B978-0-12-821996-6.00016-6.
34. Loiseau, A.; Willaime, F.; Demoncy, N.; Schramchenko, N.; Hug, G.; Colliex, C.; Pascard, H. Boron Nitride Nanotubes. *Carbon N. Y.* (1998), **36** (5–6), 743–752. https://doi.org/10.1016/S0008-6223(98)00040-2.
35. Uddin, J.; Dubey, R.; Balasubramaniam, V. S.; Kabel, J.; Khare, V.; Salimi, Z.; Sharma, S.; Zhang, D.; Yap, Y. K. Progress in Electronic, Energy, Biomedical and Environmental Applications of Boron Nitride and MoS2 Nanostructures. *Micromachines* (2024), **15** (3), 349. https://doi.org/10.3390/mi15030349.
36. Rao, C. N. R.; Govindaraj, A.; Panchakarla, L. S. Properties and Applications of Carbon Nanotubes. *Nanotub. Nanowires* (2021), 164–239. https://doi.org/10.1039/9781788019637-00164.
37. Srinivasan, V.; Kunjiappan, S.; Palanisamy, P. A Brief Review of Carbon Nanotube Reinforced Metal Matrix Composites for Aerospace and Defense Applications. *Int. Nano Lett.* (2021), **11** (4), 321–345. https://doi.org/10.1007/s40089-021-00328-y.
38. *B-C-N Nanotubes and Related Nanostructures*; Yoke Khin Yap, Ed.; Springer New York, (2009).
39. Huang, Y.; Lin, J.; Zou, J.; Wang, M.-S.; Faerstein, K.; Tang, C.; Bando, Y.; Golberg, D. Thin Boron Nitride Nanotubes with Exceptionally High Strength and Toughness. *Nanoscale* (2013), **5** (11), 4840. https://doi.org/10.1039/c3nr00651d.
40. Sun, X.; Qin, Z.; Ye, L.; Zhang, H.; Yu, Q.; Wu, X.; Li, J.; Yao, F. Carbon Nanotubes Reinforced Hydrogel as Flexible Strain Sensor with High Stretchability and Mechanically Toughness. *Chem. Eng. J.* (2020), **382**, 122832. https://doi.org/10.1016/j.cej.2019.122832.
41. Choyal, V.; Kundalwal, S. I. Transversely Isotropic Elastic Properties of Multi-Walled Boron Nitride Nanotubes under a Thermal Environment. *Nanotechnology* (2020), **31** (39), 395707. https://doi.org/10.1088/1361-6528/ab9865.
42. Ryu, K.-H.; Kang, M.; You, N.-H.; Jang, S. G.; Ahn, S.; Kim, D.-Y. Pure Boron Nitride Nanotube Thread-Based Woven Textile for Thermal Neutron Shielding with Extreme Thermal Stability. *Adv. Compos. Hybrid Mater.* (2024), **7** (5), 159. https://doi.org/10.1007/s42114-024-00986-4.
43. Mikhalchan, A.; Vilatela, J. J. A Perspective on High-Performance CNT Fibres for Structural

Composites. *Carbon N. Y.* (2019), **150**, 191–215. https://doi.org/10.1016/j.carbon.2019.04.113.

44. Sabet, M. Innovations in Carbon Nanotube Polymer Composites: Electrical, Thermal, and Mechanical Advancements for Aerospace and Automotive Applications. *Synth. Met.* (2025), **310,** 117794. https://doi.org/10.1016/j.synthmet.2024.117794.
45. Kim, J.; Lee, S.; Uhm, Y. R.; Jun, J.; Rhee, C. K.; Kim, G. M. Synthesis and Growth of Boron Nitride Nanotubes by a Ball Milling–Annealing Process. *Acta Mater.* (2011), **59** (7), 2807–2813. https://doi.org/10.1016/j.actamat.2011.01.019.
46. Wu, S.; Sikdar, P.; Bhat, G. S. Recent Progress in Developing Ballistic and Anti-Impact Materials: Nanotechnology and Main Approaches. *Def. Technol.* (2023), *21*, 33–61. https://doi.org/10.1016/j.dt.2022.06.007.
47. Yang, D. J.; Zhang, Q.; Chen, G.; Yoon, S. F.; Ahn, J.; Wang, S. G.; Zhou, Q.; Wang, Q.; Li, J. Q. Thermal Conductivity of Multiwalled Carbon Nanotubes. *Phys. Rev. B* (2002), **66** (16), 165440. https://doi.org/10.1103/PhysRevB.66.165440.
48. Lee, J.; Kyeong, D.; Kim, J.; Choi, W. Layer-by-Layer Self-Assembled Functional Coatings of Carbon Nanotube-Polyethylenimine for Enhanced Heat Transfer of Heat Sinks. *Int. J. Heat Mass Transf.* (2022), **184**, 122344. https://doi.org/10.1016/j.ijheatmasstransfer.2021.122344.
49. He, T.; Li, T.; Huang, Z.; Tang, Z.; Guan, X. Mechanical and Thermal Properties of the Coaxial Carbon Nanotube@boron Nitride Nanotube Composite. *Phys. E Low-dimensional Syst. Nanostructures* (2019), **107**, 182–186. https://doi.org/10.1016/j.physe.2018.11.037.
50. Sharma, V.; Kagdada, H. L.; Jha, P. K.; Śpiewak, P.; Kurzydłowski, K. J. Thermal Transport Properties of Boron Nitride Based Materials: A Review. *Renew. Sustain. Energy Rev.* (2020), **120**, 109622. https://doi.org/10.1016/j.rser.2019.109622.
51. Jiang, H.; Liu, B.; Huang, Y.; Hwang, K. C. Thermal Expansion of Single Wall Carbon Nanotubes. *J. Eng. Mater. Technol.* (2004), **126** (3), 265–270. https://doi.org/10.1115/1.1752925.
52. Wang, Y.; Ding, X.; Wang, H.; Wang, Q.; Zhang, M.; Yang, B. Highly Efficient and Durable Aramid Nanofibers/Carbon Nanotubes-Coated Electrothermal Paper. *ACS Appl. Polym. Mater.* (2024), **6** (13), 7612–7620. https://doi.org/10.1021/acsapm.4c01064.
53. Wang, D.; Chen, R.; Anjum, N.; Ke, C. Thermal Expansion of Boron Nitride Nanotubes and Additively Manufactured Ceramic Nanocomposites. *Nanotechnology* (2025), **36** (6), 065703. https://doi.org/10.1088/1361-6528/ad933a.
54. Liu, H.; Yan, M.; Jing, W.; Zeng, G.; XIE, G.; Pu, X.; Fu, Y.; Peng, X.; Wang, H.; Lai, C.; Huang, D.; Tang, L. Hexagonal Boron Nitride for Extreme Environment Application. *Diam. Relat. Mater.* (2024), **148**, 111410. https://doi.org/10.1016/j.diamond.2024.111410.
55. Gupta, B. K.; Shashank, T.; Vijayakumar, R. P.; Dharmadikari, K.; Ismail, S. M.; DSouza, G. C.; Ratna, D. Influence of Unzipped Multiwalled Carbon Nanotube Oxides-Epoxy Paint on the Corrosion Rate of Mild Steel in Marine Environment. *Chem. Eng. Technol.* (2024), **47** (7), 1031–1043. https://doi.org/10.1002/ceat.202400026.
56. Luo, F.; Wang, S.; Shi, W.; Zhao, Y.; Huang, J. Wear Behavior and Corrosion Resistance of Laser-Clad Ni60-1 % Carbon Nanotubes Coating. *Surf. Coatings Technol.* (2024), **482**, 130686. https://doi.org/10.1016/j.surfcoat.2024.130686.
57. Mehdi, S. M. Z.; Maqsood, M. F.; Dahshan, A.; Ahmad, S.; Ur Rehman, M.; Lee, N.; Rehman, M. A.; Khan, M. F. Emerging Boron Nitride Nanosheets: A Review on Synthesis, Corrosion Resistance Coatings, and Their Impacts on the Environment and Health. *Rev. Adv. Mater. Sci.* (2024), **63** (1). https://doi.org/10.1515/rams-2024-0075.
58. Wang, M.; Xiao, G.; Wang, F.; Chen, C.; Cao, J.; Gou, J.; Ma, X.; Yan, H. Research on BN-Based Waterborne Anticorrosive Coatings Integrating Long-Lasting Anticorrosive, High Cross-Linking and Self-Healing Properties. *Chem. Eng. J.* (2024), **497**, 154555. https://doi.org/10.1016/j.cej.2024.154555.
59. Lu, W.; Dai, L. Carbon Nanotube Supercapacitors. In *Carbon Nanotubes*; InTech, (2010). https://doi.org/10.5772/39444.
60. Aminul Islam, M.; Hasan, M.; Rahman, M.; Hosne Mobarak, M.; Akter Mimona, M.; Hossain, N. Advances and Significances of Carbon Nanotube Applications: A Comprehensive Review. *Eur. Polym. J.* (2024), **220**, 113443. https://doi.org/10.1016/j.eurpolymj.2024.113443.
61. Panigrahi, P.; Kumar, A.; Bae, H.; Lee, H.; Ahuja, R.; Hussain, T. Capacity Enhancement of Polylithiated Functionalized Boron Nitride Nanotubes: An Efficient Hydrogen Storage Medium. *Phys. Chem. Chem. Phys.* (2020), **22** (27), 15675–15682. https://doi.org/10.1039/D0CP01237H.
62. Jung, J.-H.; Yanar, N.; Yang, M.-J.; Kandula, S.; Yadav, D.; Kim, T. Y.-S.; Shim, J.-H.; Doo, S.; Kim, J. Improved Electrochemical Performance of Li-Ion Pouch Cells with Boron Nitride Nanotube-Coated Separators. *J. Power Sources* (2025), **628**, 235938. https://doi.org/10.1016/j.jpowsour.2024.235938.
63. Aliakbarinodehi, N.; Taurino, I.; Pravin, J.; Tagliaferro, A.; Piccinini, G.; De Micheli, G.; Carrara, S. Electrochemical Nanostructured Biosensors: Carbon Nanotubes versus Conductive and Semi-Conductive Nanoparticles. *Chem. Pap.* (2015), **69** (1). https://doi.org/10.1515/chempap-2015-0004.
64. Hua, Q.; Shen, G. Low-Dimensional Nanostructures for Monolithic 3D-Integrated Flexible and Stretchable Electronics. *Chem. Soc. Rev.* (2024), **53** (3), 1316–1353. https://doi.org/10.1039/D3CS00918A.

65. Yu, J.; Yu, D.; Chen, Y.; Chen, H.; Lin, M.-Y.; Cheng, B.-M.; Li, J.; Duan, W. Narrowed Bandgaps and Stronger Excitonic Effects from Small Boron Nitride Nanotubes. *Chem. Phys. Lett.* (2009), **476** (4–6), 240–243. https://doi.org/10.1016/j.cplett.2009.06.012.
66. Yang, N.; Kenion, T.; Xu, S.; Xu, C. Dielectric Property Characterization at High Temperature (RT to 1000 °C) of BN-Based Electromagnetic Transparent Materials for Hypersonic Applications. *Ceram. Int.* (2023), **49** (7), 11047–11059. https://doi.org/10.1016/j.ceramint.2022.11.300.
67. Shiraki, T.; Miyauchi, Y.; Matsuda, K.; Nakashima, N. Carbon Nanotube Photoluminescence Modulation by Local Chemical and Supramolecular Chemical Functionalization. *Acc. Chem. Res.* (2020), **53** (9), 1846–1859. https://doi.org/10.1021/acs.accounts.0c00294.
68. Zha, J.; Luo, M.; Ye, M.; Ahmed, T.; Yu, X.; Lien, D.; He, Q.; Lei, D.; Ho, J. C.; Bullock, J.; Crozier, K. B.; Tan, C. Infrared Photodetectors Based on 2D Materials and Nanophotonics. *Adv. Funct. Mater.* (2022), **32** (15). https://doi.org/10.1002/adfm.202111970.
69. Yanar, N.; Yang, E.; Park, H.; Son, M.; Choi, H. Boron Nitride Nanotube (BNNT) Membranes for Energy and Environmental Applications. *Membranes (Basel).* (2020), **10** (12), 430. https://doi.org/10.3390/membranes10120430.
70. Jin, X.; Fan, X.; Lu, C.; Wang, T. Advances in Oxidation and Ablation Resistance of High and Ultra-High Temperature Ceramics Modified or Coated Carbon/Carbon Composites. *J. Eur. Ceram. Soc.* (2018), **38** (1), 1–28. https://doi.org/10.1016/j.jeurceramsoc.2017.08.013.
71. Ahmad, M.; Silva, S. R. P. Low Temperature Growth of Carbon Nanotubes – A Review. *Carbon N. Y.* (2020), **158**, 24–44. https://doi.org/10.1016/j.carbon.2019.11.061.
72. Chen, Y.; Zou, J.; Campbell, S. J.; Le Caer, G. Boron Nitride Nanotubes: Pronounced Resistance to Oxidation. *Appl. Phys. Lett.* (2004), **84** (13), 2430–2432. https://doi.org/10.1063/1.1667278.
73. Davis, C. R.; Nuwayhid, R. B.; Campbell, C. A.; Mills, S. C.; Backman, L.; Estevez, J. E.; Schaeffer, M. R. Improved Oxidation Resistance of Boron Nitride Nanotubes with Protective Alumina Nano-Coatings. *Ceram. Int.* (2024), **50** (22), 48620–48627. https://doi.org/10.1016/j.ceramint.2024.09.211.
74. Barnard, A. S. Modelling of the Reactivity and Stability of Carbon Nanotubes under Environmentally Relevant Conditions. *Phys. Chem. Chem. Phys.* (2012), **14** (29), 10080. https://doi.org/10.1039/c2cp40862g.
75. Meskher, H.; Ragdi, T.; Thakur, A. K.; Ha, S.; Khelfaoui, I.; Sathyamurthy, R.; Sharshir, S. W.; Pandey, A. K.; Saidur, R.; Singh, P.; Sharifian jazi, F.; Lynch, I. A Review on CNTs-Based Electrochemical Sensors and Biosensors: Unique Properties and Potential Applications. *Crit. Rev. Anal. Chem.* (2024), **54** (7), 2398–2421. https://doi.org/10.1080/10408347.2023.2171277.
76. Seo, J.-W.; Pophali, A.; An, S.; Liang, C. S. L.; Li, S.; Liu, H.; Kim, J.; An, K.; Kim, J.; Kim, T. Fundamental Structural Study of Hexagonal Boron Nitride (h-BN) and Boron Nitride Nanotube (BNNT) at Low and High Temperatures. *J. Mol. Struct.* (2025), **1319**, 139545. https://doi.org/10.1016/j.molstruc.2024.139545.
77. Tian, Y.; Zhang, X.; Su, Z.; Liu, J.; Yang, H.; Khalid, M.; Xiao, H.; Hu, P. Ultra-High-Efficiency Corrosion Protection of Metallic Surface Based on Thin and Dense Hexagonal Boron Nitride Coating Films. *Langmuir* (2024), **40** (13), 7139–7146. https://doi.org/10.1021/acs.langmuir.4c00272.
78. Li, X.; Wang, L.; Fan, Y.; Feng, Q.; Cui, F. Biocompatibility and Toxicity of Nanoparticles and Nanotubes. *J. Nanomater.* (2012), **2012** (1). https://doi.org/10.1155/2012/548389.
79. M, M.; Sagadevan, S.; E, B.; Fatimah, I.; Lett, J. A.; Moharana, S.; Garg, S.; Al-Anber, M. A. Enhancing Biocompatibility and Functionality: Carbon Nanotube-Polymer Nanocomposites for Improved Biomedical Applications. *J. Drug Deliv. Sci. Technol.* (2024), **99**, 105958. https://doi.org/10.1016/j.jddst.2024.105958.
80. Ciofani, G.; Danti, S.; Genchi, G. G.; Mazzolai, B.; Mattoli, V. Boron Nitride Nanotubes: Biocompatibility and Potential Spill-Over in Nanomedicine. *Small* (2013), **9** (9–10), 1672–1685. https://doi.org/10.1002/smll.201201315.
81. Çobandede, Z.; Çulha, M. Ultrasound Stimulated Piezoelectric Barium Titanate and Boron Nitride Nanotubes in Nonconductive Poly-ε-Caprolactone Nanofibrous Scaffold for Bone Tissue Engineering. *Nanotechnology* (2024), **35** (13), 135101. https://doi.org/10.1088/1361-6528/ad1446.
82. Soni, S. K.; Thomas, B.; Kar, V. R. A Comprehensive Review on CNTs and CNT-Reinforced Composites: Syntheses, Characteristics and Applications. *Mater. Today Commun.* (2020), **25**, 101546. https://doi.org/10.1016/j.mtcomm.2020.101546.
83. Wang, J.; Zhang, Y.; Liu, G.; Zhang, T.; Zhang, C.; Zhang, Y.; Feng, Y.; Chi, Q. Improvements in the Magnesium Ion Transport Properties of Graphene/CNT-Wrapped TiO 2 -B Nanoflowers by Nickel Doping. *Small* (2024), **20** (6). https://doi.org/10.1002/smll.202304969.
84. Sasidharan, S.; Anand, A. Epoxy-Based Hybrid Structural Composites with Nanofillers: A Review. *Ind. Eng. Chem. Res.* (2020), **59** (28), 12617–12631. https://doi.org/10.1021/acs.iecr.0c01711.
85. Yao, X.; Zhang, Y.; Jin, W.; Hu, Y.; Cui, Y. Carbon Nanotube Field-Effect Transistor-Based Chemical and Biological Sensors. *Sensors* (2021), **21** (3), 995. https://doi.org/10.3390/s21030995.
86. Martel, R.; Derycke, V.; Appenzeller, J.; Wind, S.; Avouris, P. Carbon Nanotube Field-Effect Transistors and Logic Circuits. In *Proceedings 2002 Design Automation Conference (IEEE Cat. No.02CH37324)*; IEEE, (2002); pp 94–98.

https://doi.org/10.1109/DAC.2002.1012601.

87. Bishop, M. D.; Hills, G.; Srimani, T.; Lau, C.; Murphy, D.; Fuller, S.; Humes, J.; Ratkovich, A.; Nelson, M.; Shulaker, M. M. Fabrication of Carbon Nanotube Field-Effect Transistors in Commercial Silicon Manufacturing Facilities. *Nat. Electron.* (2020), **3** (8), 492–501. https://doi.org/10.1038/s41928-020-0419-7.
88. Macedo-Zamudio, H.; Pacheco-Sanchez, A.; Ramirez-Garcia, E.; Rodriguez-Mendez, L. M.; Valdez-Perez, D.; Schroter, M. Carbon Nanotube Schottky Diodes Performance Study: Static and High-Frequency Characteristics. In *2018 Nanotechnology for Instrumentation and Measurement (NANOfIM)*; IEEE, (2018); pp 1–6. https://doi.org/10.1109/NANOFIM.2018.8688611.
89. Xue, C.; Wu, W.; Yang, Y.; Zhou, J.; Ding, L.; Wang, S. Carbon Nanotube Diodes Operating at Frequencies of Over 50 GHz. *Small* (2023), 2207628. https://doi.org/10.1002/smll.202207628.
90. Xiang, L.; Zhang, H.; Hu, Y.; Peng, L.-M. Carbon Nanotube-Based Flexible Electronics. *J. Mater. Chem. C* (2018), **6** (29), 7714–7727. https://doi.org/10.1039/C8TC02280A.
91. Zhao, T.-Y.; Zhang, D.-D.; Qu, T.-Y.; Fang, L.-L.; Zhu, Q.-B.; Sun, Y.; Cai, T.-H.; Chen, M.-L.; Wang, B.-W.; Du, J.-H.; Ren, W.-C.; Yan, X.; Li, Q.-W.; Qiu, S.; Sun, D.-M. Flexible 64 × 64 Pixel AMOLED Displays Driven by Uniform Carbon Nanotube Thin-Film Transistors. *ACS Appl. Mater. Interfaces* (2019), **11** (12), 11699–11705. https://doi.org/10.1021/acsami.8b17909.
92. Amin, R.; Ramesh Kumar, P.; Belharouak, I. Carbon Nanotubes: Applications to Energy Storage Devices. In *Carbon Nanotubes - Redefining the World of Electronics*; IntechOpen, (2021). https://doi.org/10.5772/intechopen.94155.
93. Iqbal, S.; Khatoon, H.; Hussain Pandit, A.; Ahmad, S. Recent Development of Carbon Based Materials for Energy Storage Devices. *Mater. Sci. Energy Technol.* (2019), **2** (3), 417–428. https://doi.org/10.1016/j.mset.2019.04.006.
94. Fu, J.; Liu, H.; Liao, L.; Fan, P.; Wang, Z.; Wu, Y.; Zhang, Z.; Hai, Y.; Lv, G.; Mei, L.; Hao, H.; Xing, J.; Dong, J. Ultrathin Si/CNTs Paper-Like Composite for Flexible Li-Ion Battery Anode With High Volumetric Capacity. *Front. Chem.* (2018), **6**. https://doi.org/10.3389/fchem.2018.00624.
95. Zhu, S.; Sheng, J.; Chen, Y.; Ni, J.; Li, Y. Carbon Nanotubes for Flexible Batteries: Recent Progress and Future Perspective. *Natl. Sci. Rev.* (2021), **8** (5). https://doi.org/10.1093/nsr/nwaa261.
96. Pan, H.; Li, J.; Feng, Y. P. Carbon Nanotubes for Supercapacitor. *Nanoscale Res. Lett.* (2010), **5** (3), 654–668. https://doi.org/10.1007/s11671-009-9508-2.
97. Lu, Z.; Raad, R.; Safaei, F.; Xi, J.; Liu, Z.; Foroughi, J. Carbon Nanotube Based Fiber Supercapacitor as Wearable Energy Storage. *Front. Mater.* (2019), **6**. https://doi.org/10.3389/fmats.2019.00138.
98. Aval, L. F.; Ghoranneviss, M.; Pour, G. B. High-Performance Supercapacitors Based on the Carbon Nanotubes, Graphene and Graphite Nanoparticles Electrodes. *Heliyon* (2018), **4** (11), e00862. https://doi.org/10.1016/j.heliyon.2018.e00862.
99. Becher, M.; Haluska, M.; Hirscher, M.; Quintel, A.; Skakalova, V.; Dettlaff-Weglikovska, U.; Chen, X.; Hulman, M.; Choi, Y.; Roth, S.; Meregalli, V.; Parrinello, M.; Ströbel, R.; Jörissen, L.; Kappes, M. M.; Fink, J.; Züttel, A.; Stepanek, I.; Bernier, P. Hydrogen Storage in Carbon Nanotubes. *Comptes Rendus Phys.* (2003), **4** (9), 1055–1062. https://doi.org/10.1016/S1631-0705(03)00107-5.
100. Anikina, E.; Banerjee, A.; Beskachko, V.; Ahuja, R. Li-Functionalized Carbon Nanotubes for Hydrogen Storage: Importance of Size Effects. *ACS Appl. Nano Mater.* (2019), **2** (5), 3021–3030. https://doi.org/10.1021/acsanm.9b00406.
101. Mosquera-Vargas, E.; Tamayo, R.; Morel, M.; Roble, M.; Díaz-Droguett, D. E. Hydrogen Storage in Purified Multi-Walled Carbon Nanotubes: Gas Hydrogenation Cycles Effect on the Adsorption Kinetics and Their Performance. *Heliyon* (2021), **7** (12), e08494. https://doi.org/10.1016/j.heliyon.2021.e08494.
102. Deshmukh, M. A.; Park, S.-J.; Hedau, B. S.; Ha, T.-J. Recent Progress in Solar Cells Based on Carbon Nanomaterials. *Sol. Energy* (2021), **220**, 953–990. https://doi.org/10.1016/j.solener.2021.04.001.
103. Muchuweni, E.; Mombeshora, E. T.; Martincigh, B. S.; Nyamori, V. O. Recent Applications of Carbon Nanotubes in Organic Solar Cells. *Front. Chem.* (2022), **9**. https://doi.org/10.3389/fchem.2021.733552.
104. He, H.; Pham-Huy, L. A.; Dramou, P.; Xiao, D.; Zuo, P.; Pham-Huy, C. Carbon Nanotubes: Applications in Pharmacy and Medicine. *Biomed Res. Int.* (2013), **2013**, 1–12. https://doi.org/10.1155/2013/578290.
105. Oves, M.; Rauf, M. A.; Ansari, M. O.; Warsi, M. K.; Hussain, A.; Ismail, I. I. M. Polysaccharide-Based Nanocomposites for Gene Delivery and Tissue Engineering. In *Polysaccharide-Based Nanocomposites for Gene Delivery and Tissue Engineering*; Elsevier, (2021); pp 103–129. https://doi.org/10.1016/B978-0-12-821230-1.00008-6.
106. Zare, E. N.; Makvandi, P.; Ashtari, B.; Rossi, F.; Motahari, A.; Perale, G. Progress in Conductive Polyaniline-Based Nanocomposites for Biomedical Applications: A Review. *J. Med. Chem.* (2020), **63** (1), 1–22. https://doi.org/10.1021/acs.jmedchem.9b00803.
107. Sanginario, A.; Miccoli, B.; Demarchi, D. Carbon Nanotubes as an Effective Opportunity for Cancer Diagnosis and Treatment. *Biosensors* (2017), **7** (4), 9. https://doi.org/10.3390/bios7010009.
108. Hua He, Deli Xiao, Lien Ai Pham-Huy, Pierre Dramou, C. P.-H. Carbon Nanotubes Used as Nanocarriers in Drug and Biomolecule Delivery. In *Drug Delivery Approaches and Nanosystems*; Apple

Academic Press, (2017); p 50.

109. Singh, A.; Hua Hsu, M.; Gupta, N.; Khanra, P.; Kumar, P.; Prakash Verma, V.; Kapoor, M. Derivatized Carbon Nanotubes for Gene Therapy in Mammalian and Plant Cells. *Chempluschem* (2020), **85** (3), 466–475. https://doi.org/10.1002/cplu.201900678.
110. Genchi, G. G.; Ciofani, G. Bioapplications of Boron Nitride Nanotubes. *Nanomedicine* (2015), **10** (22), 3315–3319. https://doi.org/10.2217/nnm.15.148.
111. Ferreira, T. H.; de Sousa, E. M. B. Applications and Perspectives of Boron Nitride Nanotubes in Cancer Therapy. In *Boron Nitride Nanotubes in Nanomedicine*; Elsevier, (2016); pp 95–109. https://doi.org/10.1016/B978-0-323-38945-7.00006-7.
112. Rajabi, A. H.; Jaffe, M.; Arinzeh, T. L. Piezoelectric Materials for Tissue Regeneration: A Review. *Acta Biomater.* (2015), **24**, 12–23. https://doi.org/10.1016/j.actbio.2015.07.010.
113. Kakarla, A. B.; Kong, I.; Kong, C.; Irving, H. Extrusion-Based Bioprinted Boron Nitride Nanotubes Reinforced Alginate Scaffolds: Mechanical, Printability and Cell Viability Evaluation. *Polymers (Basel).* (2022), **14** (3), 486. https://doi.org/10.3390/polym14030486.
114. Singh, N. B.; Guin, M.; Tomar, R. Nanostructured Ceramics. In *Ceramic Science and Engineering*; Elsevier, (2022); pp 545–573. https://doi.org/10.1016/B978-0-323-89956-7.00013-9.
115. Bohns, F. R.; Degrazia, F. W.; de Souza Balbinot, G.; Leitune, V. C. B.; Samuel, S. M. W.; García-Esparza, M. A.; Sauro, S.; Collares, F. M. Boron Nitride Nanotubes as Filler for Resin-Based Dental Sealants. *Sci. Rep.* (2019), **9** (1), 7710. https://doi.org/10.1038/s41598-019-44246-8.
116. Wang, Y.; Xia, S.; Xiao, G.; Di, J.; Wang, J. High-Loading Boron Nitride-Based Bio-Inspired Paper with Plastic-like Ductility and Metal-like Thermal Conductivity. *ACS Appl. Mater. Interfaces* (2020), **12** (11), 13156–13164. https://doi.org/10.1021/acsami.9b21753.
117. Kim, J. H.; Pham, T. V.; Hwang, J. H.; Kim, C. S.; Kim, M. J. Boron Nitride Nanotubes: Synthesis and Applications. *Nano Converg.* (2018), **5** (1), 17. https://doi.org/10.1186/s40580-018-0149-y.
118. Zhu, H.; Li, Y.; Fang, Z.; Xu, J.; Cao, F.; Wan, J.; Preston, C.; Yang, B.; Hu, L. Highly Thermally Conductive Papers with Percolative Layered Boron Nitride Nanosheets. *ACS Nano* (2014), **8** (4), 3606–3613. https://doi.org/10.1021/nn500134m.
119. Pan, D.; Su, F.; Liu, H.; Ma, Y.; Das, R.; Hu, Q.; Liu, C.; Guo, Z. The Properties and Preparation Methods of Different Boron Nitride Nanostructures and Applications of Related Nanocomposites. *Chem. Rec.* (2020), **20** (11), 1314–1337. https://doi.org/10.1002/tcr.202000079.
120. Zhao, L.; Wei, C.; Li, Z.; Wei, W.; Jia, L.; Huang, X.; Ning, W.; Wang, Z.; Ren, J. High-Temperature Dielectric Paper with High Thermal Conductivity and Mechanical Strength by Engineering the Aramid Nanofibers and Boron Nitride Nanotubes. *Mater. Des.* (2021), **210**, 110124. https://doi.org/10.1016/j.matdes.2021.110124.
121. Zhang, D.; Zhang, S.; Yapici, N.; Oakley, R.; Sharma, S.; Parashar, V.; Yap, Y. K. Emerging Applications of Boron Nitride Nanotubes in Energy Harvesting, Electronics, and Biomedicine. *ACS Omega* (2021), **6** (32), 20722–20728. https://doi.org/10.1021/acsomega.1c02586.
122. Rahman, M. M.; Mateti, S.; Cai, Q.; Sultana, I.; Fan, Y.; Wang, X.; Hou, C.; Chen, Y. High Temperature and High Rate Lithium-Ion Batteries with Boron Nitride Nanotubes Coated Polypropylene Separators. *Energy Storage Mater.* (2019), **19**, 352–359. https://doi.org/10.1016/j.ensm.2019.03.027.
123. Rabani, I.; Park, Y.-J.; Lee, J.-W.; Tahir, M. S.; Kumar, A.; Seo, Y.-S. Ultra-Thin Flexible Paper of BNNT–CNF/ZnO Ternary Nanostructure for Enhanced Solid-State Supercapacitor and Piezoelectric Response. *J. Mater. Chem. A* (2022), **10** (29), 15580–15594. https://doi.org/10.1039/D2TA03134E.
124. Liu, C.; Wan, L.; Li, Q.; Sun, X.; Natan, A.; Cao, D.; Luan, P.; Zhu, H. Ice-Templated Anisotropic Flame-Resistant Boron Nitride Aerogels Enhanced through Surface Modification and Cellulose Nanofibrils. *ACS Appl. Polym. Mater.* (2021), **3** (3), 1358–1367. https://doi.org/10.1021/acsapm.0c01219.
125. Jakubinek, M. B.; Kim, K. S.; Kim, M. J.; Martí, A. A.; Pasquali, M. Recent Advances and Perspective on Boron Nitride Nanotubes: From Synthesis to Applications. *J. Mater. Res.* (2022), **37** (24), 4403–4418. https://doi.org/10.1557/s43578-022-00841-6.
126. Gia Ninh, D.; Trong Long, N.; Van Vang, T.; Hoang Ha, N.; Thanh Nguyen, C.; Viet Dao, D. A New Study for Aeroplane Wing Shapes Made of Boron Nitride Nanotubes-Reinforced Aluminium, Part I: Review, Dynamical Analyses and Simulation. *Compos. Struct.* (2023), **303**, 116239. https://doi.org/10.1016/j.compstruct.2022.116239.
127. Turhan, E. A.; Pazarçeviren, A. E.; Evis, Z.; Tezcaner, A. Properties and Applications of Boron Nitride Nanotubes. *Nanotechnology* (2022), **33** (24), 242001. https://doi.org/10.1088/1361-6528/ac5839.
128. Hao, W.; Marichy, C.; Brioude, A. Promising Properties of ALD Boron Nitride Nanotube Mats for Water Purification. *Environ. Sci. Nano* (2017), **4** (12), 2311–2320. https://doi.org/10.1039/C7EN00811B.
129. (129) Deshwal, D.; Narwal, A. K. Analysis of Surface Deviation Impact on Bio-Mass Sensing Application of Boron Nitride Nanotubes. *Results Eng.* (2023), **19**, 101282. https://doi.org/10.1016/j.rineng.2023.101282.
130. Deshwal, D.; Narwal, A. K. Resonant Frequency Analysis of Wavy Boron Nitride Nanotube Based Bio-Mass Sensor. *Int. J. Interact. Des. Manuf.* (2023). https://doi.org/10.1007/s12008-023-01300-0.