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Review Article

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An updated review on carbon nanomaterials: Types, synthesis, functionalization and applications, degradation and toxicity

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Abstract: As carbon-based nanomaterials have such remarkable physical, chemical, and electrical capabilities, they have become a major focus of materials science study. A thorough examination of several carbon nanomaterial varieties, such as carbon nanotubes, graphene, fullerenes, and carbon nanodiamonds, is given in this review work. These materials all have distinctive qualities that qualify them for particular uses. This work starts by examining the synthesis processes of these nanomaterials, outlining the ways by which they are made and the variables affecting their ultimate characteristics. The specific features of each kind of carbon nanomaterial will then be briefly discussed in this study, along with their size, structure, and special physical and chemical properties. These materials have a wide range of possible uses in several fields. They are employed in the electronics industry to fabricate sensors, high-speed transistors, and other devices. Their high surface area and electrical conductivity make them useful in energy storage devices like supercapacitors and batteries. They are applied to environmental remediation and water purification in environmental science. They are employed in biomedicine for biosensing, bioimaging, and medication delivery. Notwithstanding the encouraging uses, the large-scale synthesis and functionalization of carbon nanomaterials present several difficulties. This review discusses the importance of carbon nanomaterials by studying their multifaceted properties and potential applications in industries. The novelty of this work lies in its detailed examination of the degradation and toxicity of these materials, which is essential for their safe integration into various technological and biomedical applications. By thoroughly analysing recent experimental results, this review aims to bridge the gap between fundamental research and practical applications.

Keywords: carbon nanomaterials, graphene, C60 fullerene, carbon nanotubes, carbon nanodiamonds

1 Introduction

A family of carbon nanomaterials mainly made of carbon has nanoscale-sized structures. The scientific world is paying close attention to them because of their high surface areas, and exceptional magnetic, electrical, optical, mechanical, and catalytic properties, which can be tuned by controlling factors such as size, shape, synthesis conditions, and functionalization [1,2]. This tunability opens them up to a wide range of potential applications across various fields, such as medication delivery, electrochemical applications, energy storage devices, supercapacitors, electronics, environmental, medicine, agriculture, and biomedical sciences [3]. Notwithstanding their

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many advantageous uses, carbon nanomaterials may also be hazardous to the environment and public health. These nanomaterials can pass through an organism's membrane or cell wall [4], which can cause immunological responses such as inflammation and the activation of pulmonary macrophages [5]. Numerous harmful consequences of carbon nanomaterials have been documented in earlier research, such as the production of reactive oxygen species (ROS), lysosomal damage, DNA damage [6], mitochondrial malfunction, and final cell death by necrosis or apoptosis [7]. Exposure to carbon black, a type of carbon nanomaterial, is associated with a high risk of cancer, and respiratory and cardiovascular diseases [8]. Therefore, understanding the potential toxicity of these materials is crucial for their safe and sustainable incorporation into industrial products [9].

In recent years, the field of carbon nanomaterials has witnessed significant advancements, particularly in the development of novel synthesis methods and the enhancement of material properties. One notable breakthrough is the advancement in the controlled synthesis of graphene, enabling the production of high-quality, large-area graphene sheets with minimal defects. Techniques such as chemical vapour deposition (CVD) and liquid-phase exfoliation have been optimized to produce graphene with superior electrical and mechanical properties, making it ideal for applications in flexible electronics, high-frequency transistors, and advanced composites [10]. In addition, the emergence of hybrid nanomaterials, which combine carbon nanomaterials with other functional materials, has opened new avenues for multifunctional applications. For instance, graphene-based composites with metal oxides or conducting polymers have shown remarkable performance in supercapacitors and lithium-ion batteries, offering higher energy densities and longer cycle lives. In the biomedical field, the functionalization of carbon nanomaterials with targeting ligands and therapeutic agents has led to the development of highly efficient drug delivery systems and advanced imaging techniques, enabling targeted cancer therapy and improved diagnostic capabilities [11]. These advancements underscore the potential of carbon nanomaterials to revolutionize various industries through innovative applications [12].

Despite the promising advancements, the field of carbon nanomaterials is not without its controversies, particularly concerning their environmental and health impacts. One major point of contention is the potential toxicity of carbon nanomaterials, which has raised significant concerns among researchers and regulatory bodies. Studies have shown that certain carbon nanomaterials, such as carbon nanotubes (CNTs) and graphene oxide (GO), can induce cytotoxicity [13], oxidative stress, and inflammatory responses in biological systems. The debate is particularly heated around the similarities between the fibrous structure of some CNTs and asbestos, raising fears of long-term respiratory issues and carcinogenicity. Moreover, the environmental persistence and bioaccumulation of carbon nanomaterials are areas of ongoing research and debate [14]. The potential for these materials to enter and persist in ecosystems, potentially disrupting aquatic and terrestrial life, has led to calls for more stringent regulations and comprehensive risk assessments. In addition, the ethical implications of nanotechnology, including concerns about privacy, security, and societal impact, add another layer of complexity to the discourse. As the field progresses, it is imperative to balance the technological benefits with a thorough understanding of the potential risks, ensuring the responsible development and application of carbon nanomaterials.

Carbon nanomaterials, including graphene, fullerenes, CNTs, and carbon nanodiamonds (CNDs), have emerged as revolutionary materials due to their unique chemical structures and exceptional properties. These materials exhibit remarkable electrical, thermal, and mechanical characteristics, making them suitable for a wide range of applications in electronics, energy storage, biomedicine, and so on. The objective of this review is to provide a comprehensive overview of the chemical structures, properties, degradation mechanisms, and toxicity of graphene, fullerenes, CNTs, and CNDs. By elucidating these aspects, we aim to highlight the current challenges and opportunities in the field of carbon nanomaterials, paving the way for future research and development. Thus, this article focuses mainly on four major types of carbon nanomaterials, which are graphene, fullerenes, CNTs, and CNDs. This article presents their molecular structures, types of synthesis, properties, application in various fields, degradation under certain conditions, and toxicity leading to the destruction of the environment and living beings.

2 Molecular structure and hybridization

Graphene, a single layer of carbon atoms in a hexagonal lattice, exhibits unique electrical properties as a semimetal due to its σ-bonds and delocalized π-bonds connecting each atom to its three nearest neighbours [15]. Its sp^2 hybridization forms three sigma bonds with adjacent carbon atoms and a delocalized pi bond [16]. Doped graphene refers to graphene that has been intentionally modified by incorporating foreign atoms or molecules into its lattice. Nitrogen-doped graphene (N-graphene) introduces nitrogen atoms into the graphene structure, altering its electronic properties. Similarly, boron-doped graphene (B-graphene) incorporates boron atoms, affecting the electronic band structure [17].

C60 fullerene, or buckyball, is a carbon allotrope with a soccer ball-like structure formed by single and double bonds in a truncated icosahedron consisting of 12 pentagonal and 20 hexagonal faces. It has a diameter of about 0.71 nm and a molecular weight of approximately 720 atomic mass units [18]. C60 fullerene derivatives are synthesized by introducing biogenic additives such as amino acids and peptides into the fullerene C60 structure. The stability of fullerenes is due to the aromaticity of the carbon rings and the even distribution of carbon–carbon bonds [19]. Each carbon atom contributes three valence electrons, resulting in 60 pi electrons, which provide stability and unique electronic properties. The carbon atoms in fullerenes primarily exhibit sp^2 hybridization, forming sigma and pi bonds [20].

CNTs are one-dimensional nanostructures composed entirely of carbon atoms, resembling rolled-up graphene sheets with a hollow, cylindrical structure. They can be single-walled (single-walled CNTs [SWCNTs]) with one carbon layer or multiwalled (multiwalled CNTs [MWCNTs]) with several concentric layers. The chirality of CNTs, determined by the arrangement of carbon atoms in the graphene sheet, affects their electronic properties and is described by indices (n, m) [21]. Chirality influences whether CNTs exhibit metallic or semiconducting behaviour. Carbon atoms in CNTs exhibit sp^2 hybridization, forming three sigma bonds with adjacent atoms in a hexagonal lattice, while the remaining electrons form pi bonds [22]. Functionalization of CNTs involves attaching functional groups to enhance their physicochemical properties for better dispersion, manipulation, and processing. This is done using covalent methods, which form chemical bonds, or noncovalent methods, which rely on weak interactions like π–π stacking or van der Waals forces. Functionalized CNTs improve interactions with matrix materials, expanding applications in nanocomposites, sensors, optoelectronics, catalysis, and biomedical engineering, including drug delivery and tissue engineering scaffolds.

Nanodiamonds (NDs) are carbon nanostructures with a diamond-like arrangement of carbon atoms. The carbon atoms in NDs exhibit sp^3 hybridization, forming four covalent bonds in a tetrahedral pattern, resulting in a three-dimensional network. The core of NDs, approximately 2–3 nm in size, mimics the diamond structure with sp^3 carbon atoms [23], while the surface has dangling bond edges with functional groups and resembles graphite with sp^2 carbon atoms. Each carbon atom within the crystalline cubic diamond lattice is covalently bonded to four other carbon atoms. In contrast, surface atoms have fewer neighbouring atoms, allowing for nondiamond bond formation with adjacent surface atoms or bonding with various functional groups on the crystalline surface [24].

The structure of the carbon nanomaterials is shown in Figure 1. There are various derivatives of the carbon nanomaterials explained earlier, which are mentioned in Figure 2. The hybridization of the different carbon nanomaterials is shown in Figure 3.

3 Synthesis of carbon nanomaterials

Carbon nanomaterials are synthesized using a variety of techniques, which are generally divided into top-down and bottom-up processes. The top-down method, which is usually applied in severe environments, entails breaking down macroscopic carbon compounds into nanoscale particles. Atoms or molecules are assembled into nanostructures using the bottom-up method [9]. Nanomaterials can have their qualities accurately controlled by adjusting their size, shape, synthesis conditions, and functionalization. By modifying the

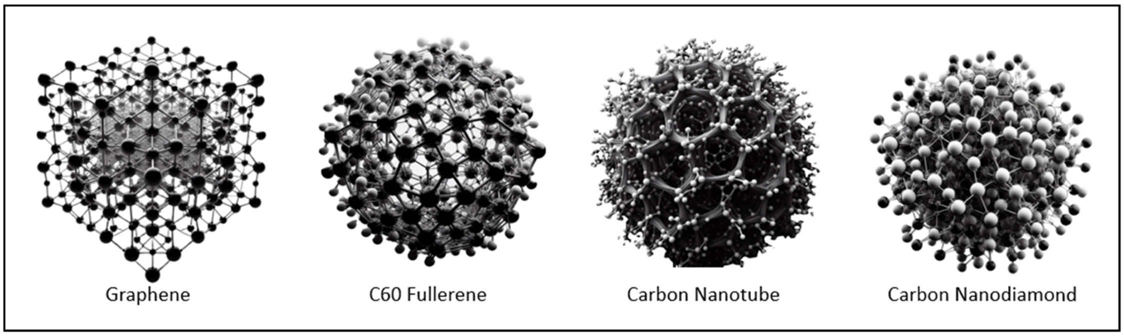

Figure 1: Molecular structures of graphene, C60 fullerene, CNT, and CND.

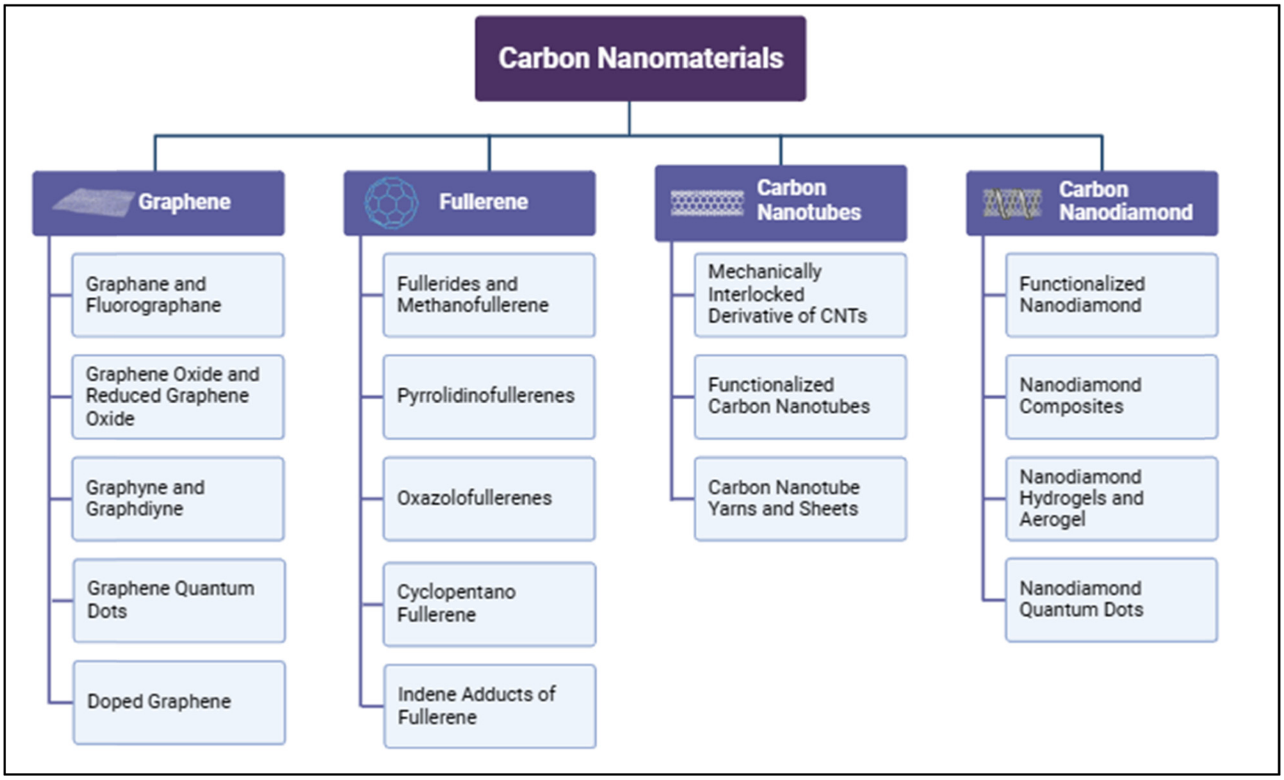

Figure 2: Derivatives of the carbon nanomaterials explained in this study.

synthesis conditions, these techniques enable the controlled production of carbon nanomaterials and allow for the tuning of their properties [6]. This article will discuss various methods to synthesize graphene, fullerenes, CNTs, and CNDs in Tables 1–3. This article will also discuss the advantages and limitations of all the different methods available for synthesizing them in Tables 1–3.

4 Properties

4.1 Electronic stability and electrical property

Graphene is a material that shows a great promise for a wide range of uses. Graphene's sp^2 hybridization and the

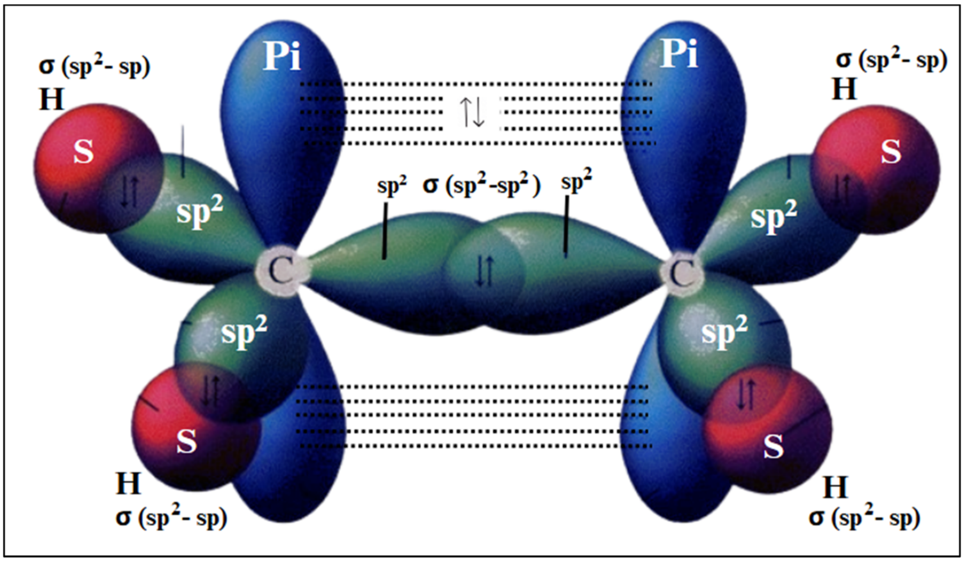

Figure 3: Representation of sp^2 hybridization to display pi and σ bond.

Table 1: Different ways of synthesizing graphene

Method	Description	Advantages	Limitations	References
CVD	Involves depositing gaseous reactants onto a substrate	Produces high-quality graphene on a large scale	Requires precise control over the process conditions	[25]
Mechanical exfoliation	Involves peeling layers of graphene from graphite	Produces high-quality graphene	Not suitable for large-scale production	[25]
Epitaxial growth	Involves growing graphene on a substrate using a crystalline template	Produces high-quality graphene	Requires a specific type of substrate	[26]
Pyrolysis	Involves the heating of organic compounds to high temperatures without the presence of oxygen	Produces graphene from a wide range of precursors	Controlling the quality and properties of the resulting graphene can be challenging	[26]
Electrochemical exfoliation	Involves applying an electric current to graphite in a solution	Produces graphene in large quantities	The quality of the graphene can vary	[26]
Rapid thermal annealing	Involves heating a substrate coated with a carbon-containing layer to high temperatures	Produces graphene quickly	Requires precise control over the process conditions	[27]
Biomass pyrolysis	Involves heating biomass materials to high temperatures in the absence of oxygen	It is a green and sustainable method but the quality	The properties of the resulting graphene can vary	[27]
Hydrothermal and solvothermal techniques	Involves reacting precursors in a solvent at high temperatures and pressures	Produces a wide range of nanomaterials	Requires specialized equipment	[28]
Microwave and ultrasonic irradiations	Involves using microwave or ultrasonic energy to drive chemical reactions	Produces nanomaterials quickly but require	Requires specialized equipment	[28]
Arc discharge	Involves creating an electric arc between two carbon electrodes in an inert gas environment	Produces high-quality graphene	Not suitable for large-scale production	[29]
Unzipping nanotubes	Involves unzipping CNTs to produce graphene	Produces high-quality graphene	Requires specialized equipment and conditions	[29]
Microwave synthesis	This method involves using microwave energy to drive chemical reactions that produce graphene	Produces graphene quickly	Requires specialized equipment	[29]
Hummer's method	This method involves oxidizing graphite to produce GO, which can then be reduced to graphene	It is a simple and cost-effective method	The resulting graphene may not have the same properties as pristine graphene	[29]
Thermal decomposition	This method involves heating a carbon-containing compound until it decomposes to form graphene	Produces graphene from a wide range of precursors	Controlling the quality and properties of the resulting graphene can be challenging	[29]
Electrolysis	This method involves applying an electric current to a solution containing a carbon precursor	Produces graphene in large quantities	The quality of the graphene can vary	[30]
Green synthesis	This method involves using environmentally friendly processes to produce graphene	It is a sustainable method but with the low quality	The properties of the resulting graphene can vary	[30]

Table 2: Different ways of synthesizing CNTs and fullerenes

Method	Description	Advantages	Limitations	References
Arc discharge	Involves creating an electric arc between two carbon electrodes	Produces high-quality CNTs and fullerenes with lengths of up to 50 μm with few structural defects	However, it uses high temperatures, which may not be suitable for all applications	[31]
Laser ablation	In this method, a pulsed laser vapourizes a graphite target in a high-temperature reactor. Nanotubes and fullerenes develop on the cooler surfaces of the reactor as the vapourized carbon condenses	About 70% of the product is yielded, mostly fullerenes and single-walled CNTs with tuneable diameters set by reaction temperature	Nevertheless, the cost is higher compared to CVD or arc discharge	[31]
CVD	Involves depositing gaseous reactants onto a substrate	Produces CNTs and fullerenes in large quantities, making it commercially viable	It requires precise control over the process conditions	[32]
High-pressure carbon monoxide disproportionation	Involves the use of high-pressure carbon monoxide gas	Produces single-walled CNTs and fullerenes	It requires a metal catalyst	[32]
Flame synthesis	Involves the combustion of hydrocarbon gases	Produces CNTs and fullerenes in a single step	Control over the properties of the resulting CNTs and fullerenes can be challenging	[33]
Plasma method	Involves using plasma to enhance the growth of CNTs and fullerenes	Produces high-quality CNTs and fullerenes	It requires specialized equipment	[33]
Aerosol precursor method	Involves the thermal decomposition of aerosol precursors	Produces CNTs and fullerenes with controlled properties	The process can be complex	[32]
Arc water process	Involves the use of water cooling during the arc discharge process	Produces high-quality CNTs and fullerenes	The yield can be low	[29]
Low-temperature route	Involves the synthesis of CNTs at low temperatures	It can be energy efficient	The quality of the resulting CNTs and fullerenes can vary	[29]
Fluidized bed method	Involves the use of a fluidized bed reactor	Produces CNTs and fullerenes in large quantities	It requires precise control over the process conditions	[32]
Plasma enhanced CVD	Involves the use of plasma to enhance the growth of CNTs and fullerenes	Produces high-quality CNTs and fullerenes	It requires specialized equipment	[34]
Thermal CVD	Involves heating a carbon-containing compound until it decomposes to form CNTs and fullerenes	Produces CNTs and fullerenes from a wide range of precursors	Controlling the quality and properties of the resulting CNTs and fullerenes can be challenging	[34]
Floating catalyst method	Involves the use of a catalyst in the gas phase	Produces CNTs and fullerenes in large quantities	The quality of the CNTs and fullerenes can vary	[34]
Alcohol catalytic CVD	Involves the use of alcohol as the carbon source	Produces CNTs and fullerenes with controlled properties	The process can be complex	[34]

Table 3: Different ways of synthesizing CND

Method	Description	Advantages	Limitations	References
Detonation technique	Involves the detonation of carbon-containing explosives	Produces NDs quickly and in large quantities	The resulting NDs may contain impurities	[35]
Laser-assisted synthesis	Involves the use of a laser to vapourize a carbon target	Produces high-quality NDs	It requires specialized equipment and conditions	[35]
High-temperature high pressure	Involves subjecting carbon materials to high temperatures and pressures	Produces NDs with controlled properties	The process can be complex	[25]
High-energy ball milling	Involves the use of high-energy ball milling to reduce the size of diamond crystals	Produces NDs with a wide range of sizes	Controlling the size distribution can be challenging	[25]
Hydrothermal synthesis	Involves reacting carbon precursors in a high-temperature, high-pressure aqueous environment	Produces NDs with controlled properties	It requires specialized equipment	[30]
CVD	Involves depositing gaseous reactants onto a substrate	Produces NDs in large quantities, making it commercially viable	It requires precise control over the process conditions	[30]
Ion bombardment on graphite	Involves bombarding a graphite target with ions	Produces NDs with controlled properties	It requires specialized equipment	[36]
Chlorination of carbides	Involves the reaction of carbides with chlorine	Produces NDs with controlled properties	The process can be complex	[36]
Ultrasonic cavitation	Involves the use of ultrasound to create cavities in a liquid	Produces NDs with controlled properties	It requires specialized equipment	[36]
Autoclave synthesis	Involves the use of an autoclave to create a high-pressure, high-temperature environment	Produces NDs with controlled properties	Controlling the size distribution can be challenging	[36]

delocalized π-bond that permeates the entire sheet are responsible for its electrical stability. Graphene's exceptional electrical conductivity and electron mobility are a result of the π electrons' delocalization [37]. Because of its unique electrical characteristics, intrinsic graphene material is a semimetal or zero-gap semiconductor with outstanding opacity for an atomic monolayer low absorption ratio of 2.3% of visible light. In addition, it has been investigated that the graphene sheet's resistance is higher than that of platinum, which is believed to have the lowest resistivity at ambient temperature [38]. Studies by Sang et al. highlight graphene's exceptional electrical conductivity, outperforming copper by up to 70% and achieving up to 80% of its nanoscale conductivity when properly processed. Sang et al. also examined graphene's quantum Hall effect and Dirac fermions, underscoring its superior electronic properties, which could revolutionize next-generation electronic devices [39]. Research focused on enhancing macroscopic conductivity through doping and optimizing the spatial distribution of graphene flakes, paving the way for high-performance applications in flexible electronics, sensors, and transparent electrodes for solar cells and displays [40]. It was discovered that the width of armchair graphene nanoribbons (GNRs) inversely affects their energy band gap. Because of its two-dimensional (2D) Dirac-like electronic excitations, graphene, an allotrope of carbon that is only one atom thick, exhibits special electrical properties. These Dirac electrons can be manipulated by changing the geometry and/or topology of the sample, as well as by adding external electric and magnetic fields. In confinement, tunnelling, and the integer quantum Hall effect, they exhibit peculiar behaviour [41]. The number of layers and stacking sequence of graphene stacks affect its electrical characteristics. The physical properties of nanoribbons are influenced by edge (surface) states in graphene, which are contingent upon the edge termination (zigzag or armchair). Distinct forms of disorder alter the Dirac equation, resulting in peculiar transport and spectroscopic characteristics. Notable are also the effects of electron–phonon and electron–electron interactions in single-layer and multilayer graphene [42]. Every carbon atom in graphene has four valence electrons. Not involved in the conduction process, three of them (named σ-electrons) create strong connections with adjacent atoms in the plane. Alternatively, the fourth electron, also referred to as the π-electron, may freely flow between the lattice's positive ions [43].

Fullerenes, such as C60 (buckminsterfullerene), are carbon allotropes known for their electronic stability and unique properties. They exhibit aromaticity similar to benzene rings due to the delocalization of π electrons in their hexagonal and pentagonal ring structure [44]. This structure, along with strong carbon–carbon bonds, creates a robust molecular framework. Fullerenes have high symmetry, resulting in a low dipole moment and enhancing their stability in various environments. Their hollow, cage-like structure allows for the encapsulation of other molecules or ions, and they can be modified by adding functional groups to their surface for specific chemical reactions [45]. Pure fullerenes are generally poor conductors of electricity due to carbon–carbon single bonds, but their electrical conductivity can be significantly enhanced through doping or chemical modification, which introduces other elements or molecules into the fullerene structure [24]. Fullerenes also exhibit photoconductivity, generating electron-hole pairs (excitons) when exposed to light, which enhances their electrical conductivity. They have interesting dielectric properties that are important for designing capacitors and energy storage devices, and they can undergo redox reactions, gaining or losing electrons, which is important in various electrochemical applications [46].

The strong connections between carbon atoms in CNTs and their distinct structure provide exceptional electrical stability. CNTs can withstand current densities up to $10^9\ \mathrm{A{\cdot}cm^{-2}}$, which is two to three orders of magnitude higher than copper and aluminium [47]. Transport within MWCNTs is ballistic and does not disperse, while certain SWCNT architectures exhibit semiconductor behaviour, and others demonstrate excellent electrical conductivity [48]. Despite challenges such as breakdown, degradation, and threshold voltage fluctuations, CNTs find extensive utility in electronics and materials science due to their electronic stability in various environmental conditions [49]. CNTs display metallic or semiconducting behaviour along their tubular axis. The curvature of the tube surface shifts the degenerate point, influencing band dispersion and modifying the band structure [50]. Known as “one-dimensional conductors,” single-walled CNTs have a maximum electrical conductance of $2G_o$, where $G_o = 2e^2/h$ represents the conductance of a single ballistic quantum channel. Doping in CNTs differs from bulk crystalline semiconductors; substitutional dopants like boron or nitrogen can induce p-type or n-type behaviour, while nonsubstitutional dopants such as metallocenes or alkali metals donate or accept electrons, influencing the nanotubes’ conduction properties [51].

Electrical stability is a critical aspect of CNTs’ composition and functionality. Surface functional groups cover the diamond core of NDs, breaking dangling bonds and stabilizing the particle. Conversion of sp^3 carbon into sp^2 carbon is another technique for surface stabilization. The electrical properties of NDs are primarily influenced by the higher occupied molecular orbital (HOMO) and lower unoccupied molecular orbital (LUMO) [52]. Factors such as the HOMO–LUMO gap, relative stabilities, and the impact of chemical decorating on the gap size and nature contribute to their electrical stability. Diamond clusters become more stable than their graphitic counterparts below a size of 3–6 nm, indicating that stabilizing diamond-like nanocrystallites is favoured by an increase in particle size and hydrogenation. Intermediate nanostructures resembling diamonds can form inside the fullerene cage [53]. Similar to other forms of carbon, CNDs possess unique electrical properties. ND composites, comprising ND, pyrolytic carbon, and nanosized holes, are p-type semiconductors. As the pyrocarbon-to-diamond ratio increases, their resistance decreases significantly due to a higher concentration of surface Tamm states [54]. Paramagnetic features are explained by electron spins localized on the composite’s ND surface. In diamonds, electrons are too firmly bonded to conduct electricity under normal conditions, requiring significant energy to excite them. This energy, equivalent to 5.6 electron volts (eV), creates a bandgap. Surface doping and the addition of functional groups can alter the optical, electrical, mechanical, and chemical properties of ND formations, making them valuable in electrochemical and electrical applications [55].

4.2 Mechanical property

Graphene is a 2D lattice consisting of covalently bonded carbon atoms organized hexagonally. It is well known for its remarkable mechanical properties. It is projected that graphene, as a single, nearly flawless crystal, will have tensile stiffness comparable to graphite and an intrinsic tensile strength greater than any other known material. Graphene has a mechanical strain of roughly 25% and a yield power of $42\ \mathrm{N{\cdot}m^{-1}}$ [56]. Graphene has a fixed tensile strength of 130 GPa and a theoretical elastic modulus as high as 1 TPa. Because of these characteristics, graphene has a high mechanical strength. Graphene possesses exceptional mechanical capabilities due in part to its unusual structure, which is a hexagonal honeycomb lattice made of carbon atoms with sp hybrid orbitals. The mechanical qualities of metal materials, such as strength and stiffness, as well as their physical qualities, such as conductivity and thermal conductivity, can be significantly enhanced by using this structure as a reinforcing phase [57]. A cantilever beam configuration with poly(methyl methacrylate) bars has been used to investigate the mechanical behaviour of graphene under compressive and tensile loadings in addition to these characteristics. The inserted flake appears to withstand strains of up to 1.3% when under tension, but at roughly 0.7% strain when under compression, there is a sign of flake buckling. Its high tensile strength, stiffness, and strain capacity, along with its unique structure, contribute to its versatility and potential for use in a wide range of applications [58].

Fullerenes, particularly C60, have unique mechanical properties. They are exceptionally hard, resistant to deformation, and can withstand substantial compressive forces, making them suitable for applications requiring hardness and wear resistance [59]. They are lightweight due to their hollow structure, beneficial in fields like aerospace. Fullerenes exhibit high elasticity, allowing them to recover their original shape after deformation, and are useful in shock-absorbing materials. They are known for their resilience and ability to absorb impact energy. However, they can be brittle under extreme stress [32]. Fullerenes, especially C60 nanoparticles, can act as solid lubricants due to their spherical structure. When incorporated into nanocomposites, they enhance the mechanical strength of the materials. Their mechanical properties can be tailored through functionalization, enabling the design of materials with customized characteristics. Techniques like atomic force microscopy (AFM) and scanning tunneling microscopy (STM) are advanced level microscopy techniques which have been utilized to determine the topology of the surface and used to study their mechanical properties at nanoscale [31].

CNTs are the stiffest and strongest materials discovered to date in terms of elastic modulus and tensile strength. This strength is provided by the covalent sp^2 bonds that develop between the individual carbon atoms. Tensile strength of 63 GPa (9,100,000 psi) was measured in 2,000 for a multiwalled CNT. CNTs are not nearly as strong when compressed [32]. Their hollow structure and high aspect ratio make them buckle easily under compressive, torsional, or bending force. Elasticity [34] suggests that van der Waals forces might even be able to deform two adjacent nanotubes. Later, single-walled CNTs were also subjected to tapping/contact mode atomic force microscopy, while other groups employed an atomic force microscope to measure the radial elasticity of multiwalled CNTs using nanoindentations. Young's modulus revealed how radially soft CNTs are; it is on the order of several gigapascals. It is stated that using CNTs-filled polymer nanocomposites with 4 and 6 wt% loadings will provide the offshore umbilical sheathing layer with mechanical capabilities that are best balanced between resilience to ultraviolet exposure and mechanical properties in 2020 [60].

There are numerous advantageous mechanical features of CNDs. They can withstand hostile environments and have improved chemical stability and toughness. In addition, their friction coefficient is lower than that of other nanomaterials. Researchers have been drawn to investigate the potential applications of ultra-fine ND powders as coatings and composite coatings due to their distinctive mechanical and tribological features, such as their low friction coefficient and high hardness [46]. Densification of the powder compacts is aided by the volume expansion that results from the phase transition of diamond to graphite when ND is mixed with other materials. The as-prepared carbon bulks have outstanding mechanical qualities because of the strong bond between the ordered mesoporous carbon (OMC) and the graphite onions generated from the ND. With their nano size, resilient inert core, adaptable surface shape, excellent thermal constancy, and exceptional mechanical capabilities, NDs are allotropic carbon nanomaterials that hold great promise as reinforcing materials for a range of technological applications [47].

4.3 Thermal properties

The 2D materials like graphene exhibit heat flow anisotropy between in-plane and out-of-plane directions that is nearly 100 times greater than random. High in-plane thermal conductivity is caused by the covalent sp^2 interaction between carbon atoms [48]. In contrast, weak van der Waals coupling restricts heat transport out of the plane. The extremely anisotropic character of this crystal is reflected in the thermal properties of graphene, which are derived from those of graphite. For example, with a bonding energy of about 5.9 eV, the in-plane covalent sp^2 connections between neighbouring carbon atoms are among the strongest – slightly stronger than the sp^3 bonds in diamond. In contrast, mild van der Waals interactions (~50 meV) with a distance of h = 3.35 Å connect the neighbouring graphene planes within a graphite crystal [17,49]. A study by Tarhini and Tehrani-Bagha report graphene's remarkable thermal conductivity, reaching up to 5,300 $W \cdot m^{-1} \cdot K^{-1}$ at room temperature, significantly higher than metals like copper (400 $W \cdot m^{-1} \cdot K^{-1}$) and aluminium (237 $W \cdot m^{-1} \cdot K^{-1}$), as well as ceramics such as aluminium nitride (285 $W \cdot m^{-1} \cdot K^{-1}$) and silicon carbide (120 $W \cdot m^{-1} \cdot K^{-1}$) [61]. Danial and Abdul Majid attributes this to graphene's 2D structure and strong sp^2 carbon–carbon bonds, while Ghosh highlights the absence of substrate interactions in suspended graphene [62]. In addition, A study found that incorporating graphene into polymer matrices enhances their thermal properties, with just 1% graphene increasing the thermal conductivity by up to 50%, due to graphene's intrinsic high thermal conductivity and efficient heat-conducting network formation [63].

Fullerenes, particularly C60, have unique thermal properties due to their structure and composition. They exhibit high thermal stability and can withstand high temperatures. Pure fullerenes generally have low thermal conductivity due to their carbon–carbon bonds, but this can be improved by modifying their structure or incorporating them into composites [61]. This is primarily due to their unique molecular structure, where carbon atoms form a spherical shape, leading to less-efficient phonon transport. Recent studies by Mortazavi have investigated the thermal properties of fullerene networks [58], revealing significantly lower thermal conductivities compared to graphene [64]. Mortazavi found that the quasi-hexagonal-phase fullerene (qHPC60) network has room temperature thermal conductivities of around 2.9 $W{\cdot}m^{-1}{\cdot}K^{-1}$ along the *x*-direction and 5.7 $W{\cdot}m^{-1}{\cdot}K^{-1}$ along the *y*-direction [65], while Mortazavi estimated the thermal conductivity of C60-based fullerene networks to be around 10 $W{\cdot}m^{-1}{\cdot}K^{-1}$. These values are considerably lower than graphene's thermal conductivity, which can reach up to 5,300 $W{\cdot}m^{-1}{\cdot}K^{-1}$, highlighting the limitations of fullerenes in thermal management applications [66]. Fullerenes can absorb and store heat, making them useful in thermal energy storage applications. They exhibit thermal expansion behaviour and possess excellent photothermal properties, efficiently converting light energy into heat. At the nanoscale, fullerenes demonstrate unique thermal properties, valuable in thermal management applications [67].

Every nanotube is expected to have very good "ballistic conduction," or thermal conductivity along the tube, and excellent lateral-to-tube axis insulators. The room-temperature thermal conductivity of single-walled CNTs is measured to be about 3,500 $W{\cdot}m^{-1}{\cdot}K^{-1}$; in comparison, 385 $W{\cdot}m^{-1}{\cdot}K^{-1}$ is transmitted by copper, a metal that is well known for having a high thermal conductivity [68]. With a room-temperature thermal conductivity lateral to its axis (in the radial direction) of 1.52 $W{\cdot}m^{-1}{\cdot}K^{-1}$, single-walled CNTs have about the same thermal conductivity as dirt. To date, macroscopic assemblages of nanotubes, like films or threads, have been used to achieve up to 1,500 $W{\cdot}m^{-1}{\cdot}K^{-1}$. Nanotube networks have variable thermal conductivity; it can be as low as 0.1 $W{\cdot}m^{-1}{\cdot}K^{-1}$, the degree of thermal insulation, or as high as [69]. That is dependent on how much the system's thermal resistance is influenced by impurities, misalignments, and other elements. CNTs are thought to be able to tolerate temperatures of about 750°C in air and up to 2,800°C in a vacuum [70].

When compared to other bulk materials, CNDs are well known for their comparatively excellent heat conductivity and toughness. Strong carbon–carbon covalent bonds, limited phonon dispersion, and the intrinsic crystal structure of diamond are the main causes of its high heat conductivity [46]. Recent studies have elucidated the mechanisms behind the high thermal conductivity of ND composites. Mortazavi et al. (2023) found that NDs enhance thermal conductivity by effectively scattering phonons due to numerous interfaces within the composite matrix, acting as phonon scattering centres [58]. Alexander et al. (2024) highlighted that the high concentration of sp^3-bonded carbon atoms in NDs and strong interface interactions facilitate efficient phonon transfer, reducing thermal resistance [71]. In addition, a review by Mumtaz et al. (2022) emphasized that NDs improve thermal transport by altering the microstructure of the host material, suppressing grain growth, and introducing pores, dislocations, and strain, while their significant phonon frequency mismatch with the host material further enhances phonon scattering [72]. As a result, there is an extraordinarily high characteristic Debye temperature of about 2,000 K and a high sonic velocity. NDs are regarded as one of the best fillers because of their exceptional heat conductivity and unique carbon structure, which enhance the performance of the polymeric matrix. For example, the CND nanofibre composite nanofibres with 50 wt% ND incorporation attained 6.7 $W{\cdot}m^{-1}{\cdot}K^{-1}$ for thermal conductivity, which is approximately 2.7 times that of the CND composite nanofibre without NDs [47]. Furthermore, ND is a perfect thermal conductivity filler material for raising the thermal conductivity of polymers because of diamond's high thermal conductivity, which can reach up to 2,000 $W{\cdot}m^{-1}{\cdot}K^{-1}$ [73]. One significant challenge for ND composites, nevertheless, is getting NDs into a polymer matrix as well-dispersed particles. The aggregation and deagglomeration of the NDs within the polymer matrix have resulted in poor dispersion when using traditional processing techniques like casting and extrusion [74].

4.4 Hydrophobic properties

Graphene – a 2D carbon crystal – was thought to have hydrophobic surfaces and comparable wetting characteristics as graphite. Recent research, however, indicates that graphene on copper may have started more hydrophilic and that its apparent hydrophobicity may have been caused by water adsorption or airborne pollutants. Like many other carbon-based materials, graphene is often believed to be hydrophobic [19]. The question of whether graphene is hydrophilic or hydrophobic, however, is far more nuanced than previously believed, according to studies. Using hydrophobic probe chemical force microscopy, the adhesion and friction properties of single- and double-layer graphene were investigated [29]. When compared to single-layer graphene, a greater adhesion force was observed between the probe and double- or triple-layer graphene, indicating the hydrophobic nature of the latter. This implies that the hydrophobicity is dependent on the graphene layer thickness. The mapping of friction forces at the nanoscale further supported these findings: hydrophobic domains exhibited a lower friction force, which is consistent with the idea that varying degrees of hydrophobicity influence the arrangement of nearby water molecules and, consequently, the sliding motion of the probe tip [37].

Fullerenes, particularly C60, exhibit hydrophobic properties due to their unique molecular structure and surface characteristics. Their non-polar nature leads to low interaction with polar substances like water, making them sparingly soluble. This property is advantageous in applications requiring water resistance [33]. Fullerenes can reduce the surface tension of water, which is useful in controlling surface properties. They are used in the development of hydrophobic coatings and materials, enhancing the water-repelling properties of surfaces [43]. In nanotechnology, fullerenes are used to create nanomaterials that repel water, resulting in self-cleaning surfaces and anti-fouling coatings. In biomedical applications, their hydrophobic properties are utilized in drug delivery systems, where the fullerene cage can encapsulate hydrophobic drug molecules. Researchers continue to explore these hydrophobic properties in various fields [44].

In nature, carbon–carbon bonds are nonpolar. This results in a symmetrical charge distribution because the electrons in the covalent bonds between carbon atoms are distributed equally. Contrarily, the hydrogen and oxygen atoms in water are polar molecules with partial positive and negative charges. CNTs have no affinity for water molecules because of their nonpolarity [47]. Graphene is a material that is known to be hydrophobic, and CNTs are essentially graphene sheets rolled up. One reason CNTs are hydrophobic is that they retain the hexagonal lattice structure of graphene, which is devoid of polar functional groups. Since CNTs have a low surface energy (SE), polar molecules like water are not strongly attracted to them. Rather, they usually engage in more positive interactions with nonpolar or hydrophobic materials [24]. Pristine CNTs typically have a limited number of surface functional groups, such as carboxyl or hydroxyl groups, which would increase their hydrophilicity. In their pristine state, CNTs have few sites for water molecules to bond. It is important to note that while CNTs are inherently hydrophobic, their surface properties can be modified or functionalized to become more hydrophilic [75]. This can be achieved through various chemical treatments and functionalization methods. Functionalization introduces hydrophilic groups to the CNT surface, making them more compatible with water and aqueous environments [76].

Carbon nanoparticles are often hydrophobic, which includes NDs. The range of SE for CNTs is 27–45.3 $\mathrm{mJ \cdot m^{-2}}$. The SE of graphene flake that was normally present was around 54.8 $\mathrm{mJ \cdot m^{-2}}$, whereas GO and chemically exfoliated graphene had SE of 46.7 and 62.1 $\mathrm{mJ \cdot m^{-2}}$, respectively [39]. Enhancing surface roughness, creating nano-/micro-hierarchical surface structures, reducing surface area (removing hydrophilic surface groups), and adding low surface area treatments can all help make carbon nanomaterials more hydrophobic. The surface of the detonation ND particles has a wide variety of carbonyl, hydrocarbon, and oxygen functional groups, such as –C=O, O–H, O–CH, –COOH, and C–O–C [48]. Clean NDs may easily interact with polymers to form compact composite materials thanks to these functional groups. Super hydrophobicity may result from appropriate SE (low SE) and surface roughness (micro/nano-hierarchical surface structuring) optimization. Low sliding angle (SA < 5°) and contact angle hysteresis (CAH < 10°) yield further self-cleaning properties [55].

4.5 Optical activity

Graphene is a complex nanomaterial that has unique optical properties that are worth talking about. For example, a single layer of graphene absorbs about 2.3% of light; so, 97.7% of light passes through a single layer and only around 0.1% of light is deviated from its original path. Nevertheless, the optical transparency decreases and the amount of light absorption increases with the number of graphene layers layered on top of one another. All layers absorb 2.3% of the light, although the relationship is linear [49]. When it comes to its interactions with electromagnetic radiation, graphene possesses numerous other unique features. Graphene, for example, has distinct optical transitions and a broad frequency range of light absorption. Graphene can absorb radiation from a wide range of electromagnetic spectrum regions due to its band structure, lack of a band gap, and the way electromagnetic radiation interacts with the Dirac fermions in the graphene sheet [19]. Every one of these optical reactions is different; visible to near-infrared light causes intraband transitions, whereas far-infrared absorption can be facilitated by either intraband transitions or free carrier absorption mechanisms [77].

Optical activity, also known as chirality, refers to the property of some molecules to rotate the plane of polarized light. Fullerenes, including the most well-known fullerene C60 (buckminsterfullerene), are generally not optically active because they lack chirality [78]. This means that they do not have asymmetrical carbon centres or other structural features that would allow them to interact with polarized light in a way that causes rotation of the light's plane. The lack of chirality in fullerenes is primarily due to their highly symmetric and cage-like molecular structure, which consists of carbon atoms arranged in a perfectly symmetrical pattern [49]. Chirality typically arises from the presence of asymmetric carbon atoms (chiral centres) or other structural features that create a lack of superimposability, leading to the ability to rotate polarized light. While fullerenes themselves are not optically active, they can become optically active when chemically modified or when they form compounds or complexes with other chiral molecules [62].

The absorption, photoluminescence (fluorescence), and Raman spectroscopy properties of CNTs are useful. A rather substantial volume of CNTs may be quickly and non-destructively characterized using spectroscopic approaches [79]. From an industrial perspective, there is a strong need for this kind of characterization because several parameters during the synthesis of nanotubes can be altered, either purposefully or accidentally, affecting the quality of the final product. These parameters include the amount of non-tubular carbon, the chirality of the produced nanotubes, and structural defects [64]. The majority of other important optical, mechanical, and electrical properties are then determined by these traits. For use in devices like light-emitting diodes (LEDs) and lab-produced photodetectors based on a single nanotube, CNT optical characteristics have been investigated [45]. Their narrow selectivity in the light emission and detection wavelengths, as well as the ability to fine-tune the light through the nanotube structure, are what make them special rather than their efficiency, which is still comparatively low [34].

Because of their diverse spectroscopic features, CNDs have garnered a lot of attention recently. This makes them promising for possible uses in optoelectronics, quantum computation, and bio/medical applications. Defects in the diamond lattice are the main cause of the optical characteristics of NDs [80]. The nitrogen-vacancy (N-V) core, which gives the diamond its red/near-infrared fluorescence, is the most well known of these flaws. A neighbouring vacancy and one substitutional nitrogen atom combine to generate the N-V centre, a defect in diamonds. The nitrogen-vacancy-nitrogen (N-V-N) colour centre, also known as the H3 centre, is another significant defect that displays brilliant green photoluminescence [81]. These optically active defects are readily characterized, their surface modified, or their conjugation with molecules of interest made possible by their easy detection utilizing infrared and Raman spectroscopy. In addition, NDs can be used for drug administration, bio-labelling, and biosensing because of their stable photoluminescence and visible light active nitrogen-vacancy centres (with zero-phonon lines, ZPL; NV− ~636 nm, NV0 ~575 nm) [57,72] (Figures 4 and 5).

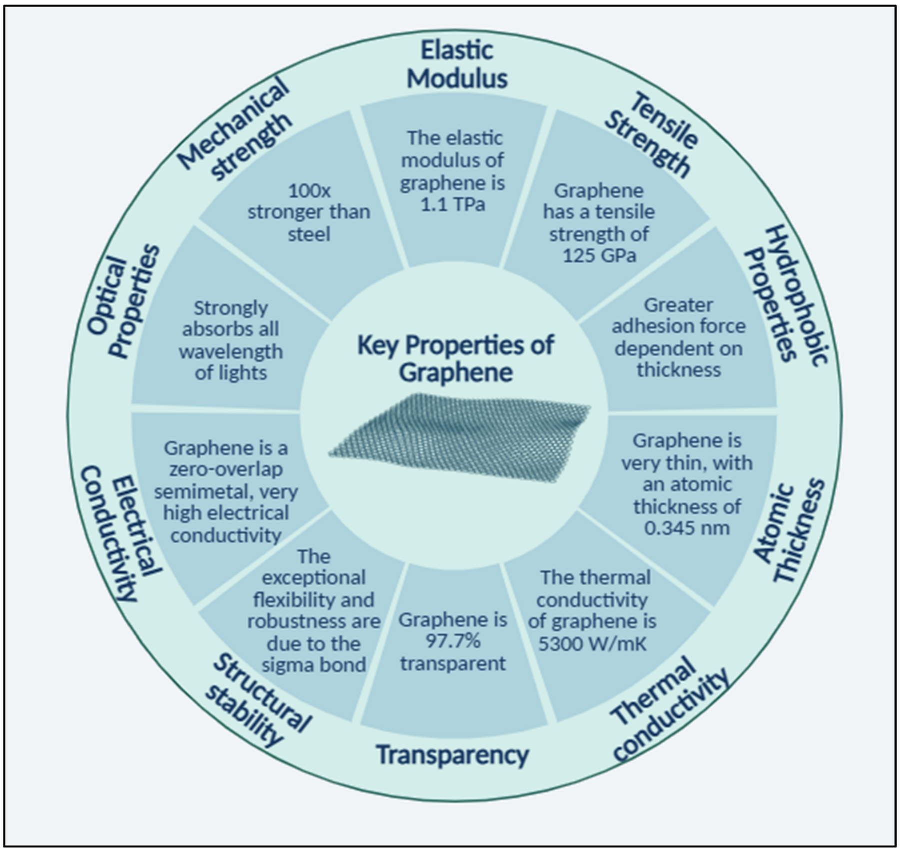

Figure 4: Key properties of graphene.

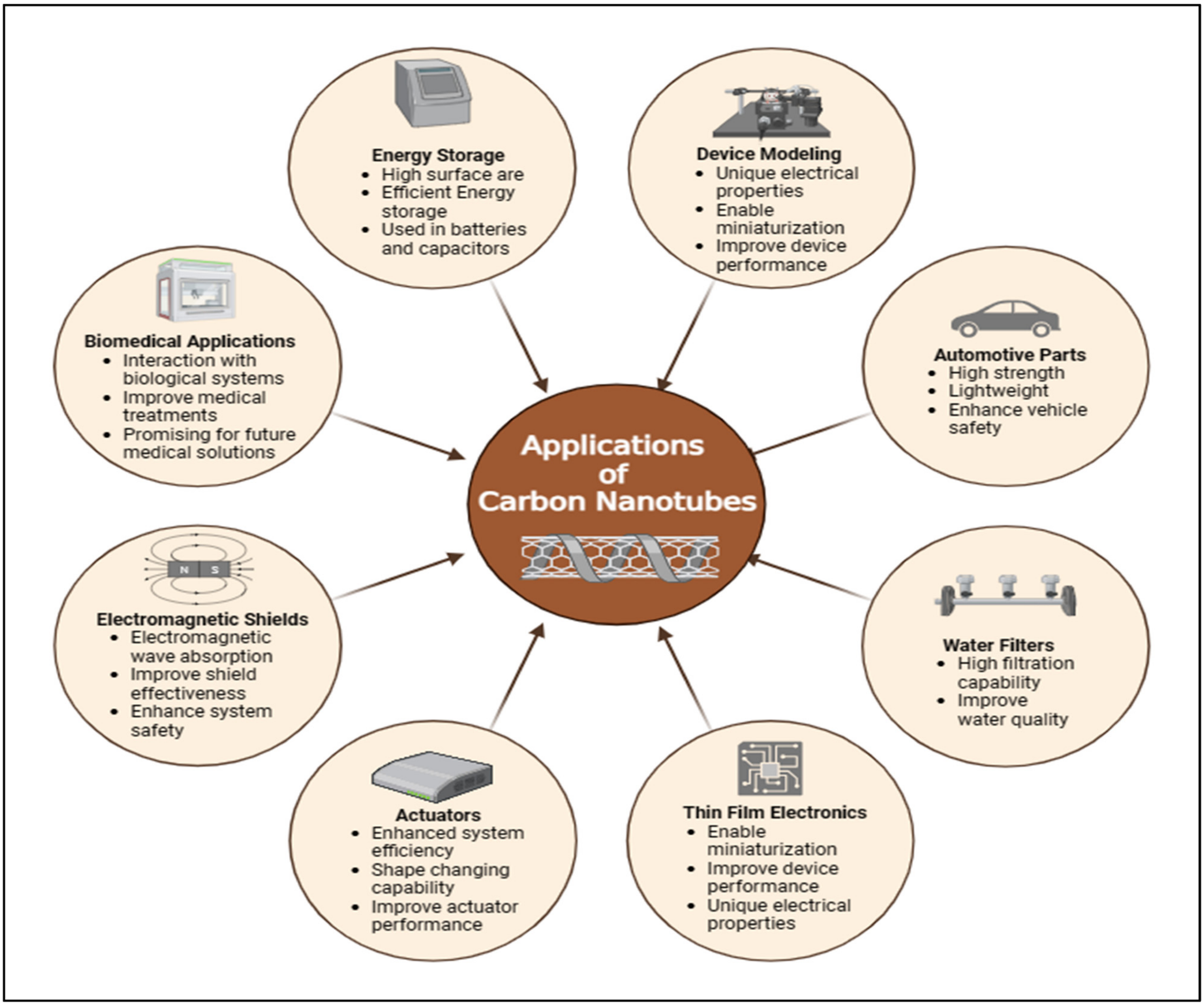

Figure 5: Various applications of CNTs.

5 Applications

5.1 Electronics

The 2D carbon crystals called graphene have the power to completely transform the electronics industry. Numerous electronic applications have made use of its special electrical qualities. Transistors represent one of graphene's most important electronic uses. Graphene has previously been used by researchers at The University of Manchester to produce the tiniest transistor ever made. In circuits, transistor performance improves with decreasing size. The primary obstacle confronting the electronics sector over the next two decades is the ongoing reduction in technology's size [82]. Another application for graphene is as a covering to enhance existing touch displays on smartphones and tablets. It can also be utilized to create the extremely fast circuitry seen in our computers. These are only two instances of how graphene can improve the technology available today. Furthermore, graphene has the potential to inspire the next wave of electronics. Wearable technology, for example, would see a tablet that you could fold up like a newspaper or a smartphone that you could wear on your wrist. Both the mechanical and electrical properties of graphene are utilized in flexible, wearable electronics [83]. Moreover, the worldwide investigation into graphene's potential uses as a semiconductor has been sparked by the material's exceptional thinness and conductivity. Graphene semiconductors, which are only one atom thick and carry electricity at normal temperature, have the potential to replace current computer chip technology. Studies have already demonstrated that graphene processors outperform current silicon-based ones in terms of speed [84].

Fullerenes, especially C60 (buckminsterfullerene) and its derivatives, have found various applications in the field of electronics. Their unique properties, such as high electron mobility, excellent electron acceptor characteristics, and the ability to transport charge, make them suitable for a range of electronic applications. Fullerenes are commonly used in organic photovoltaic (OPV) devices, also known as organic solar cells. In these devices, fullerenes serve as electron acceptors that help facilitate the efficient separation and transport of electrons [20]. They are typically combined with organic semiconductors to create active layers that convert sunlight into electricity. Fullerenes have been used in organic light-emitting diodes (OLEDs) to enhance electron injection and transport properties. In organic light-emitting devices, they can improve electron mobility and contribute to better device performance, leading to brighter and more efficient displays and lighting sources. Fullerenes can be used in organic field-effect transistors (OFETs). This use in organic field effect transistors can lead to flexible and low-cost electronic devices. Fullerenes, especially their derivatives like PCBM (phenyl-C61-butyric acid methyl ester), are used as electron acceptors in organic electronic devices. They can facilitate charge transport and improve the efficiency of charge separation and collection. Fullerenes have been employed in various sensor applications [18]. Their high surface area and electronic properties make them suitable for gas sensors, biosensors, and chemical sensors. For example, fullerenes can be used as sensing elements in detecting specific gases or biomolecules. Fullerenes are used in the construction of photoconductive devices. They can be applied as photoconductors in photodetectors and other light-sensitive devices, where their electron transport properties are advantageous. Fullerenes, with their large third-order nonlinear optical responses, are used in nonlinear optical devices such as frequency converters and optical limiters. These devices are crucial in optical communications and laser technology. Fullerene-based electronics face significant challenges, including low solubility and processability, which complicate their integration into devices, as fullerenes tend to aggregate and cause phase separation in OPV devices, reducing efficiency. In addition, the stability of fullerene-based devices under operational conditions is a concern, as they can undergo photochemical reactions that degrade performance over time. Limited tunability of electronic properties and high production and purification costs also hinder their commercial viability. However, emerging trends offer potential solutions. Functionalized fullerene derivatives with attached functional groups improve solubility, stability, and electronic properties, as demonstrated by Liu et al. Fullerenes are also enhancing perovskite solar cells, increasing efficiency to over 20%, according to Zhang et al. Moreover, organic electrochemical transistors benefit from fullerenes' high electron mobility and stability, making them suitable for bioelectronics and sensing applications [85].

With their special features, CNTs are quasi-one-dimensional materials that are perfect for use in electronic devices. Because of their special electrical qualities and nanoscale size, CNTs offer a wide range of possible uses in the field of electronics. In addition to symmetric complementary metal oxide semiconductor devices being proven and pass-transistor-logic, a circuit architecture that is more efficient than complementary metal oxide semiconductors, being investigated, both n-type and p-type CNT field-effect transistors with near ballistic performance limitations have been produced. High-performance field-effect transistors can be made with CNTs [86]. Depending on their chirality and diameter, they can function as metallic conductors or semiconductors. Transistors based on CNTs can function exceptionally well, with low power consumption, great carrier mobility, and high on-off current ratios. These transistors could be used in upcoming electronic device generations. Because of their good thermal characteristics, tiny diameter, and high electrical conductivity, CNTs are a desirable option for interconnects in integrated circuits [87]. They could be able to get beyond some of the drawbacks and difficulties that come with using conventional copper interconnects, like resistivity and heat dissipation. The possibility of using CNTs in quantum computing systems has been investigated. They are intriguing candidates for quantum electronic applications because of their electrical characteristics, nanoscale size, and quantum confinement effects [88].

CNDs have found a wide range of applications in the field of electronics due to their unique properties. They are used in batteries due to their strong adsorption capacity, chemical stability, and high mechanical strength. Their use in metal plating is facilitated by their easy modification and high mechanical strength. In chromatography and proteomics, NDs are used due to their strong adsorption capacity [89]. They are also used in magnetic resonance imaging and mass spectroscopy due to their exceptional optical properties. Nanodiamonds are used in the manufacturing of capacitors and as components in nanoscale electronic devices. Their high mechanical strength and easy modification make them suitable for these applications. They are also used in the production of surgical implants, lubricants, nanocomposites, nanocoatings, and nanosensors. These applications leverage the unique properties of NDs, including their strong adsorption capacity, chemical stability, high mechanical strength, and easy modification [90].

5.2 Environmental

Graphene, a 2D carbon crystal, has shown great promise for environmental applications. It has been used as a membrane material for detoxicating and purifying water, as well as an active material for CO_2 conversion, gas sensing, and heavy metal ion detection. Graphene and CNT hybrid materials in particular have been used for pollution treatment, monitoring, and detection. These 3D network materials offer more surface area, better thermal and electrical conductivity, porosity, reduced agglomeration, and stronger mechanical strength when compared to their component building blocks [83]. The highly interconnected structures and porosity of these hybrid materials enable effective mass transfer, a readily accessible internal surface area, etc. These remarkable properties, in addition to the materials hydrophobicity, robustness, and conductivity, provide a wide range of options for the detection and elimination of various pollutants. Materials based on graphene have also been used for photocatalytic pollution adsorption and detection. For instance, hybrid systems can detect pollutants at levels of 0.3 μmol Cu^{2+} per L, 5 nM Hg^{2+}, and 0.1 nM Pb^{2+} and respond more quickly [91]. Materials based on graphene have an adsorption range of 1–827 $mg\cdot g^{-1}$ for organic contaminants and 21–117.5 $mg\cdot g^{-1}$ for metal ions. GO-based photocatalytic devices can degrade dyes more than 95% of the time. In conclusion, graphene is a potential material for environmental applications because of its special qualities. Its use in water purification, gas sensing, heavy metal ions detection, CO_2 conversion, and pollutant adsorption highlights its potential to mitigate environmental pollution [82].

Fullerenes, especially C60 (buckminsterfullerene) and its derivatives, have shown promise in various environmental applications due to their unique properties. These applications aim to address environmental challenges and improve sustainability. Fullerenes can be used in water treatment processes to remove contaminants and improve water quality. They have a high surface area and can adsorb a wide range of organic and inorganic pollutants [92]. Functionalized fullerenes can be designed to target specific contaminants, making them useful in the removal of heavy metals, organic pollutants, and even certain pathogens from water sources. Fullerenes can aid in the remediation of contaminated sites, including soil and groundwater. When used as part of nano remediation strategies, fullerenes can enhance the removal of pollutants such as chlorinated solvents, heavy metals, and polycyclic aromatic hydrocarbons. They can serve as catalysts for chemical reactions that break down or transform contaminants into less toxic forms. Fullerenes can be used in air purification technologies to capture and neutralize airborne pollutants [83]. They can act as adsorbents for gases and volatile organic compounds that contribute to air pollution. Incorporating fullerenes into air filtration systems can help improve indoor air quality and reduce emissions of harmful substances. Fullerenes, particularly metallofullerenes, have been explored as catalysts for various environmental reactions. They can facilitate reactions that break down pollutants and convert them into less harmful substances. These catalytic properties can be harnessed for applications such as exhaust gas treatment in automobiles and industrial processes [93]. Fullerenes have been used in OPV cells, contributing to the development of renewable energy sources. Organic solar cells containing fullerenes can convert sunlight into electricity and offer a more sustainable alternative to traditional photovoltaic technologies. Fullerenes and fullerene-based materials have been studied for their potential in carbon capture and storage, a key strategy to mitigate greenhouse gas emissions. They can adsorb CO_2 and other greenhouse gases, helping to reduce their release into the atmosphere. Fullerenes are used in environmental sensors and monitoring devices. Their properties allow them to detect and respond to specific environmental changes or the presence of certain pollutants. This can aid in environmental monitoring, early pollution detection, and data collection for better environmental management [18].

With their stronger chemical and physical interactions, quick equilibrium, high sorbent capacity, and customized surface chemistry, CNTs were thought to be a better material than traditional sorbents like clay, zeolite, and activated carbon for the remediation of a wide range of organic and inorganic contaminants. To eliminate impurities and toxins from water, CNTs can be employed in the treatment process. Heavy metals, chemical molecules, and certain pathogens can be effectively captured by them due to their high surface area and adsorption capabilities. Systems based on CNTs have the potential to offer economical and effective water-filtering solutions [87]. Through their ability to absorb contaminants and improve the removal of organic debris and harmful substances, CNTs can aid in the treatment of wastewater. When combined with other materials, they can result in more effective treatment procedures. Applications for cleaning up oil spills have been investigated with CNTs. Because CNTs are hydrophobic, they can collect and absorb oil from water surfaces. They can lessen the negative effects of oil spills on the environment and are reusable. To improve the mechanical, thermal, and electrical qualities of materials used in a variety of environmental applications, such as strong and lightweight building materials, coatings that absorb pollutants, and long-lasting filtering systems, CNTs are added to nanocomposite materials [86].

There are numerous uses for CNDs in the environmental field. Because of their special optical characteristics, they are utilized in photovoltaic devices such as dye-sensitive solar cells. They are perfect for use in energy storage devices because of their large surface area and lack of toxicity. In addition, sensors for the detection of polluting chemicals are developed using NDs. They are very selective and sensitive in sensing applications because of their large surface area and adaptable surface structure [90]. In addition, NDs can withstand combustion when heated in air to a temperature of up to 450°C and can be heated in a vacuum to a temperature of about 800°C without experiencing significant graphitization. They can therefore be used in challenging environmental settings. Furthermore, a wide range of industries, including aerospace, batteries, the chemical industry, fuel cells, optics, power generation, space exploration, solar hydrogen, sensors, and thermoelectric devices, use NDs. They are ideal for various applications because of their special qualities, which include innate biocompatibility, stable photoluminescence, high thermal conductivity, and adaptable surfaces [94].

5.3 Biomedical applications

The 2D carbon crystal known as graphene has demonstrated remarkable promise in the field of biomedicine. Because of its special qualities, it has the potential to revolutionize biomedical applications, including more precise drug delivery, enhanced brain penetration, do-it-yourself health testing kits, and “smart” implants. Drug delivery is one of the most important uses of graphene in biomedicine. These 2D materials have tuneable lateral dimensions between nanometres and millimetres, a tuneable thickness ranging from one to hundreds of monolayers, and modifiable flexural rigidity [95]. It is simple to functionalize the flat surface, which allows for surface property alteration (from hydrophobicity to hydrophilicity). This is unparalleled in the realm of nanomaterials, presenting immense design potential as a medium for medication administration and incredibly sensitive biosensors. There are many uses for graphene in biomedicine, which can be broadly categorized into four categories: biological agents (such as antimicrobials), sensors, tissue engineering, and transport (distribution) systems. Researchers at the University of Manchester are looking at the many possibilities and encouraging qualities of graphene and 2D materials to create ground-breaking and inventive medical gadgets that may enhance health [96].

The special qualities of fullerenes, especially C60 (buckminsterfullerene), and its derivatives, such as their high surface area and ability for functionalization, have made them promising for use in a variety of biomedical applications. In the realm of drug delivery, fullerenes can be employed as drug carriers. Drug compounds can be encapsulated by functionalized fullerenes in their cage-like structure. This not only keeps the medication from degrading but also makes it possible to distribute the medication specifically to the right cells or tissues. Drugs that are poorly soluble in water can have their solubility and bioavailability increased by fullerenes. Because of their potent antioxidant qualities, fullerenes can scavenge dangerous free radicals and shield cells from oxidative damage. Because of this, they may be useful as cytoprotective agents in the treatment of a variety of illnesses, including neurological diseases, as well as in the development of antioxidant therapies. Tissue engineering scaffolds can benefit from the addition of fullerenes and their derivatives to promote tissue regeneration and repair. They might encourage the development of cells and give tissue constructions mechanical support [97]. Fullerenes can be used in diagnostic applications to identify certain diseases or chemicals using biosensors and tests. They may aid in the creation of diagnostic exams that are more accurate and focused. Thus, among other applications, fullerenes demonstrate their promise in tissue engineering, medication administration, therapy, and diagnostics [98].

Numerous sectors and businesses, such as electronics, manufacturing, nanotechnology, healthcare, and construction, use CNTs in their operations. A few applications that should be highlighted are high-strength composites, actuators, energy storage and conversion devices, sensors and nanoprobes, hydrogen storage medium, electrical devices, and catalysis. However, the sections that follow go into great detail regarding the existing applications of CNTs in the biomedical industry [99]. Before CNTs are employed in biological and biomedical contexts, three issues must be resolved: the toxicity, pharmacology, and functionalization of CNTs. The intractable characteristic of CNTs in aqueous solutions is one of their main disadvantages. To solve this problem, scientists have been modifying the surface of CNTs by imbuing them with different hydrophilic compounds and chemistries, which improves their water solubility and biocompatibility. Another problem with CNTs is their biodistribution and pharmacokinetics, which are affected by a variety of physicochemical characteristics like as size, shape, chemical composition, aggregation, solubility surface, and fictionalization. Studies have demonstrated that water-soluble CNTs are biocompatible with biological fluids and do not show any toxicity or mortality [100]. Another major barrier is the toxicity of CNTs. In general, the combination of the high surface area and inherent toxicity of the surface is responsible for the detrimental effects of nanoparticles. The toxicity of CNTs may vary depending on their size. It is well recognized that particles smaller than 100 nm can be highly harmful to the lungs, resistant to typical phagocytic defences, modify the structure of proteins, trigger immunological and inflammatory reactions, and even move from the site of deposition [101].

Because of their special qualities, CNDs have several uses in the biomedical industry. Biologically active compounds, biomarkers, biosensors, high-efficiency adsorbents, and coatings for surgical instruments are all carried by them. In addition, they are added to dental materials, sunscreen creams, and cosmetic formulations [102]. Nanodiamonds have been investigated in bioimaging and super-resolution imaging research because of their distinct optical and spectroscopic characteristics. Preclinical investigations on the pharmacokinetics and biodistribution of therapeutic cells have been conducted with NDs. Because NDs are invariant to the local chemical environment, they have also been investigated as a potential nanothermometer for the study of nanoscale chemical reactions. Furthermore, because of their distinct chemical and physical characteristics, NDs hold considerable promise for the identification and management of neurological disorders. Their application in nano-enzymes and antiaging is also being investigated. Last but not least, a novel approach that uses NDs to eradicate aging cells is being explored for the possible diagnosis and therapy of neurological disorders [103].

5.4 Energy storage

The 2D carbon crystal known as graphene has demonstrated remarkable promise for use in energy storage applications. It is perfect for use in a variety of energy storage systems because of its special qualities, which include excellent mechanical stability, electrical and thermal conductivity, and absorption of solar radiation. Rechargeable batteries represent one of graphene's most important uses in energy storage. For this use, graphene is highly desired due to its large energy capacity and charge rate [91]. The remarkable impact of graphene in the energy field can be attributed to its thermal characteristics, better electrical conductivity, and huge theoretical specific surface area of approximately 2,600 $m^2 \cdot g^{-1}$. While electrical conductivity is crucial for electronics and electrical applications, same qualities are advantageous for heat transfer applications. Supercapacitors provide yet another significant graphene use [81]. Compared to activated carbon, which is the material currently utilized in supercapacitors, graphene has larger surface area, higher conductivity, open porosity, and electrochemical stability, making it an ideal material for this use. Because of its high mechanical flexibility, electrical and thermal conductivity, and fuel cell and lithium-ion battery applications, graphene has also been utilized in fuel cells and dye-sensitized solar cells. Graphene's architecture enables it to be strengthened and made easier to use in the energy sector. In conclusion, graphene is a potential material for energy storage applications because of its special qualities. Its potential to enhance energy storage methods is demonstrated by its application in fuel cells, lithium-ion batteries, supercapacitors, rechargeable batteries, and dye-sensitized solar cells [83].

Fullerenes, particularly C60 (buckminsterfullerene) and its derivatives, have shown promise in various energy storage applications due to their unique properties. Fullerenes have been researched for their potential use in batteries. They can serve as materials in the electrodes or electrolytes, contributing to the development of better-performing batteries [96]. Their high theoretical capacity for lithium-ion batteries and good electrical conductivity make them attractive candidates. Fullerenes have been investigated in supercapacitors due to their ability to store charge at the electrode–electrolyte interface. These devices have the advantage of faster charging and discharging compared to traditional batteries. Fullerenes, especially their derivatives, have high surface areas that can enhance the storage of electrical charge [20]. Hydrogen is seen as a potential clean energy carrier, and fullerenes have been studied for their capacity to adsorb hydrogen molecules. These molecules can be stored within the fullerene structure, offering a potential solution for hydrogen storage and release. Fullerenes are used in OPV cells as electron acceptors. When exposed to sunlight, these cells generate electricity by converting light into electrical energy. Fullerenes' properties, such as high electron mobility and good electron acceptor capabilities, have made them valuable in improving the efficiency of solar cells. Fullerenes have been explored in fuel cells due to their electrocatalytic activity, aiding in the oxygen reduction reaction or other reactions within the fuel cell. They can potentially enhance the efficiency and performance of fuel cells [91].

Because of their special qualities, CNTs have found extensive applications in energy storage devices. Depending on their structural and morphological requirements, they can be utilized as an active anode component or as an addition to increasing the electronic conductivity of cathode materials. CNTs have been employed directly as fuel cells and supercapacitors' electrode materials. When CNTs are added to other materials, their open structure and enhanced chirality allow for enhancements in their performances and attributes. CNTs have the potential to have a major impact on the electrochemical performances and storage mechanisms of energy storage and conversion devices [86]. CNTs have remarkable tensile strength and flexibility, ultrahigh surface area, good thermal and electrical conductivity, and promising electrochemical performance, rendering them suitable for a multitude of energy storage applications. CNTs have been specifically used in rechargeable batteries and electrochemical capacitors, which are acknowledged as the main power sources for applications ranging from electric vehicles to portable electronic devices [18]. Power sources must support high degrees of deformation and stretchability in addition to high energy and power density, lightweight, size miniaturization, safety certification, and other important features to power the developing flexible and stretchable electronics. The study of CNTs macro-films with large-scale ordered nanostructures of the required form and shape as well as special and improved qualities has attracted increasing attention lately. To create larger-scale energy storage devices, these CNTs macro-films are essential and stable [104].

CNDs have found a wide range of applications in the field of energy storage due to their unique properties. They are used in batteries due to their strong adsorption capacity, chemical stability, and high mechanical strength. Their easy modification and high mechanical strength facilitate their use in metal plating. In chromatography and proteomics, NDs are used due to their strong adsorption capacity [93]. They are also used in magnetic resonance imaging and mass spectroscopy due to their exceptional optical properties. NDs are used in the manufacturing of capacitors and as components in nanoscale electronic devices. Their high mechanical strength and easy modification make them suitable for these applications. They are also used in the production of surgical implants, lubricants, nanocomposites, nanocoatings, and nanosensors. These applications leverage the unique properties of NDs, including their strong adsorption capacity, chemical stability, high mechanical strength, and easy modification [105] (Table 4).

6 Degradation

6.1 Chemical processes

Graphene can be broken down chemically in several ways. The most popular technique for synthesizing graphene is the chemical process of oxidizing and reducing graphite. On chemically produced graphene, however, the high concentration of oxygen functionalities may cause a reduction in electrical conductivity [54]. This results from intricate chemical and oxidative reactions that destroy the basal plane. Another technique for graphene breakdown is electrochemical synthesis. This method can exfoliate graphene and manipulate its properties, including thickness, flake area, and number of flaws, by adjusting a pulsed voltage. First, the graphite is dipped into an intercalation solvent [112]. By using an light emitting devices and photodiode to measure the transparency of the solution, one may track the process [113].

The chemical degradation of fullerenes, such as C60 (buckminsterfullerene) and its derivatives, can occur through various processes, often resulting in the alteration of the fullerene structure or the formation of byproducts. Fullerenes are susceptible to oxidation, particularly in the presence of strong oxidizing agents such as ozone, oxygen, or other ROS. This process can result in the addition of oxygen atoms to the fullerene structure, leading to the formation of fullerene oxides [114]. Oxidation alters the properties of fullerenes and can affect their stability and reactivity. Fullerenes can undergo hydrolysis in the presence of strong acids or bases. This chemical reaction involves the cleavage of chemical bonds due to the interaction with acidic or basic substances, resulting in the degradation of the fullerene structure. Photodegradation: Exposure to high-energy radiation, particularly ultraviolet light, can induce photodegradation of fullerenes. The high-energy photons can break the chemical bonds in the fullerene structure, leading to the formation of smaller carbon-based compounds or byproducts [115].

Chemical degradation of CNTs involves the use of various chemical reactions to break down the structure of CNTs. This process can involve the use of acids, which can cause substantial destruction on the surface of the CNTs or even induce unrolling [116]. The incorporation of defects in their tube-shaped structure can negatively influence their physicochemical characteristics. However, it is important to note that while chemical degradation can effectively break down CNTs, it can also negatively impact their unique properties. Therefore, careful control of the degradation process is necessary to ensure that the desirable properties of CNTs are preserved while unwanted components are effectively removed [117]. In addition to chemical degradation, biodegradation methods of CNTs by microbes and enzymes have also been explored. These methods can be more environmentally friendly and potentially less damaging to the structure of the CNTs [117].

A chemical reaggregation technique can be used to break down CNDs. This procedure consists of two steps that are air oxidation and boiling acid treatment. The NDs undergo oxidation in the first stage when they are

Table 4: Market availability of the carbon nanomaterial-based products and their applications, limitations, and characterization techniques

Product	Type	Applications	Limitations	Characterization techniques	References
GO sheets	Graphene derivative	Electronics, energy storage, sensors	High production cost, scalability issues	Raman spectroscopy, TEM, AFM, XRD	[106]
C60 fullerene	Fullerene	OPVs, OLEDs, drug delivery	Low solubility, stability issues	NMR, mass spectrometry, UV-Vis spectroscopy	[107]
MWCNTs	CNTs	Composite materials, electronics, biomedical	Toxicity concerns, dispersion issues	SEM, TEM, Raman spectroscopy, TGA	[107]
SWCNTs	CNTs	Sensors, energy storage, drug delivery	High production cost, toxicity concerns	SEM, TEM, Raman spectroscopy, TGA	[108]
Graphene quantum dots	Graphene derivative	Bioimaging, sensors, drug delivery	Limited quantum yield, stability issues	Fluorescence spectroscopy, TEM, AFM	[108]
Carbon nanofibres	Carbon nanofibres	Composite materials, energy storage	High production cost, scalability issues	SEM, TEM, XRD, Raman spectroscopy	[109]
Nanodiamond powder	Nanodiamonds	Drug delivery, biomedical imaging, lubricants	High production cost, limited functionalization	XPS, TEM, FTIR, DLS	[25]
Carbon black	Amorphous carbon	Rubber reinforcement, pigments, conductive fillers	Environmental concerns, health risks	SEM, TEM, XRD, BET surface area analysis	[25]
Carbon nanohorns	CNTs	Drug delivery, energy storage, catalysis	High production cost, limited functionalization	SEM, TEM, Raman spectroscopy, XRD	[30]
Graphene nanoplatelets	Graphene derivative	Composite materials, energy storage	Scalability issues, high production cost	Raman spectroscopy, TEM, AFM, XRD	[30]
Carbon aerogels	Amorphous carbon	Insulation, energy storage, catalysis	Fragility, high production cost	SEM, TEM, BET surface area analysis	[110]
CNT yarn	CNTs	Textiles, conductive wires, sensors	High production cost, scalability issues	SEM, TEM, Raman spectroscopy, TGA	[110]
Carbon quantum dots	Carbon quantum dots	Bioimaging, photovoltaics, sensors	Low quantum yield, stability issues	Fluorescence spectroscopy, TEM, AFM	[110]
CNT films	CNTs	Transparent conductors, flexible electronics	High production cost, scalability issues	SEM, TEM, Raman spectroscopy, XRD	[111]
CNT composites	CNTs	Structural materials, conductive composites	Dispersion issues, high production cost	SEM, TEM, Raman spectroscopy, TGA	[111]

exposed to air [118]. The aggregated NDs are broken down by this procedure, which also gets them ready for the following stage. A treatment with boiling acid is the second stage. The NDs are further broken down by this process, leaving very stable single-digit NDs in a solution. This chemical disaggregation procedure is straightforward and simple enough to be performed with readily accessible laboratory equipment in a typical chemistry lab [119]. It is a crucial stage in a lot of ND-based applications, from biological or medical to materials research [120].

6.2 Physical processes

The characteristics of graphene may deteriorate as a result of delamination and lamination, two important steps in the graphene transfer process. Problems that emerge at each level may cause the characteristics of graphene to deteriorate. Thermal treatment is another physical method that can break down graphene [104]. Upon thermal treatment at elevated temperatures, graphene experiences a structural transformation characterized by the abrupt removal of oxygen functions. The abrupt increase in temperature shocks graphene's functions, causing oxygen-containing groups to vanish as CO_2, H_2O, and water vapour. Another physical mechanism that can break down graphene is mechanical deterioration. For example, graphene may mechanically degrade due to epoxidation. The C–O–C bond is formed during this process, which is typical of oxidation. According to research, epoxidation can decrease graphene's Young's modulus by a factor of 20%, 23%, and 27% for C_6O_1, C_6O_2, and C_6O_3, respectively [30]. This suggests that epoxidation degrades monotonically.

The physical degradation of fullerenes, particularly C60 (buckminsterfullerene) and its derivatives, can occur through various physical processes that do not involve chemical reactions but result in changes to the fullerene structure. Fullerenes can undergo thermal degradation at elevated temperatures. This process involves the breaking of chemical bonds within the fullerene structure due to the increased thermal energy [111]. The exact temperature at which thermal degradation occurs can vary depending on the specific fullerene and its environment. Exposure to ionizing radiation, such as X-rays or gamma rays, can induce physical damage to fullerenes. High-energy radiation can lead to bond cleavage and the formation of defects within the fullerene molecules [121]. Fullerenes can be physically damaged through mechanical processes, such as grinding, milling, or high-energy ball milling. These processes can result in the deformation, fragmentation, or disintegration of fullerene particles, altering their physical properties. Ultrasonication involves subjecting fullerenes to high-intensity ultrasonic waves, leading to cavitation and mechanical forces that can cause physical changes in the structure of fullerenes. This can result in the breaking of chemical bonds and changes in the fullerene morphology [122].

Mechanical stress, heat treatment, radiation, and ultrasonication are a few examples of this. The tubes will experience plastic deformation at extreme tensile strain, which indicates that the distortion is irreversible. By releasing strain energy, this deformation, which starts at strains of about 5%, can raise the maximum strain the tubes experience before breaking [117]. The nanotubes irreversibly lose their elasticity when they undergo plastic deformation, a phenomenon brought on by severe stress [119]. CNT deterioration can also result from thermal treatment. The carbon atoms in the nanotubes may reorganize and form new structures when heated to high temperatures. This can lead to changes in the physical and chemical properties of the CNTs. Irradiation, such as with high-energy particles or electromagnetic radiation, can also cause physical degradation of CNTs. The energy from the radiation can break the bonds between the carbon atoms in the nanotubes, leading to structural changes. Ultrasonication is another method used for the physical degradation of CNTs. The high-frequency sound waves can cause the nanotubes to vibrate and break apart [123].

The degradation of CNDs can be achieved through physical processes, such as high-power sonication or bead milling. These techniques primarily rely on mechanical forces. However, these methods have certain drawbacks, such as the potential for contamination of the sample and the requirement for specialized apparatus. In the case of bead milling, the NDs are placed in a milling chamber with small beads [118]. The chamber is then shaken at high speeds, causing the beads to collide with the NDs and break them apart. High-power sonication, on the other hand, uses sound waves to create pressure changes in a liquid or slurry where the NDs are suspended. These pressure changes generate tiny bubbles that implode, producing intense local heat and pressure. This process, known as cavitation, can break apart the ND aggregates [119].

6.3 Biological

The biological degradation of graphene involves the use of various biological entities such as enzymes, microbes, and even certain species of fish. This process can involve the use of enzymes like myeloperoxidase (MPO), which have been shown to degrade GO [124]. Primary human neutrophils are capable of degrading GO when activated to undergo degranulation with the release of myeloperoxide. In addition to enzymatic degradation, microbial degradation of graphene has also been explored. Certain species of bacteria, such as *Shewanella* and *Geobacter*, are known to produce graphene through the biological reduction of GO [125]. Furthermore, certain species of fish have been shown to degrade GO in their gastrointestinal tract. This degradation was found to be nitric oxide dependent and was confirmed *in vitro* by combining a superoxide-generating system with an nitric oxide donor [126]. Graphene and its derivatives, such as GO and reduced GO, interact with biological entities through various mechanisms. Recent studies have shown that graphene can adsorb proteins, enzymes, and other biomolecules due to its large surface area and π–π interactions [95]. For instance, a study by Sanchez et al. demonstrated that GO exhibits preferential adsorption of single-stranded over double-stranded DNA, which can be utilized in biosensing applications. In addition, graphene's interaction with lipid bilayers can lead to membrane disruption, which has implications for its cytotoxicity and antimicrobial properties. Another study highlighted that graphene-based materials can activate immune cells, such as neutrophils, leading to the production of ROS and inflammatory responses [92].

The biological degradation of fullerenes involves the use of various biological entities such as enzymes and microbes. Enzymes like MPO have been shown to degrade fullerene derivatives. Primary human neutrophils are capable of degrading fullerene derivatives when activated to undergo degranulation with the release of myeloperoxide. Microbial degradation of fullerenes has also been explored [121]. Certain species of bacteria, such as *Shewanella* and *Geobacter*, are known to produce graphene through the biological reduction of GO. Moreover, nanoparticles including fullerene-60 and other pretreatments like UV treatment, prooxidants, and photocatalysis are promising techniques for combining with bacteria to increase biodegradation results [121]. Fullerenes, particularly C60, interact with biological systems through their ability to generate ROS and their radical-scavenging properties. A recent review by Siringan et al. highlighted that fullerenes can be functionalized to improve their solubility and biocompatibility, enabling their use in drug delivery and photodynamic therapy. Fullerenes can interact with enzymes and proteins, affecting their activity. For example, fullerenes have been shown to inhibit the activity of acetylcholinesterase, an enzyme crucial for neurotransmission. In addition, fullerenes can penetrate microbial cell walls, leading to oxidative stress and cell death, making them effective antimicrobial agents [44].

Biological degradation of CNTs involves the use of various biological entities such as enzymes and microbes. Enzymes like MPO have been shown to degrade CNTs. Primary human neutrophils are capable of degrading CNTs when activated to undergo degranulation with the release of myeloperoxide [117]. Microbial degradation of CNTs has also been explored. Certain species of bacteria, such as Shewanella and Geobacter, are known to produce graphene through the biological reduction of GO. Many studies have shown that macrophages can biodegrade CNTs through enzymatic oxidation [121]. Moreover, nanoparticles including fullerene-60 and other pretreatments like ultraviolet light treatment, prooxidants, and photocatalysis are promising techniques for combining with bacteria to increase biodegradation results [127]. CNTs interact with biological entities through their high surface area and ability to penetrate cell membranes. A study by Murjani et al. discussed how functionalized CNTs can be used for targeted drug delivery, where they interact with specific cell receptors to deliver therapeutic agents directly to diseased cells. CNTs can also interact with enzymes, affecting their activity [73]. For instance, CNTs have been shown to enhance the activity of horseradish peroxidase, an enzyme used in biosensing applications. However, the interaction of CNTs with immune cells can lead to inflammatory responses and cytotoxicity, which are critical considerations for their biomedical applications [76].

The degradation of CNDs using biological processes is not well documented in the literature. However, it is important to note that NDs are generally considered to be biocompatible and stable, which means they do not readily degrade in biological environments [120]. Their stability and biocompatibility are some of the reasons why NDs are being explored for various biomedical applications, such as cell labelling, imaging, and sensing. Moreover, the surface of NDs can be modified with various functional groups, which can interact with biological molecules and systems. This allows NDs to be used in a controlled manner in biological environments without causing harmful effects [121]. CNDs exhibit unique interactions with biological entities due to their surface chemistry and biocompatibility. Recent studies have shown that CNDs can be functionalized to enhance their interaction with proteins and enzymes. For example, a study by Alexander and Leong demonstrated that functionalized NDs can be used for targeted drug delivery, where they interact with specific cellular receptors to deliver therapeutic agents [76]. CNDs can also interact with microbial cells, leading to membrane disruption and cell death, making them effective antimicrobial agents. In addition, CNDs have been shown to interact with immune cells, such as neutrophils, without inducing significant inflammatory responses, highlighting their potential for safe biomedical applications [63].

7 Toxicity

7.1 Environment

With its sp^2-bonded carbon atoms, graphene is a 2D nanomaterial with a broader range of uses in biomedical applications, drug transport, photothermal ablation of tumours, biosensors, and disease diagnostics. Nonetheless, there is a progressive rise in the unintentional or deliberate exposure of humans, plants, and ecosystems to graphene [42]. Consequently, despite graphene's many uses in a variety of industries, its toxicity has become a serious problem that needs to be addressed. Graphene's physiochemical properties are interconnected and govern its environmental fate, which in turn determines its toxicity, dimensions, form, boundaries, perforations, surface charge, π–π stacking of nanoholes, the ability to conduct Hydrophilicity: surface functionalization and hydrophobicity [49]. Because these 2D carbon nanomaterials leak particles into the air, water, and soil, they could pose harm to the environment. Furthermore, graphene family nanomaterials may experience subsequent environmental variables that alter their structure and physical and chemical properties, such as physical, chemical, and biotransformation [20].

The toxicity of fullerenes, particularly C60 (buckminsterfullerene) and its derivatives, in the environment, is a subject of research aimed at understanding the potential risks and impacts associated with these nanoparticles [63]. Research on the toxicity of fullerenes contributes to the development of environmental regulations and guidelines. It helps establish safe exposure levels and implement measures to prevent or reduce potential harm to ecosystems. The findings from toxicity studies can guide the disposal and management of materials containing fullerenes [75]. This includes recommendations for handling and treating waste materials to minimize environmental impact. Toxicity studies can inform the development of bioremediation and phytoremediation techniques that utilize microorganisms or plants to mitigate the presence of fullerenes in contaminated environments [83].

The scientific community has engaged in numerous discussions over CNTs because of possible toxicity-related concerns. Applications of CNTs in business, research, and laboratories are severely limited by the debatable facts regarding toxicity dosages, potential hazards, and human health issues [122]. Oxidative stress, inflammatory reactions, malignant transformation, DNA damage and mutation, granuloma formation, and interstitial fibrosis are some of the fundamental mechanisms behind CNT toxicity. Several toxicity mechanisms for CNTs have been proposed, including disruption or penetration of the cell envelope, oxidation of cell components, and production of secondary products like ROS or dissolved heavy metal ions [123]. A CNT sample's toxicity is determined by its composition, shape, and surface functionalization. Changes can be made to CNTs to make them resistant to biodegradation, more cellular absorption, reactive, and toxic to aquatic, terrestrial, and aerial plants and animals. Because CNTs and asbestos have similar pathological effects, public opinion may be negatively impacted, and there may be calls for a ban on CNTs [117].

Research on the environmental toxicity of CNDs is still underway. Large surface areas, variable surface topologies, remarkable mechanical and optical properties, and limited toxicity make NDs perfect for a wide range of applications. But as nanoparticles continue to advance in the realm of biomedicine, the toxicity of NDs has taken on more significance. Many screens have been conducted to generate ND's complete toxicological features. Cell death, the creation of oxidative stress, DNA damage, apoptosis, and the promotion of inflammatory responses are some of the harmful impacts of nanoparticles, which include CNTs and NDs [124]. It is crucial to remember that there is a wide range of reported toxicity for CNTs, ranging from $5\ \text{ng}\cdot\text{ml}^{-1}$ to $10\ \text{mg}\cdot\text{ml}^{-1}$, which is a difference of six orders of magnitude. This implies that the toxicity can change significantly based on the circumstances and concentration [125].

7.2 Microorganisms

It has been discovered that nanomaterials based on graphene contain cytotoxic qualities. Although the exact mechanism of their cytotoxicity is still unknown, the most well-established pathways for the toxicity of graphene-based nanomaterials in aquatic creatures are oxidative stress, cellular penetration, and inflammation. A*STAR researchers in Singapore have released a study on the potential effects of graphite, graphite oxide, GO, and decreased GO on bacteria (in this case, *Escherichia coli*) [49]. The scientists demonstrated that materials based on graphene kill a significantly higher number of bacteria than those based on graphite. GO was found to have mild toxicity to organisms in another study. At $50\ \text{mg}\cdot\text{L}^{-1}$, it was found to cause a modest delay in hatching and a minor (approximately 20%) suppression of cell development in zebrafish embryos. However, the embryo's rate of apoptosis did not significantly rise as a result [126].

Toxicity studies of fullerenes, such as C60 (buckminsterfullerene) and its derivatives, on microorganisms are important for understanding how these nanoparticles may affect various microbial species. Understanding the toxicity of fullerenes on microorganisms can inform the development of bioremediation strategies. Microbes can be harnessed to clean up contaminated environments, and knowledge of their sensitivity to fullerenes is important for effective bioremediation [70]. Microorganisms are used in wastewater treatment processes to break down organic matter and pollutants. Microorganisms are commonly used as model organisms in nanotoxicology research. Understanding how fullerenes interact with microorganisms can provide insights into broader principles of nanomaterial toxicity [79]. The toxicity of fullerenes on microorganisms is relevant for environmental protection, bioremediation, waste management, and various applications where microorganisms are involved. These studies help assess the potential risks and benefits of utilizing fullerenes in different contexts and contribute to the responsible development and use of nanomaterials [121].

Several variables, including diameter, length, residual catalyst, metal content, surface coating, electrical structure, and dispersibility, might affect how poisonous CNTs are to microorganisms. Oxidative stress, inflammatory reactions, malignant transformation, DNA damage and mutation, granuloma formation, and interstitial fibrosis are some of the fundamental mechanisms behind CNT toxicity. CNTs can oxidize cell components, damage or penetrate the cell envelope, stop transmembrane electron transmission, and produce secondary products such as ROS or dissolved heavy metal ions. Apoptosis or necrosis are two ways in which these actions might cause cell death [125].

Research on CND toxicity in microbes is still in progress. Large surface areas, variable surface topologies, remarkable mechanical and optical properties, and nontoxicity make NDs perfect for a wide range of applications. But as nanoparticles continue to advance in the realm of biomedicine, the toxicity of NDs has taken on more significance. To produce comprehensive toxicological features of NDs, a variety of tests have been conducted [127]. Nanoparticles, such as CNTs and NDs, can be harmful in that they can cause oxidative stress, DNA damage, apoptosis, and the stimulation of inflammatory responses in addition to killing cells. It is crucial to remember that there is a wide range of reported toxicity for CNTs, ranging from 5 $\text{ng}\cdot\text{ml}^{-1}$ to 10 $\text{mg}\cdot\text{ml}^{-1}$, which is a difference of six orders of magnitude. This implies that the toxicity can change significantly based on the circumstances and concentration [126].

7.3 Animals and human

It has been discovered that graphene, a 2D nanomaterial with sp^2-bonded carbon atoms, has cytotoxic qualities. Although the exact mechanism of their cytotoxicity is still unknown, the most well-established mechanisms for the toxicity of graphene-based nanomaterials in people and animals are oxidative stress, cellular penetration, and inflammation [126]. It has been discovered by researchers that the sharp and powerful jagged edges of graphene nanoparticles can readily break through the immune system, lungs, and skin cell membranes. This implies the possibility of causing significant harm to both people and other creatures. Numerous investigations have demonstrated that graphene materials generate dose-dependent toxicity in both animals and cells, resulting in apoptosis, decreased cell viability, liver and kidney damage, and lung granuloma development [127]. According to *in vivo* research, mice given low and intermediate dosages of GO (0.01 and 0.25 mg, respectively) did not reveal any toxicity from the substance, while larger doses did result in some damage. Researchers claim that graphene-based materials produce toxicity and limit cell viability through physical damage and the generation of active oxygen species, albeit the exact mechanism underlying graphene toxicity is still unknown. There is currently no solid evidence to support this theory [30].

Toxicity studies of fullerenes, such as C60 (buckminsterfullerene) and its derivatives, in animals and humans are essential for evaluating the potential risks and safety of these nanoparticles in various applications. Understanding the effects of fullerenes on animals and humans is crucial for assessing the potential environmental risks associated with their use [93]. Fullerenes have been explored for various biomedical applications, including drug delivery, imaging, and therapeutic agents. Fullerenes have been investigated for their potential use in food packaging and preservation. Fullerenes can serve as model nanoparticles in nanotoxicology research. Understanding their interactions with animals and humans can help elucidate general principles of nanomaterial toxicity and guide the safe use of various nanomaterials [43].

The scientific community has engaged in numerous discussions over CNTs because of possible toxicity-related concerns. Applications of CNTs in biological research, laboratory operations, and industry are severely limited by contentious evidence regarding toxicity dosages, potential hazard effects, and human health issues. Oxidative stress, inflammatory reactions, neoplastic transformation, DNA damage and mutation, granuloma formation, and interstitial fibrosis are among the fundamental mechanisms of CNT toxicity [64]. Several toxicity mechanisms for CNTs have been hypothesized, including disruption/penetration of the cell envelope, oxidation of cell components, and formation of secondary products including ROS or dissolved heavy metal ions [34]. A CNT sample's toxicity is determined by its composition, shape, and surface functionalization. Changes can be made to CNTs to make them resistant to biodegradation, more cellular absorption, reactive, and toxic to aquatic, terrestrial, and aerial plants and animals. Because CNTs and asbestos have similar pathological effects, public opinion may be negatively impacted, and there may be calls for a ban on CNTs [32].

Human exposure to CNDs, a rapidly expanding class of materials with special physicochemical features, is rising along with their broad use. The formation of ROS [28], DNA damage, lysosomal damage, mitochondrial malfunction, and final cell death through apoptosis or necrosis were the primary cytotoxicity effects that were described. The immune effects of carbon-based nanoparticles, such as the activation of pulmonary macrophages and inflammation caused by carbon nanomaterials, have been well-researched despite their cellular toxicity [32]. It has also been discussed how carbon nanostructures can stimulate some immune cells or cause immunosuppression. The wider use of these materials is hampered by toxicity problems and health hazards, which need to be addressed responsibly. Because of their small size, low toxicity, and large surface area, carbon nanomaterials can effectively affect biological systems through hospitable environmental processes. Simultaneously, observation of microinjected early-stage embryos revealed that carboxylated nanodiamond–CO_2H may be teratogenic and potentially harmful to embryos. Nanodiamond appears to negatively impact the neurulation and gastrulation phases, resulting in phenotypic defects and elevated mortality [40].

8 Challenges and opportunities

Graphene, a single layer of carbon atoms arranged in a hexagonal lattice, has garnered significant attention due to its exceptional electrical, thermal, and mechanical properties. However, challenges such as large-scale production, defect control, and integration into existing technologies remain. Experimental results have shown that CVD can produce high-quality graphene [128], but scalability and cost-effectiveness are still hurdles. For instance, a study by Li et al. demonstrated that CVD-grown graphene on copper substrates could achieve a carrier mobility of up to 15,000 $cm^2 \cdot V^{-1} \cdot s^{-1}$, but the process required precise control of temperature and gas flow [96]. Opportunities lie in developing new synthesis methods, such as liquid-phase exfoliation, which could offer more efficient production. In addition, graphene's potential in flexible electronics, energy storage, and biomedical applications continues to drive research and innovation [129].

Fullerenes, spherical carbon molecules, exhibit unique properties like high electron affinity and photoconductivity, making them suitable for applications in photovoltaics and drug delivery. However, their practical use is limited by challenges in purification, functionalization, and stability. Experimental studies have demonstrated that functionalized fullerenes can enhance the efficiency of organic solar cells [130]. For example, a study by Brabec et al. showed that incorporating [6,6]-phenyl-C61-butyric acid methyl ester (PCBM) into polymer solar cells increased the power conversion efficiency to 3.5%. However, issues like aggregation and phase separation need to be addressed. Opportunities exist to improve functionalization techniques to enhance solubility and stability, which could expand their use in medical and electronic applications [131].

CNTs are cylindrical nanostructures with remarkable electrical conductivity, mechanical strength, and thermal stability. Despite their potential, challenges such as chirality control, dispersion, and toxicity hinder their widespread application. Experimental results have shown that techniques like ultrasonication and surfactant-assisted dispersion can improve CNT dispersion in various matrices [118]. For instance, a study by Islam et al. demonstrated that using sodium dodecyl sulphate (SDS) as a surfactant could achieve stable dispersions of SWCNTs in water [132]. Opportunities include developing scalable methods for chirality-specific synthesis and exploring CNTs' use in nanocomposites, sensors [133], and energy storage devices. Addressing toxicity concerns through biocompatible coatings could also pave the way for biomedical applications [134].

CNDs possess unique properties such as high hardness, chemical stability, and biocompatibility, making them attractive for applications in drug delivery, imaging, and coatings. However, challenges like surface functionalization, aggregation [135], and cost-effective production need to be overcome. Experimental studies have shown that surface modification techniques, such as hydrogenation and oxidation, can improve the dispersibility and functionality of CNDs [136,137]. For example, a study by Chang et al. (2022) demonstrated that oxidized NDs could be dispersed in water and used for drug delivery applications [24]. Opportunities lie in developing new functionalization methods to enhance their compatibility with biological systems and exploring their use in advanced coatings and composite materials [138].

9 Conclusions and future perspective

The objectives of discussing graphene, fullerenes, CNTs, and NDs were comprehensively met. Our investigation delved into the unique properties, potential applications, and inherent limitations of each of these advanced carbon-based materials. Through our analysis, we provided a clear understanding of the challenges associated with integrating these materials into existing technologies and emphasized the necessity for large-scale production techniques to fully harness their capabilities. This work underscores the distinctive attributes of each material, spotlighting graphene's unparalleled electron acceptor qualities and rapid electron mobility, which render it ideal for a multitude of electrical applications. In addition, we highlighted fullerenes, particularly C60, for their remarkable thermal stability despite their intrinsic heat conductivity limitations. The exceptional electrical and thermal properties of CNTs, along with their chemical stability and scalability to molecular dimensions, were also discussed. Finally, the unique mechanical, optical, and biological characteristics of NDs, produced via the detonation process, were examined. Our discussion sheds light on the ongoing research efforts aimed at overcoming the limitations of these materials and exploring novel applications, thus contributing new insights into their future potential. Our discussion aligns with the prevailing understanding and existing body of knowledge regarding these carbon nanomaterials. It corroborates previous findings related to their properties and challenges, while also emphasizing the critical need for further research to address the existing obstacles. By confirming the well-documented benefits and limitations of these materials, our work reinforces the foundation laid by earlier studies and builds upon it by identifying areas that require additional investigation. Looking ahead, future research should prioritize the development of scalable production methods and the seamless integration of these materials into practical devices. Addressing toxicity concerns is imperative to ensure their safe application across various fields. Furthermore, exploring emerging applications such as energy storage, nanoelectronics, and sensing technologies will be crucial in unlocking the full potential of these materials. By focusing on these areas, future studies can contribute to the advancement of carbon nanomaterials and their widespread adoption in cutting-edge technologies. In conclusion, while significant progress has been made in understanding and utilizing graphene, fullerenes, CNTs, and NDs, the journey toward fully exploiting their potential continues. Our work not only confirms existing knowledge but also provides a roadmap for future research, emphasizing the need for innovation in production techniques, practical integration, and exploration of new applications.

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