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Emerging Trends In Carbon Nanotube Research: Scalable Synthesis, Surface Engineering And Application-Oriented Developments.

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Abstract

Carbon nanotubes are one of the most investigated forms of carbon nanomaterials that have been attributed to their unique one-dimensional properties. Since CNTs emerged in the early 1990s, they have moved from being a laboratory curiosity to an essential part of state-of-the-art technology in a wide range of sectors such as electronics, energy storage materials, environmental applications, and biomedicine. CNTs are essentially sp^2-hybridized nanometer-scaled cylinders of pure carbon that have exceptionally high 'aspect ratios,' high strength, high electrical and thermal conductivities, as well as high specific surface area. The motive of this review article is to present a comprehensive literature review of CNTs by summarizing the latest literature from 2019 through 2024.

The literature review conceal some of the most important methodologies for synthesizing CNTs like Arc Discharge, Laser Ablation, as well as Chemical Vapor Deposition.

This focuses on developments in methods for purification, as well as covalent, non-covalent, dispersion, biocompatibility, and performance improvements. A detailed study is presented on characterization methods such as SEM, TEM, Raman spectroscopy, XRD, and FTIR.

The application of CNTs in drug delivery systems, tissue engineering, biosensing, electronics, energy storage, and environment remediation has been discussed.

On the other hand, the review considers the toxicity and related challenges associated with the use of CNTs.In summary, the paper introduces the current challenges and the future trends in the study. It always stresses the need for sustainable methods, standard safety testing, and the design according to each application.

Introduction

Carbon nanotubes (CNTs), as one of the most prominent nanomaterials in today's nanoscience world, find themselves positioned as an intermixture between the basic chemistry of carbon and its many technological applications. With their unique status as quasi-one-dimensional cylindrical materials based on sp^2-hybridized carbons, they occupy a special position within the broader group of nanomaterials based on carbon, which also includes fullerenes, graphene, and carbon quantum dots. Over the past three decades, they have assumed an extremely important position in such fields as nanotechnology and nanoelectronics, energy, and nanobiotechnology. [1][2]

Historically, the foundational structures of CNTs draw roots from early studies of graphite and carbon fibers. The crystal structure of graphite was elucidated in the 1920s and, in the 1950s, Radushkevich and Lukyanovich reported hollow carbon filaments of nanometrical diameters, followed by the similar work of Oberlin et al. in the 1970s [5, 6]. The field saw significant expansion following the 1991 report by Iijima, which used TEM to highlight multi-walled carbon nanotubes produced via arc discharge; this was shortly succeeded by independent discoveries of SWCNTs by Iijima, Bethune, and others [4, 7]. Since then, CNTs have been recognized as archetypal one-dimensional nanostructures and building blocks of various nanotechnological applications [3, 11].

The specific characteristics of carbon nanotubes (CNTs), as viewed from materials science, relate to having an extremely high aspect ratio, low density, high specific surface area, and their remarkable mechanical, electrical, and thermal properties. The sp^2 bonds between the C atoms in CNTs offer these nanotubes high tensile strength and values for the Young's modulus that can compete with and even exceed the steel's, and even approach that of diamond's, while being extremely elastic and flexible in nature as well [4][5]. The delocalized π-electron system in these nanotubes can display either metallic or semiconductor characteristics depending on the chirality, and they also offer high carrier mobility and electrical conductivity, which finds use in designing transistors and sensitive sensors as well as various interconnects in microelectronic devices [10][11]. Moreover, their high value of axial thermal conductivity and chemical inertness make them suitable for use in applications like thermal and catalysis applications as well as energy storage devices and other related uses as well [7][12].

At the same time, carbon nanotubes (CNTs) have shown considerable importance in the area of biomedicine. The tube-like structure along with the outer surface of CNTs renders them particularly efficient in carrying drugs, genetic materials, and imaging molecules; in fact, functionalization of CNTs significantly improves their water solubility, biocompatibility, and specificity [1,3]. CNT-based systems have been explored as promising candidates in cancer drug delivery, photothermal therapy, gene therapy, bio-sensing, and tissue repair, which includes electric conductively supportive matrices and hydrogels in wound care applications in medicine [13,17]. However, because of the strong aspect ratio, fiber morphology, and inertness of CNTs, issues have arisen concerning their toxicity, inflammation, and safe use in health care; in fact, functionalizations, green protocols, and regulatory norms have been explored in-depth in recent scientific literature [18,19].

Within the last five years, there has been significant advancement in the area of basic as well as application-oriented research on carbon nanotubes (CNTs). The current literature surveys the advancements that have taken place on scalable routes for CNT synthesis, with a special emphasis on chemical vapor deposition, sustainable precursors, CNT purifications, assembly, multifunctional CNT-based composites, as well as diverse applications that encompass super-capacitor, battery, catalysis, environment, biosensing, smart drug delivery, and so forth [10,20]. On the other hand, with increasing concern for green CNTs derived from biomass, the search for green CNTs for environment-friendly applications has gained prominence [14].

In view of the above context, carbon nanotubes (CNTs) can be considered a relatively established but constantly evolving platform technology. The journey of CNTs from a lab phenomenon to a usable element in energy applications, sensors, paint, and research drugs is a reflection of the complexities surrounding the utilization of CNTs, as well as their true potential based on their applications in engineering carbon at the nanoscale [3][7]. This review of CNTs will seek to place their current position within their realm of applications with the aim of providing the reader with a perspective of their past and present significance in the field of nanomaterials research and the significance of giving CNTs their current prominence with regard to synthesis, functionalization, and their current safety considerations.

Figure 1:*Conceptual illustrations of carbon nanotubes and their functionalized forms, prepared by the author for explanatory purposes.*

1.1 Background and discovery of carbon nanotubes

In view of the above context, carbon nanotubes (CNTs) can be considered a relatively established but constantly evolving platform technology. The journey of CNTs from a lab phenomenon to a usable element in energy applications, sensors, paint, and research drugs is a reflection of the complexities surrounding the utilization of CNTs, as well as their true potential based on their applications in engineering carbon at the nanoscale [3][7]. This review of CNTs will seek to place their current position within their realm of applications with the aim of providing the reader with a perspective of their past and present significance in the field of nanomaterials research and the significance of giving CNTs their current prominence with regard to synthesis, functionalization, and their current safety considerations.

1.2 Importance of carbon nanotubes in modern science

The carbon nanotube (CNT) has a very high aspect ratio, high mechanical stiffness and strength, excellent electrical and thermal conductivity properties, a large specific surface area, and tunable surface chemistry properties. Aforementioned properties make CNTs crucial materials with a wide range of applications not only in electronic devices and energy storage materials but also in water treatment and biomedicine applications [21][23]. More recent reviews mention that CNTs are base materials used for many innovative technologies such as flexible batteries and hydrogen storage materials, water treatment materials, and biomedicine applications [24][25].

1.3 Scope and objectives of the review

More recent assessments have examined CNTs separately concerning synthesis, properties, biomedical compatibility, environmental uses, and toxicities in turn ([26], [27]). The manuscript will highlight briefly all mentioned aspects: (i) classification, structure, and methods of current synthesis, (ii) physiochemical properties, biologic properties, (iii) uses in biomedicine, electronics, energy, environmental fields, (iv) toxicities, and finally development strategies, mainly based upon literature published between 2019 and 2024.

Classification of carbon nanotubes.

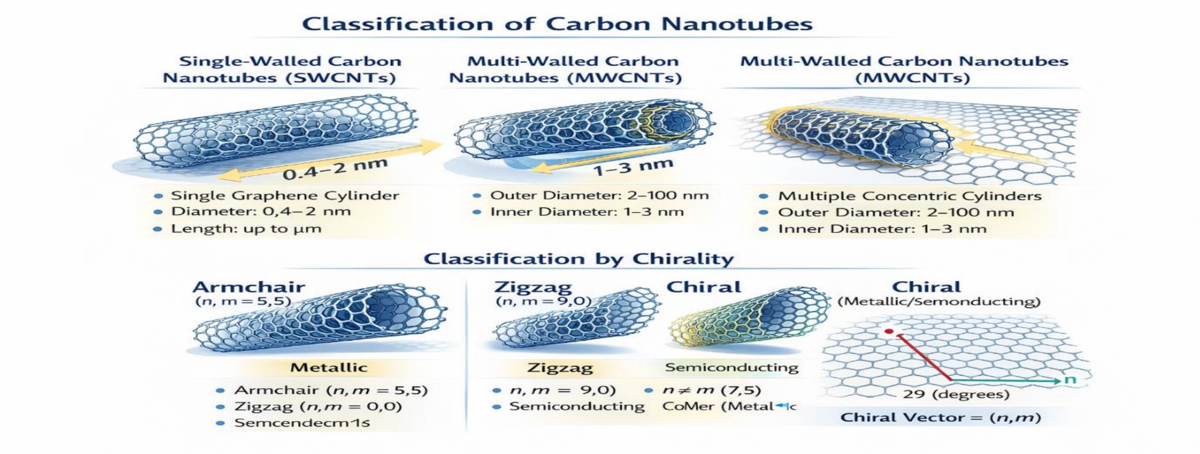

Figure 2:*Classification of carbon nanotubes. Author-generated schematic (AI-assisted)*

2.1 Single-walled carbon nanotubes (SWCNTs)

A single-walled carbon nanotube (SWCNT) is formed from a single graphene cylinder with diameters ranging from 0.4 to 2 nm, along with lengths of several micrometers to many micrometers in size, as mentioned in numerous literature reports [7][29]. The electronic structure primarily in one dimension gives rise to distinctive properties in metals or semiconductors depending upon chirality, making them valuable candidates in nanotechnology electronics, biosensing, and imaging applications [30][31].

2.2 Multi-walled carbon nanotubes (MWCNTs)

MWCNTs are composed of multiple graphene cylindrical structures with diameters of 2–100 nm while their core diameter may range from 1-3 nm in size [21][29]. They are more robust in nature than SWCNTs along with easy scalability, typically being dominantly used in composites, surface treatment, as well as matrices in catalysis and cleansing processes respectively [27][32].

2.3 Classification based on chirality (armchair, zigzag, chiral)

Carbon nanotubes are further classified according to the chiral vector, given by the parameters (n, m); the arrangements determined by them are armchair when n = m, zigzag when m = 0, or chiral in nature otherwise [7]. This chirality arises as an important factor in deciding the band structure; the armchair nanotubes are metallic, but the zigzag and chiral nanotubes could be semiconducting or metallic, depending on the nature, which hugely influences electronic and optical properties relevant to sensors, transistors, and fluorescent probes [4][30].

Type	Structure	Diameter range	Key properties	Typical applications
SWCNTs	Single graphene cylinder	0.4–2 nm	High electrical tunability, high surface area	Biosensors, drug delivery, nanoelectronics
MWCNTs	Multiple concentric cylinders	2–100 nm	Mechanical robustness, easier synthesis	Composites, coatings, catalysis
Armchair CNTs	n = m	~1–2 nm	Metallic behavior	Interconnects, conductors
Zigzag CNTs	m = 0	~1–3 nm	Metallic or semiconducting	Sensors, transistors
Chiral CNTs	n ≠ m	Variable	Semiconducting	Optoelectronics, imaging

Table 1: Classification of carbon nanotube

Structure and morphology of carbon nanotubes

3.1 Atomic structure

Carbon nanotubes are made up of sp^2 hybridized carbon atoms that are arranged in hexagonal patterns; otherwise, in the case of amorphous carbon nanotubes (aCNTs), these patterns are distorted to some extent, leading to both crystalline and non-crystalline patterns with distinct properties [27]. Other types of imperfections like vacancy, Stone-Wales defect, and open tips, as well as additional functional groups introduced during their preparation, play major roles in their electronic as well as mechanical properties [21].

3.2 Dimensions and aspect ratio

CNT diameters range from sub-nanometer (USWCNTs) to around 100 nm (MWCNTs), and length varies from hundreds of nanometers to several centimeters, leading to aspect ratios of over 10^3–10^6 [29]. The large aspect ratio is a criterion for good load transfer in composites, percolation at low concentrations in conductive paths, and good cell uptake in bio-medical applications [18][31].

3.3 Surface characteristics

Pristine carbon nanotubes are water repellent and tend to agglomerate through van der Waals forces, causing poor dispersive stability when placed in aqueous media and other polymers [21, 25]. Surface functionalization, or oxidation, introduces polar functionalities such as –COOH, –OH, and $–NH^2$, and/or layers of polymers and biomolecules, Enhance their capacity to disperse and facilitates their processing, and further provides sites for drug, catalyst, or recognition molecule binding [32].

Methods of synthesis of carbon nanotubes

4.1 Arc discharge method

The arc discharge method produces highly crystalline carbon nanotubes using graphitic electrodes in an inert atmosphere. However, it offers poor control over diameter and chirality and suffers from limited scalability and complex purification steps [22]. It is mainly used for fundamental studies and high-purity MWCNT synthesis.

4.2 Laser ablation method

Laser ablation of graphite targets at high temperatures yields high-quality SWCNTs with narrow diameter distribution. Its high cost and low scalability limit large-scale production [23].

4.3 Chemical vapor deposition (CVD)

CVD and its variants are widely employed for large-scale CNT synthesis, enabling better control over alignment, length, and substrate-specific growth at lower temperatures and costs. It is also used to produce amorphous CNTs and hybrid materials [29][7].

4.4 Comparison of synthesis methods

Arc discharge and laser ablation provide highly crystalline CNTs but face scalability and purification challenges, whereas CVD offers better scalability and control with higher defect dependence on catalyst conditions [21]. Sustainable precursors such as biomass are emerging as alternative CNT sources [7].

Method	Temperature	CNT Type	Advantages	Limitations
Arc Discharge	~3000–4000 °C	Mainly MWCNTs	High crystallinity	Poor scalability, purification needed
Laser Ablation	~1200 °C	SWCNTs	Narrow diameter distribution	High cost
CVD	600–1000 °C	SWCNTs & MWCNTs	Scalable, controllable	Higher defect density
Green/Biomass CVD	<900 °C	CNT composites	Eco-friendly, low cost	Limited chirality control

Table 2: Method of synthesis of carbon nanotube

Purification and functionalization of carbon nanotubes

Purification and functionalization are very important processes that can tune unrefined and contaminated CNT powders into tailored nanocarbons suitable for various applications in composites, water filtration membranes, sensors, and bio-medicines. Recent reviews have emphasized the crucial effect of the respective techniques of CNT purification and modification on the dispersibility, properties, and toxicity of CNTs [38][39].

5.1 Purification Techniques

Because as-synthesized CNTs contain entrapped metal catalyst particles, amorphous carbon, and other graphitic debris, the purification technique includes:

• **The chemical/oxidative methods** involve gas phase (air, CO_2, steam) and liquid phase acids (HNO_3, HCl, H_2SO_4, mixed acids) to remove amorphous carbon and dissolve metals. However, excessive oxidation leads to shortening of tubes and introduction of defects.

• **Physical methods:** filtration, centrifugation, annealing, and size-selective centrifugation; the methods above allow the separation of CNTs from bigger-sized particles without the deterioration of the structure of CNTs. Hybrid gas-liquid methods could remove more than 75–90% impurities with less structure damage effectively. [40][43]

5.2 Covalent Functionalization

The covalent bonds oxidize the CNTs and allow –COOH/–OH groups that can later be bonded using amidation/esterification reactions, cycloaddition reactions, diazonium coupling, and/or radical decarboxylation reactions [44]. These reactions allow the creation of stable functional groups that improve their compatibility and ease of binding with drugs or polymers [45]. The major limitation is that the sp^2 bonds can transform into sp^3 bonds, reducing their electrical conductivity and mechanical properties, but these latest methods can preserve the π bonds [38,46].

5.3 Non-Covalent Functionalization

Non-covalent techniques employ surfactants, polymers, aromatics, peptides, or DNA that bind by π-π, hydrophobic, and electrostatic interactions respectively [49]. The technique greatly enhances dispersion and biocompatibility with minimal loss of the CNT lattice and electrical properties; yet the reduced adhesion may impact the shelf life [38; 50].

5.4 Significance in Biomedical Applications

In the applications of drug delivery, imaging, and tissue engineering, functionalization is especially important for the regulation of dispersion, targeting, circulation time, immune recognition, and toxicity [47]. Multifunctional CNTs are currently under development to provide targeting capabilities, controlled drug release, imaging improvement, and reduced oxidative stress for the cancer diagnosis and treatment application [51].

Physicochemical properties of carbon nanotubes

6.1 Mechanical properties

The Young's modulus of CNTs is remarkably high (approaching 1 TPa), and they also possess high tensile strength, which is largely owing to their strong sp^2 bonds and defect-free tubular structure [23]. These properties could be effectively harnessed for their use as composite coatings, bone scaffolds, and reinforced implants in improving their stiffness, wear resistance, and fracture toughness accordingly [32].

6.2 Electrical Properties

On the basis of the chirality and diameter of the material, SWCNTs can be used as metals or semiconducting devices; MWCNTs are usually metallic in nature [30]. The high value of carrier mobility and conductance in CNTs has led to the discovery of field effect transistors and biosensors with high sensitivity for the detection of gases, metabolites, DNA, and cells [33].

6.3 Thermal properties

Carbon Nanotubes (CNTs) have an extremely high axial thermal conductivity, often described as higher than for diamond, which, in turn, makes them very attractive for application in thermal interface materials, heat spreaders, and thermally stable coatings [27]. In biomedicine, near-infrared NIR-absorbing CNTs are explored for photothermal ablation of tumors and also serve as localized heaters in antimicrobial treatments and regenerative therapies [36].

6.4 Chemical Properties

The mainly sp^2 carbon configuration is chemically stable; however, the material can undergo oxidation or functionalization, which enables hydrophobicity, redox activity, and ion-, pollutant-, or biomolecule-binding ability to be tailored. Modified CNTs exhibit high sorption capacity for metals, organic compounds, and biomacromolecules, thus justifying their use in chromatography, water treatment, and sensing technologies.[33]

Characterization techniques for carbon nanotubes

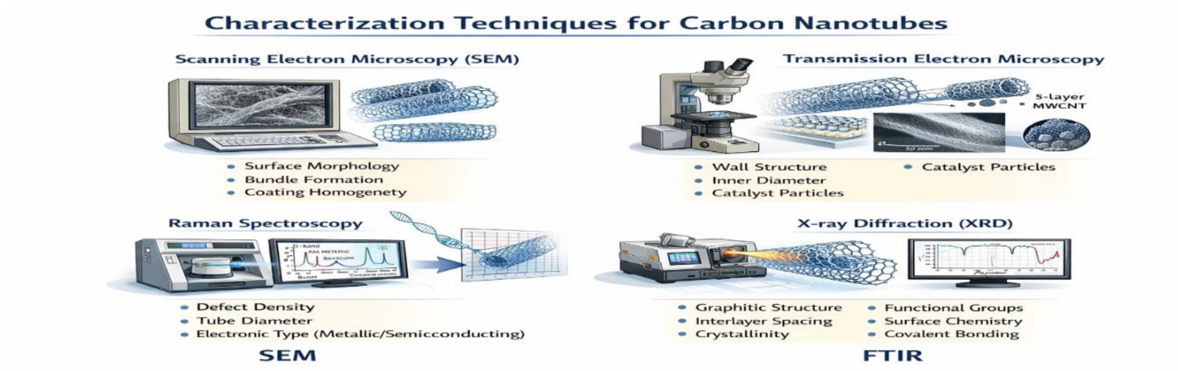

Figure 3:*Schematic representation of common characterization techniques for carbon nanotubes prepared by the author based on standard literature.*

7.1 Scanning electron microscopy (SEM)

SEM provides information on surface morphology, bundle formation, and coating uniformity for CNT-based composites and films [22]. It is also extensively employed in the assessment of the quality of deposition and surface coverage on implants and electrodes [32].

7.2 Transmission Electron Microscopy (TEM)

TEM and high-resolution TEM are indispensable for resolving individual walls and measuring the inner and outer diameters, identification of defects, and location of catalyst particles; they also enable distinguishing between SWCNTs, MWCNTs, and amorphous CNTs [21]. In biomedical coatings, TEM is used to assess the state of dispersion of CNTs and their interaction with substrates and biological tissues [29].

7.3 Raman Spectroscopy

Raman spectroscopy, which probes the D, G, and radial breathing modes, is used to assess graphitic order, defect density, and tube diameter distribution, and to identify whether SWCNTs are metallic or semiconducting [27]. Shifts in Raman bands also inform about functionalization and strain.

7.4 X-ray diffraction (XRD)

X-ray Diffraction (XRD) studies have played an important role in the verification of graphitic phases, determination of the distance between the graphitic layers, as well as the overall graphitic crystallinity; further, they have been used to distinguish ordered CNTs from amorphous carbon and to analyze the composites of

7.5 Fourier Transform Infrared Spectroscopy

Fourier Transform Infrared Spectroscopy (FTIR) allows functional groups created by the oxidation or covalent functionalization process (for example, C=O, O–H, C–N) to be determined, thus ensuring successful interactions of the surface with polymers or biomolecules [32].

Applications of carbon nanotubes

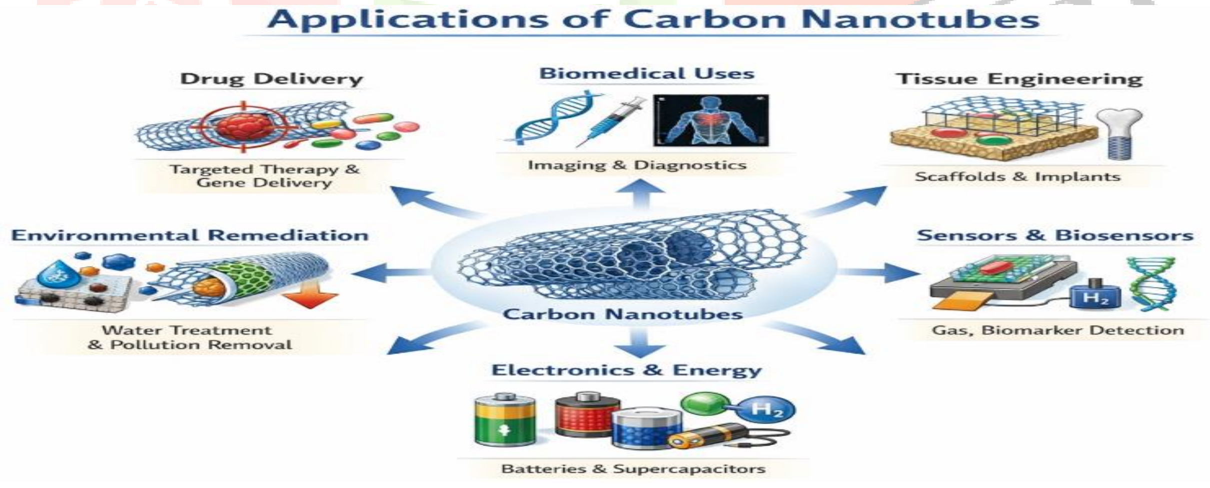

Figure 4: *Illustrative overview of major applications of carbon nanotubes, compiled by the author from standard literature sources.*

8.1 Drug delivery systems

Carbon nanotubes (CNTs) have good drug loading properties, which can be realized by π-π stacking interactions, adsorption, or covalent bonding. Additionally, they can improve the ability to cross cell membranes and realize targeted or stimulus-responsive drug release after surface modification with ligands, polymers, or stimuli-responsive linkers [35, 36]. Recently, it has been reported that CNTs-based systems have potential applications in chemotherapy, gene therapy, and combination photothermal-chemotherapy in cancer treatment [34].

8.2 Biomedical and pharmaceutical applications

Apart from their use in drug delivery, the utilization of carbon nanotubes (CNTs) in other biomedical applications, such as imaging agents, delivery carriers for vaccines, antibacterial materials, and their incorporation in diagnostic devices, has also been explored [31]. Hence, reviews of carbon nanomaterials discuss the importance of these materials in diagnosing or treating conditions, ranging from biosensing to disease monitoring, to therapies in gene therapy or phototherapy, though the need to test their toxicity is essential [37].

8.3 Tissue engineering

Carbon Nanotubes (CNTs) are used in scaffolds and coatings to provide improved mechanical properties, electrical conduction, as well as cell signaling in the development of bone, nerve, and cardiac tissues [29]. Composite coatings of CNTs are used on implants with the potential of having improved bioactivity, osseointegration, and antibacterial effects, but the clinical safety of use still remains under investigation [18].

8.4 Sensors and biosensors

Due to the large surface area and conductivity of CNTs, the detection of gas, ions, biomolecules, and cells is made possible.
Recently reviewed works describe the design of CNT-based electrochemical, chemiresistive, optical biosensors intended for glucose, DNA, cancer biomarkers, pathogens, along with environmental pollutants and organic volatile compounds [4][35].

8.5 Electronics and energy storage

Carbon nanotubes (CNTs) are used in flexible conductors, transistors, field emitters, and active or conductive components in batteries, supercapacitors, and hydrogen storage devices [7]. Amorphous carbon nanotubes or carbon nanotube nanocomposites have promising properties for energy storage and catalysis [27].

8.6 Environmental applications

Due to their high surface area and tunable chemical characteristics, CNTs find applications in water remediation, adsorption of heavy metals and organic contaminants, degradation by catalysis, and as sorbents and stationary phases in chromatography [33]. CNT-based materials are being gradually used in membranes and filters for improved water treatment processes [24].

Toxicity and safety aspects of carbon nanotubes

9.1 In vitro toxicity studies

Some in vitro studies suggest the potential of oxidative stress, inflammation, DNA damage, cytoskeletal disruption, or mitochondrial impairment with specific CNT preparations, depending on size, purity, surface chemistry, and dose [29]. CNT functionality and dispersibility have been shown to play a crucial role, with a number of studies having demonstrated good cell compatibility at specific concentrations of well-engineered CNTs [35].

9.2 In vivo toxicity studies

In vivo studies demonstrate that the biodistribution, clearance, and toxicity of CNTs can depend on the route of administration, the extent of functionalization, and the aggregated state [26]. Some studies have shown the occurrence of granulomas, fibrosis, or immune system activation, particularly for long, Straight, non-functionalized MWCNTs, rather than having negligible acute toxicity and a certain level of biodegradability for properly dispersed and functionalized CNTs [25].

9.3 Factors affecting CNT toxicity

The key variables include length, diameter, aspect ratio, extent of aggregation, concentration of metal fibers, surface charge, and functional groups [28]. The comparisons regarding asbestos-like effects highlight the risk associated with long biopersistent fibers, thus stressing the need to control morphology and improve biodegradability [23].

9.4 Regulatory and safety considerations

The existing legislation on carbon nanotubes (CNTs) is today generally evolving, with emphasis from the respective agencies on the need for effective characterization, exposure evaluation, and life-cycle analysis [27]. Emerging literature points to the need for standardization on issues relating to synthesis, characterization, toxicity evaluation, and reporting to enable safe transition to medical and environmental applications [32].

Challenges and limitations of carbon nanotubes

10.1 Production and scalability issues

These include industrial-scale control of chirality, purity, and homogeneity; increased energy and feedstock-related costs in some processes; and the environmental impact of the synthesis itself [25]. Gas consumption and handling of catalysts in CVD and related techniques also need to be optimized, if production is to be made more sustainable [7].

10.2 Biocompatibility concerns

Although promising data are present, there are still concerns about long-term accumulation, chronic inflammation, immunogenicity, and interaction with microbiota. Functionalization improves biocompatibility, but on the other hand, can complicate its regulatory evaluation process [35].

10.3 Environmental impact

CNT' release during manufacturing, usage, and disposal gives rise to questions about its persistence, ecotoxicity, and its potential bioaccumulation in ecosystems [24]. Studies also stress the need for full environmental fate and degradation analyses along with application development.

Recent advances and future perspectives

11.1 Recent research trends

Publication analysis shows a marked rise in CNT research, with more than 30,000 publications during the period 2017-2022, along with numerous reviews related to synthesis, properties, and applications [7]. Recent areas of interest include multifunctional CNT composites, application of amorphous CNTs for energy and catalysis, along with their combination with other forms of carbon nanomaterials like graphene or carbon dots [37].

11.2 Emerging applications

Some of the unexplored areas of research and applications of CNTs include the preparation of CNTs on a wound dressing and regenerative material, advanced coatings for implant devices, intelligent biosensors designed for personalized biomedicine, high frequency electronics, and energy devices to harvest sustainable energy [31]. The chromatographic and extraction methods have also been aided by CNTs [33].

11.3 Future scope of carbon nanotubes

Future studies will focus on controlled chirality growth, sustainable large-scale functionalization, the development of standardized functionalization protocols, and comprehensive toxicological assessment. It is expected that multi-functional and biodegradable carbon nanotube (CNT) platforms with special applications designed for certain biomedicals and biotechnical applications will shift the focus toward final industrial applications [36].

Conclusion

Carbon nanotubes have matured from a mere curiosity observed in electron microscopy studies to being a core nanomaterial in modern science and technology. Recent publications have emphasized the enormous promise offered by carbon nanotubes in biomedicine, electronics, energy storage, and environmental clean up, while also stressing the burning need to address challenges associated with the control of synthesis, toxicity, and regulatory matters.

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