

**CARBON NANOTUBES: SYNTHESIS, PROPERTIES, AND MULTIDISCIPLINARY APPLICATIONS A COMPREHENSIVE REVIEW****Thibiraj C.¹, Chittesh K. A.¹, Jeyaprabha P.^{1*}, Sambath Kumar R.¹**

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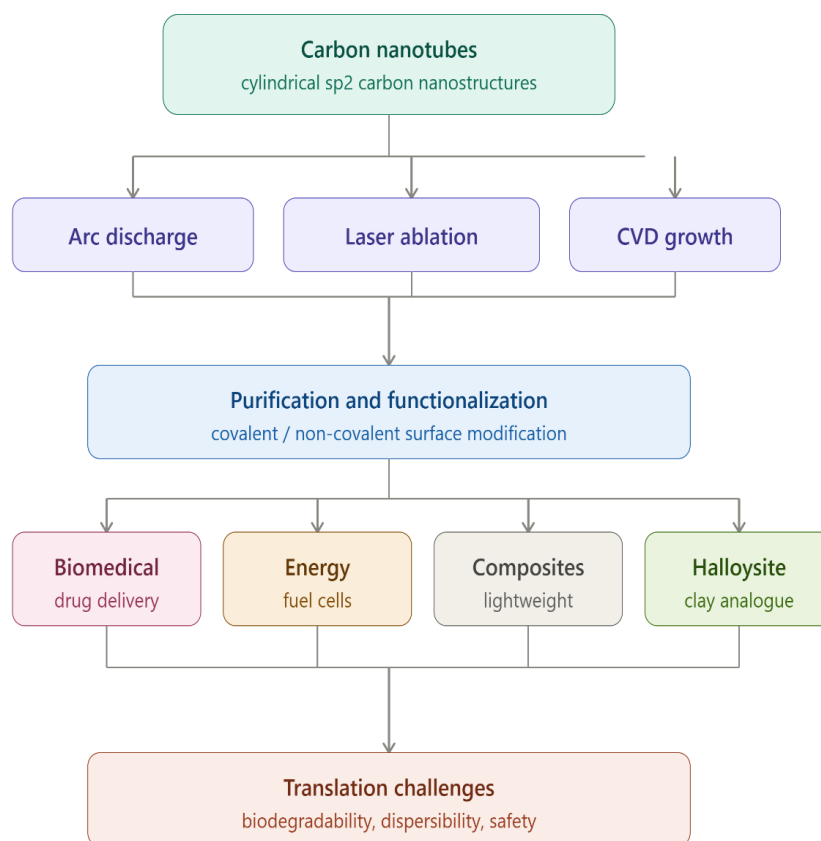
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ABSTRACT

Carbon nanotubes (CNTs) have become one of the most versatile classes of nanomaterials in the last three decades, due to their outstanding mechanical strength, tunable electrical conductivity, high thermal stability and large accessible surface area. CNTs are cylindrical, sp²-hybridized carbon nanostructures. This review summarizes recent work on the synthesis, structure, and physicochemical behavior of single-walled and multi-walled carbon nanotubes, with special attention to arc discharge, laser ablation, and chemical vapor deposition routes, as well as post-synthesis purification and covalent or non-covalent functionalization strategies to improve dispersibility and biocompatibility. Based on these basic principles, four key application areas are discussed in the review: (i) biomedical applications, including targeted and controlled drug delivery, gene therapy, tissue engineering scaffolds, biosensing and photothermal or photodynamic cancer therapy; (ii) electrocatalytic and energy applications including fuel cells, batteries, electrochemical sensors and CO₂ electroreduction; (iii) polymer-matrix composites produced by melt mixing, solution mixing, in-situ polymerization and additive manufacturing, which produce lightweight materials with improved mechanical, electrical and thermal properties for aerospace, automotive, construction and electronics applications; and (iv) natural nanotubular clay analogues such as halloysite that provide a lower-cost, more abundant alternative platform for carbon capture and environmental remediation. Toxicological issues such as biodegradability, dispersibility and long-term biocompatibility remain impediments to translation. The research finds that ongoing improvement in scalable synthesis, reproducible functionalization, and application-specific material design will be necessary for carbon nanotubes to move from laboratory-scale demonstrations to widely deployed industrial and clinical applications.

KEYWORDS: Carbon nanotubes; SWCNT; MWCNT; drug delivery; electrocatalysis; polymer composites; halloysite; carbon capture.



GRAPHICAL ABSTRACT

1. INTRODUCTION

Since their first description by Iijima in 1991, carbon nanotubes (CNTs) have been one of the most intensely investigated families of manufactured nanomaterials.^[6] Structurally, CNTs can be considered as rolled-up graphene sheet in a seamless cylinder form. The direction of rolling is determined by a chiral vector, which determines whether the tube is metallic or semiconducting.^[7] Two basic structural types are distinguished: single-walled carbon nanotubes (SWCNTs) that are formed by a single rolled graphene layer and multi-walled carbon nanotubes (MWCNTs) consisting of a few concentrically nested SWCNT-like shells.^[1,2] This structural variety, together with a nanometer scale width and a length that can be several micrometers, offers CNTs an extraordinarily high aspect ratio and a correspondingly huge specific surface area.

Technological attractiveness of CNTs results from a combination of properties that rarely coexist in a single material: tensile strengths in the order of tens to hundreds of gigapascals, Young's moduli approaching the terapascal range, electrical conductivities exceeding those of copper on a per-mass basis and thermal conductivities comparable to or exceeding diamond.^[4,7,20] These properties have inspired a huge and ever-growing community of research to use CNTs for medicinal delivery, tissue engineering, biosensing, electrocatalysis,

energy storage, structural composites, and electronics.^[1-5] However, the actual application of CNTs is limited by the remaining issues related to synthesis reproducibility, purification, dispersion, and toxicological characterisation, all of which are ongoing research topics.^[3,16]

This review offers an overview of the recent literature reporting the synthesis and structure of CNTs, their main physicochemical properties, their inclusion in polymer composites and in additively manufactured components and their uses in the biomedical, electrocatalytic and structural/industrial fields. This review also looks at haloysite nanotubes as an alternative nanotubular platform, stressing their increasing importance in carbon capture and secondary utilization^[5], as the tubular clay mineral haloysite has many of the geometrical and surface-chemistry advantages of CNTs at a much lower cost and with natural abundance. The performance, cost, scalability and safety trade-offs that will determine which CNT-based technologies will finally make the leap from bench-scale demonstrations to commercial products are given special emphasis throughout.

The structure of this review follows the logical flow from material basics to application. The structural classification of CNTs is given in Section 2 and the main synthesis methods applied for their production are

discussed. Section 3 highlights their main mechanical, electrical, thermal and chemical properties. Section 4 explores the integration of CNTs into polymer matrices and their processing into composite filaments and additively made objects. We address biological, electrocatalytic/energy, and structural/industrial applications in Sections 5–7, respectively, based on recent original literature in each area. In Section 8, halloysite nanotubes are introduced as a naturally occurring nanotubular counterpart, with a lower cost and a developing function in carbon capture. Section 9 highlights crosscutting problems and future research goals. Section 10 ends.

2. STRUCTURE, TYPES, AND SYNTHESIS OF CARBON NANOTUBES

2.1 Structural classification and chirality

CNTs are composed of only carbon atoms in condensed hexagonal (benzenoid) rings rolled in a tubular form. CNTs are thought to be members of the fullerene family

with graphite and diamond.^[1] The way the underlying graphene lattice is rolled up is characterized by a pair of integers (n, m), called the chiral vector, for which m = 0 gives a "zigzag" tube, n = m a "armchair" tube and all other combinations give "chiral" tubes.^[2]

The indexing technique defines if a given SWCNT is metallic or semiconducting, which has a major impact on electronic and sensor applications.^[2,7] SWCNTs are essentially 1-dimensional nanowires with sizes of about 1-2 nm while MWCNTs are made from multiple graphene cylinders arranged concentrically with outer diameters varying from around 2 to 100 nm and inner diameters of roughly 1-3 nm.^[1,4,20] MWCNTs are comprised of a number of SWCNT-like shells, and many of the concepts used to describe SWCNT chirality and electronic structure are used to explain MWCNT behavior, although the dominant metallic nature of the outer shells tends to dominate the overall conductivity of the tube.^[2]

Table 1: Representative structural and property comparison of SWCNTs and MWCNTs.

Parameter	SWCNT	MWCNT
Typical outer diameter	~1-2 nm	~2-100 nm
Typical inner diameter / lumen	single wall (no separate lumen)	~1-3 nm
Typical length	up to ~1 mm (lab scale)	up to ~1 mm
Elastic modulus	~1000-3000 GPa	~300-1000 GPa
Tensile strength	~50-100 GPa	~10-50 GPa
Electrical conductivity	10 ⁴ -10 ⁶ S/cm; metallic or semiconducting	10 ³ -10 ⁵ S/cm; predominantly metallic
Thermal conductivity (300 K)	~3000-6000 W/(m·K)	~2000-3000 W/(m·K)
Relative production cost	Higher (limited scalability)	Lower (favored for bulk production)

2.2 Synthesis techniques

The dominant techniques used to produce CNTs are arc discharge, laser ablation, and chemical vapor deposition (CVD). Each of the techniques uses a different energy source to liberate the carbon atoms to form the tubes. Arc discharge uses electricity, laser ablation uses a high power laser, and CVD uses thermal decomposition of a hydrocarbon feedstock.^[2,4,18] In the arc discharge, a direct current is carried between two graphite electrodes in a chamber filled with an inert atmosphere.^[8] The arc produces temperatures above 3000 °C which vaporizes the anode. The carbon species emitted into the plasma diffuse to colder areas of the reactor, where they self-assemble into nanotubes. When a metal-doped electrode is utilized, metal catalyst nanoparticles (often Fe, Co or Ni) act as the nucleation sites.^[1] Arc discharge can be used to produce short SWCNTs and MWCNTs, although with little control over chirality.^[4] Laser ablation entails vaporization of a graphite or metal-graphite target in a heated inert-gas-purged chamber by a continuous or pulsed laser (e.g., Nd: YAG or excimer laser).^[9]

The resulting vapor plume then condenses on a water-cooled collector downstream, with metal catalyst particles serving as nucleation sites.^[1,4] The method yields fairly clean nanotubes with fewer structural

imperfections than arc discharge, but it is relatively expensive and difficult to scale.^[1] The CVD^[2,4] is the most common approach for large-scale, industrially relevant synthesis, especially of MWCNTs. A hydrocarbon gas such as acetylene, ethylene, or methane is decomposed at 500-900 °C over metal catalyst nanoparticles supported on a substrate (e.g. zeolite, silica, or iron-coated silicon) with an inert carrier gas such as argon maintaining an oxygen-free environment.^[1]

The catalytically degraded carbon atoms diffuse to and precipitate at the catalyst particle, creating the nanotube from the base or tip depending on the strength of the catalyst-substrate contact.^[18] CVD also allows for good control over nanotube diameter, length and alignment and is more easily adapted to continuous, large volume manufacturing than either arc discharge or laser ablation and therefore forms the basis of most CNT-polymer composite and filament production processes discussed later in this review.^[4,18]

Table 2: Comparison of the three principal CNT synthesis routes.

Method	Energy source / typical conditions	Main advantages	Main limitations
Arc discharge	DC arc between graphite electrodes; >3000 °C; inert gas (He/Ar), 50-500 torr	Simple setup; can yield both SWCNT and MWCNT	Poor chirality control; significant impurities
Laser ablation	Continuous (CO ₂) or pulsed (Nd: YAG) laser vaporizing a graphite/metal target; inert gas flow	Relatively pure product; good for SWCNT	High cost; difficult to scale
Chemical vapor deposition (CVD)	Hydrocarbon gas (e.g., acetylene, ethylene, methane) decomposed at 500-900 °C over supported metal catalyst	Scalable; good control of length/alignment; suited to continuous processing	Requires catalyst removal; defect density can vary with conditions

2.3 Purification and functionalization

As-synthesized CNTs always contain impurities such as amorphous carbon, residual metal catalyst particles and shorter fullerene fragments, which can affect the intrinsic mechanical and electrical properties of the material and must be eliminated prior to most applications.^[1,3] Typical purification routes include oxidation treatment (removing carbonaceous impurities and exposing the metal catalyst for subsequent removal), acid treatment (dissolving metal catalysts via oxidation or sonication-assisted solvation), high-temperature annealing (repairing lattice defects and volatilizing residual metal), and functionalization-assisted separation.^[1]

Functionalization is frequently necessary to produce the dispersibility, biocompatibility, and selective reactivity required for biomedical or composite applications, because virgin CNTs are hydrophobic and tend to bundle up by van der Waals interactions.^[3,4] Functionalization can be covalent, in which carboxyl, hydroxyl, amine or other reactive groups are grafted directly onto the CNT sidewalls or end caps (typically after a first oxidative treatment to generate anchoring -COOH groups), or non-covalent, in which surfactants, polymers or biomolecules wrap around or adsorb onto the tube surface without breaking the underlying sp² lattice.^[3,14,15]

Covalently functionalized CNTs (CNT-F) have substantially improved solubility and serum stability, and can be conjugated to a wide range of therapeutic or targeting molecules including peptides, proteins, nucleic acids and polyethylene glycol (PEG) chains that prolong blood circulation time and reduce non-specific uptake by the reticuloendothelial system.^[3] The downside is that aggressive functionalization can generate sidewall defects that decrease the mechanical and electrical qualities for which pristine CNTs are sought, therefore the level of functionalization is often optimized for the particular end use.^[3,4]

In practice, most labs will combine a number of these purification and functionalization steps in sequence: an initial oxidative or acid treatment to remove amorphous carbon and metal catalyst residues and generate carboxyl groups at defect sites and tube ends, followed by a covalent coupling step (e.g., carbodiimide-mediated amide formation) to attach a targeting ligand, imaging tag, or solubilizing polymer such as PEG, and finally a

purification step (dialysis, centrifugation, or chromatographic separation) to remove unreacted reagents.^[3]

The general degree of functionalization is often described in terms of the number of functional groups per gram of CNT, or the weight percent of a grafted polymer such as polyethylenimine, and this parameter has been shown time and again to determine the tradeoff between improved dispersibility/reactivity and reduced accessible surface area or blocked pore/lumen space, which trend is repeated throughout the drug-delivery, gas-adsorption and catalytic applications covered later in this review.^[3,5]

3. PHYSICOCHEMICAL PROPERTIES OF CARBON NANOTUBES

3.1 Mechanical properties

CNTs have very high Young's modulus in the axial direction, commonly reported in the range of 300–1000 GPa for MWCNTs and 1000–3000 GPa for SWCNTs, and tensile strengths in the range of tens to hundreds of gigapascals.^[4,20,10] But this rigidity is compensated by the skinny, high aspect ratio geometry of the single tubes, which makes them very flexible in total, so they can bend, buckle and recover elastically without breaking.^[1] The unique combination of axial stiffness and overall flexibility contributes to much of their usefulness as reinforcing fillers in composite materials, where even little amounts of loading can greatly improve strength, stiffness, and toughness relative to the pure polymer matrix.^[20]

3.2 Electrical, thermal and optical properties

The properties of individual SWCNTs depend on their chirality and can be either metallic or semiconducting with bandgaps about 0–2 eV, while MWCNTs are mostly metallic because the properties of their outer shells with high diameters govern the total conduction.^[1,2] Electrical conductivities reported span several orders of magnitudes (of the order of 10⁴–10⁶ S/cm) and CNTs can support current densities far beyond traditional metallic conductors such as copper or aluminum, motivating the use of CNTs in flexible electronics, transparent conductive films and electromagnetic shielding materials.^[2,4,20,11]

Individual tubes have been reported to exhibit thermal conductivities of 2000–6000 W/(m·K) at ambient temperature, comparable to or even greater than diamond, making CNTs suitable fillers for thermal interface materials and heat-spreading applications.^[4,12,13]

CNTs also exhibit unique optical and electromechanical properties, e.g., the photoluminescence of semiconducting SWCNTs and piezoresistive effects that have been utilized in strain and pressure sensors, as explored in more detail in Section 6.

3.3 Chemical reactivity

CNTs possess very high Young's modulus in the axial direction, often stated to be in the range of 300–1000 GPa for MWCNTs and 1000–3000 GPa for SWCNTs, and tensile strengths in the range of tens to hundreds of gigapascals.^[4,20] But the rigidity is offset by the slender geometry of high aspect ratio of the single tubes that makes them exceedingly flexible in total, so that they can bend, buckle and rebound elastically without breaking.^[1] Their utility as reinforcing fillers in composite materials arises mainly from their unique blend of axial stiffness and general flexibility, where even minor loading can dramatically improve the strength, stiffness and toughness over the pure polymer matrix.^[20]

3.2 ELECTRICAL, THERMAL AND OPTICAL PROPERTIES

The properties of individual SWCNTs depend on their chirality and they can be metallic or semiconducting with band gaps roughly in the range of 0–2 eV, while MWCNTs are typically metallic since their conductivity is determined by the properties of their outer shells with enormous diameters.^[1,2] The reported electrical conductivities are of several orders of magnitudes (of the order of 10²–10⁶ S/cm) and CNTs can support current densities far beyond those of traditional metallic conductors such as copper or aluminum, motivating the use of CNTs for applications such as flexible electronics, transparent conductive films and electromagnetic shielding materials.^[2,4,20] It has been reported that individual tubes can have thermal conductivities of 2000–6000 W/(m·K) at room temperature, which are comparable or even larger than diamond.^[4] so that CNTs are good candidates as fillers for thermal interface materials and heat spreading applications. In addition, unique optical and electromechanical properties are present in CNTs, such as photoluminescence of semiconducting SWCNTs and piezoresistive effects exploited in strain and pressure sensors, as described in Section 6.

4. CARBON NANOTUBE-POLYMER COMPOSITES AND ADDITIVE MANUFACTURING

The incorporation of CNTs into thermoplastic or thermosetting polymer matrices such as acrylonitrile butadiene styrene (ABS), polylactic acid (PLA), polypropylene, epoxy resins and polyurethane, may

significantly improve the mechanical strength, electrical conductivity and thermal stability of the resultant composite relative to the neat polymer.^[4,19,17] The magnitude of these improvements is strongly dependent on the CNT weight fraction, with loadings of between approximately 1 and 10 wt% most often used; below approximately 1 wt% the effect on properties is often negligible, while above approximately 10 wt% the cost increases rapidly and uniform dispersion is increasingly difficult to achieve.^[4]

4.1 Fabrication methods

Mixing of CNTs with a molten polymer in the presence of large shear forces, usually in a twin-screw extruder, is called melt mixing and is well suited to thermoplastics that can be melted many times without significant degradation. However, melt mixing alone does not always result in a fully uniform CNT dispersion especially at higher loadings.^[4] In solution mixing the CNTs are dispersed in a solvent in which the polymer is dissolved and the solvent is then evaporated or the polymer precipitated. This method provides a better control over the dispersion and is compatible with a wide variety of polymers but the removal of solvent is quite slow and poses environmental disposal difficulties.^[4,23]

In-situ polymerization is the direct dispersion of CNTs in a monomer with or without solvent before conventional polymerization. This procedure is especially beneficial when dealing with polymers that are insoluble or thermally unstable and are therefore not amenable to processing in the melt or in solution. In-situ polymerization can produce nicely aligned CNT structures but has the disadvantage of increasing the viscosity as the polymerization progresses.^[4]

4.2 Filament extrusion and 3D printing

The preparation of CNT-polymer composite filaments for Fused Deposition Modeling (FDM) is typically carried out by single or twin screw extruders with independently controlled heating zones. The temperature of extrusion, the screw speed and the residence time have a significant effect on the degree of CNT dispersion and the uniformity of the filament diameter.^[4,21,22] Research on ABS/MWCNT filaments has found an appropriate MWCNT loading (often stated around 2.0 wt%) to optimize tensile strength improvements versus manufacturing challenges including clogging of the nozzle at low extrusion temperatures or uneven filament diam. Adding CNTs to polymers has been shown to increase density modestly, raise the material's electrical conductivity from insulating (as low as 10⁻¹²–10⁻¹⁵ S/cm for neat polymers) to semi-conductive or conductive levels once a percolation threshold is exceeded (often between about 0.5 and 5 wt% CNT, depending on polymer and dispersion quality), and improve thermal conductivity, with reported gains of tens to well over a hundred percent at CNT loadings around 0.5–1 vol%.^[4] Mechanically, tensile strength, Young's modulus and, in some formulations, elongation

at break, have all been found to increase with CNT inclusion up to an optimum loading, beyond which agglomeration starts to outweigh further advantages.^[4,54,55] These property advantages set the stage for the rising usage of CNT-polymer composites to replace heavier and less conductive engineering materials in the industries outlined in Section 7.

5. BIOMEDICAL APPLICATIONS OF CARBON NANOTUBES

The hollow and needle-like geometry of CNTs in addition to their capability to be functionalized on the surface have made them attractive candidates to directly deliver drugs, genes, proteins and imaging agents into cells. Their electronic and optical properties are conducive to various biosensing and phototherapeutic methods.^[1,3] Functionalization plays an important role in almost all biomedical applications, since it is responsible for providing the water solubility, reduced non-specific toxicity and molecular targeting capabilities that are required for use in live systems.^[3]

5.1 Drug delivery systems

CNTs can act as "magic bullet"-type carriers, encapsulating a drug within the tube lumen or conjugating it to the functionalized outer wall and releasing it in a controlled, and in some cases stimuli-responsive, manner at a target site.^[1,3] Reported systems include CNTs loaded with cisplatin, doxorubicin, paclitaxel, curcumin, and methotrexate, frequently combined with targeting ligands such as folic acid, hyaluronic acid, or monoclonal antibodies that promote selective uptake by cancer cells while reducing exposure of healthy tissue.^[1,3,24]

pH- or redox-responsive release has been demonstrated in several of these systems, allowing drug release to be triggered preferentially within the acidic or reducing microenvironment characteristic of many tumors.^[3,50,51]

Beyond oncology, CNT-based carriers have been explored for transdermal delivery (for example, in smoking-cessation nicotine patches that use an applied electrical bias to modulate release) and for neglected tropical diseases such as leishmaniasis, where CNT conjugates of betulin or cisplatin have shown markedly greater antiparasitic potency than the free drug.^[3]

5.2 Gene therapy and nucleic acid delivery

Their wire-like structure and capacity to penetrate cell membranes have also been exploited to deliver DNA, siRNA and antisense oligonucleotides to sites of illness, in some cases in conjunction with dendrimer coatings to enhance nucleic-acid loading and transfection effectiveness.^[1,3,25,26] In vivo silencing of oncogenes such as c-myc and siRNA-mediated knockdown leading to tumor cell death has been achieved utilizing carbon nanotube (CNT)-based gene-delivery vectors.^[1,3]

5.3 Tissue engineering

CNTs are promising as reinforcing and conducting elements in scaffolds for regeneration of heart, bone and connective tissue.^[3,27,32] Within the discipline of cardiac tissue engineering, fibrous scaffolds containing CNTs have been demonstrated to enhance electrical conductivity and stimulation of cardiomyocytes, facilitating cell proliferation, differentiation, and maturation which are critical for myocardial repair following infarction.^[3] It is hypothesized that the porous, three dimensional nature of CNTs supports nucleation and formation of hydroxyapatite crystals in bone tissue engineering and that CNT-coated biopolymer nanofibers increase osteoblast proliferation and expedite bone matrix creation.^[3] CNT-chitosan composites have been employed in connective tissue to modulate stiffness, contraction and elasticity of engineered tissues for a better mimicry of target tissues.^[3]

5.4 Biosensors and diagnostics

CNT-based electrochemical and field-effect biosensors take advantage of the high surface area, molecular specificity and rapid electron-transfer kinetics of the material to detect biomarkers, pathogens and small molecules with a sensitivity and speed that often surpasses that of traditional immunoassays such as ELISA.^[3,33,34] Reported applications include detection of prostate specific antigen and other cancer biomarkers, cardiac troponin T for diagnosis of myocardial infarction, glucose for diabetes monitoring, and antigens or nucleic acids related with malaria, TB, HIV, Zika virus and influenza.^[3] CNT based chemical sensors have been utilized for detection of pharmaceuticals, oxidative stress markers such as hydrogen peroxide and endogenous biomolecules such as dopamine and ascorbic acid, often by immobilization of a suitable enzyme, antibody or aptamer onto the surface of a CNT modified electrode.^[3]

5.5 Photothermal and photodynamic therapy

CNTs efficiently absorb near infrared light and convert it to heat. This has been used for photothermal ablation of tumors alone or in combination with photosensitizer-generated reactive oxygen species for photodynamic therapy.^[3] CNT complexes with ruthenium(II), indocyanine green, gold nanoparticles and different targeting antibodies have been reported to achieve tumor suppression in vitro and in vivo. CNT based photothermal platforms were also studied for antibacterial applications against *Staphylococcus aureus* and *Pseudomonas aeruginosa*.^[35,36,37]

5.6 TOXICOLOGY AND BIOCOMPATIBILITY

Despite this broad range of promising applications, the clinical translation of CNT-based medical devices remains incomplete, largely because their toxicological profile is not yet fully resolved.^[3,38,39] Genotoxicity studies have produced mixed findings: some report that CNTs trigger inflammatory responses in lung tissue without directly damaging genetic material, while others

report mitotic and chromosomal disruption, altered mitochondrial gene expression, or reduced cell viability, particularly after long-term exposure.^[3]

Functionalization and appropriate surface chemistry appear to reduce toxicity and improve biodegradability in several studies, but the field still lacks standardized testing protocols, meaning that toxicity data from different research groups are not always directly comparable.^[3] Continued investigation of dose-, exposure-duration-, and functionalization-dependent toxicity will therefore be essential before CNT-based therapeutics and diagnostics can be more widely adopted in clinical practice.

6. ELECTROCATALYTIC AND ENERGY-RELATED APPLICATIONS

CNTs combine high electrical conductivity, broad surface area and strong chemical and electrochemical durability, which makes them suitable supports and active components for electrocatalytic devices, such as fuel cells, batteries, electrochemical sensors and electrocatalytic organic production.^[2]

6.1. Fuel cells

The high cost of platinum-based catalysts has been a major barrier to commercialization of fuel cells, and as a consequence, CNTs have been widely investigated as catalyst supports that reduce the required platinum loading while improving catalytic activity and current density relative to conventional carbon black supports.^[2,40,41] Comparative study of Pt/MWCNT, PtNi/MWCNT and The PtRu/MWCNT electrodes have shown that trimetallic PtRuNi/MWCNT catalysts display enhanced electrocatalytic activity. Moreover, CNTs have proven their capability to support non-precious metal catalysts such as Cu/Cu₂O, SnO₂, and Mo₂C, achieving electrocatalytic activities comparable to those of platinum-based systems.^[2]

Nitrogen- or boron-doped CNTs are synthesized by introducing nitrogen- or boron-containing precursors during the CVD synthesis, which further tune the electronic structure of the nanotube and have been used in the development of multi-heteroatom-doped, defect-enriched CNT cathodes achieving a significant fraction of the power density of conventional Pt/C catalysts in anion-exchange-membrane fuel cells.^[2,42]

6.2 Batteries

The combination of mechanical robustness and electrical conductivity makes CNTs and CNT based hybrid materials appealing building blocks for flexible battery components.^[2] CNTs can be utilized in lithium-ion and lithium-air batteries as a conductive addition, as an active lithium storage material or as a structural support for other active materials. Of particular interest is the fact that nitrogen doped CNTs exhibit a larger specific capacity and a better cycling stability than undoped tubes

due to an increase of the number of nucleation sites and a more homogenous distribution of discharge products.^[2,43] Moreover, CNT-based cathodes have been studied for zinc-air and sodium-air batteries, using CNT-supported catalysts like LaNiO₃/nitrogen-doped CNT hybrids and atomic-layer-deposited Co₃O₄ on CNTs, which show stable performance under mechanical deformation and longer lifetime compared to simple mechanical mixtures.^[2]

6.3 Electrochemical sensor

The electrochemical sensors based on the CNTs have a low detection limit and a short reaction time in comparison to many of the traditional analytical procedures^[2] since the sensors exploit the signal amplification, which is due to the large surface area, low overvoltage and fast electrode kinetics of the material. Reported applications include the detection of methanol, dissolved sulfide, glucose, lead ions, caffeic acid and decomposition products of sulfur hexafluoride used in gas insulated electrical switchgear, often by modification of CNT electrodes with metal nanoparticles, metal-organic frameworks or enzyme layers such as tyrosinase or laccase.^[2,44,45]

6.4 Organic synthesis and CO₂ electroreduction

The mechanical robustness and electrical conductivity of CNTs and CNT based hybrid materials make them attractive building blocks for flexible battery components.^[2] CNTs can function as a conductive additive, an active lithium storage material or a structural support for other active materials for lithium-ion and lithium-air batteries. It is interesting to note that nitrogen doped CNTs show a higher specific capacity and a better cycling stability compared with undoped tubes, due to the increase of the number of nucleation sites and a more uniform distribution of discharge products.^[2,46]

CNT-based cathodes have also been studied for zinc-air and sodium-air batteries, using CNT-supported catalysts such as LaNiO₃ /nitrogen-doped CNT hybrids and atomic-layer-deposited Co₃O₄ on CNTs, which have stable performance under mechanical deformation and a longer lifetime than simple mechanical mixtures.^[2]

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7. STRUCTURAL AND INDUSTRIAL APPLICATIONS

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7.3 Construction

The incorporation of CNTs into cementitious materials has been demonstrated to improve flexural, tensile and compressive strength at relatively low CNT loadings (often less than about 0.1 wt% relative to cement) and CNT-reinforced concrete and beam systems have been proposed for application in bridges, tunnels, railway tracks, vibration absorbers and other civil-engineering infrastructure requiring both mechanical performance and long-term durability.^[4,47,48]

7.4 Electronics and energy storage

CNTs offer electrical conductivity that can exceed that of copper and aluminum on a per-mass basis, making CNT-polymer composites attractive for flexible electronics, printed circuit boards, electromagnetic interference shielding, transparent conductive films, and micro-battery components.^[4,49] In energy storage more broadly, CNTs' high surface area, aspect ratio, and electrochemical stability support their use in supercapacitors, where CNT/metal electrodes have achieved relatively high energy density and CNT/graphene electrodes have achieved high power density, complementing the fuel-cell and battery applications discussed in Section 6.^[4]

Taken together, the aerospace, automotive, construction, and electronics case studies summarized above illustrate a common pattern: CNT incorporation tends to deliver the largest relative gains in properties that are otherwise weak in the base material for example, electrical conductivity in an insulating thermoplastic, or tensile and flexural strength in a brittle cementitious binder—while the magnitude of the benefit is consistently reported to be dosage-dependent, with an optimal CNT loading beyond which agglomeration, reduced workability, or increased material cost erode the net advantage.^[4] This dosage-dependence, together with the sensitivity of composite performance to dispersion quality discussed in Section 4, reinforces the view that CNT-based structural materials are best developed through application-specific optimization rather than through a one-size-fits-all loading strategy.

8. BEYOND CARBON: HALLOYSITE NANOTUBES AS A COMPLEMENTARY NANOTUBULAR PLATFORM

Carbon nanotubes dominate the nanotube literature, but naturally occurring tubular clay minerals possess several of the geometric and surface-chemistry attributes that make CNTs attractive, at substantially lower cost, are naturally abundant, and in many cases, have more favorable environmental and safety profiles.^[5,52] Halloysite (Al₂Si₂O₅(OH)₄·nH₂O) is a dioctahedral 1:1 clay mineral from the kaolin group, typically found in nanotubular form (halloysite nanotubes, HNTs) generated by the rolling-up of hollow cylindrical aluminosilicate layers, with lengths ranging from about 20-1500 nm and lumen diameters of approximately 10-30 nm.^[5,28,31]

The alumina-rich inner lumen and silica-like outer surface bear opposite charges over a wide pH range, making HNTs suitable for selective charge-directed loading of positively or negatively charged species into the lumen or outer wall. This approach has been widely exploited for the controlled release of drugs, corrosion inhibitors, antimicrobials and other functional agents.^[5,30]

Recent studies have begun to assess HNTs and HNT-rich clays as inexpensive sorbents for CO₂ capture.^[5]

Their innate mesoporosity, tailorable surface chemistry and ability to be modified via thermal, mechanochemical, acid/alkali or amine-grafting methods all provide potential to tune their CO₂ uptake. Despite this, their absolute uptake, in general, remains less than high-end synthetic sorbents such as zeolites, activated carbons or metal-organic frameworks.^[5] Modification strategies reported include impregnation with polyethylenimine, grafting of aminosilanes, hybridization with metal-organic frameworks loaded into the acid-etched lumen, and formation of HNT-biopolymer composites, some of which have attained severalfold increases in CO₂ uptake relative to

unmodified HNTs while maintaining good cyclic regenerability.^[5,29,53]

Spent HNT-based sorbents have been proposed for reuse in soil amendment, construction materials, dye removal, fire retardancy, antibacterial coatings, and catalysis in addition to their primary capture purpose, illustrating a circular-economy model where a nanotubular adsorbent

is valorized across several life-cycle stages rather than being discarded following a single use.^[5] Considered alongside the CNT literature reviewed above, this body of work underscores a broader principle: whether carbon-based or clay-based, nanotubular architecture combined with tunable inner/outer surface chemistry is a recurring and versatile design motif across environmental, energy, and materials engineering applications.

Table 3: Summary of major application domains reviewed, illustrative examples, and principal reported benefits.

Domain	Illustrative example	Principal reported benefit
Drug delivery	CNT-doxorubicin/folic acid conjugates	Tumor-selective, pH/redox-responsive release[3]
Gene therapy	CNT-siRNA / dendrimer-CNT complexes	Improved intracellular nucleic-acid transfection [1,3]
Tissue engineering	CNT-polymer cardiac and bone scaffolds	Enhanced conductivity and cell proliferation [3]
Biosensing	CNT-antibody field-effect and electrochemical sensors	Low detection limits, rapid, low-cost diagnostics [3]
Phototherapy	CNT-Ru(II) and CNT-ICG complexes	NIR-triggered tumor ablation (PTT/PDT) [3]
Fuel cells	PtRuNi/MWCNT, non-precious-metal/MWCNT catalysts	Reduced Pt loading, higher current density [2]
Batteries	N-doped CNT Li-air and Li-S electrodes	Higher specific capacity, improved cycling [2]
Structural composites	MWCNT/ABS, MWCNT/epoxy, MWCNT/concrete	Higher strength, stiffness, conductivity [4]
Carbon capture (halloysite)	Amine-impregnated HNT adsorbents	Low-cost, reusable CO ₂ sorption [5]

9. CHALLENGES AND FUTURE PERSPECTIVES

Several recurring challenges cut across the application areas reviewed above. First, achieving uniform, reproducible CNT dispersion within a host matrix—whether a polymer, a biological medium, or a porous adsorbent—remains difficult, and incomplete dispersion is repeatedly identified as the primary factor limiting the mechanical, electrical, and thermal gains that CNT incorporation can, in principle, deliver.^[4]

Second, functionalization strategies that improve dispersibility and biocompatibility often introduce defects that partially offset the intrinsic mechanical or electronic advantages of pristine CNTs, so functionalization protocols must be tailored to the specific balance of properties required for a given application.^[3,4] Third, synthesis and purification methods that are well suited to laboratory-scale demonstrations do not always translate efficiently to industrial volumes, and the literature reviewed here consistently calls for further work on cost-effective, scalable manufacturing routes, particularly for filament extrusion and additive manufacturing processes.^[4]

On the biomedical side, the absence of standardized, harmonized toxicological testing protocols continues to generate divergent and sometimes contradictory findings regarding CNT genotoxicity and long-term biocompatibility, which in turn slows regulatory approval and clinical translation.^[3] Addressing this will

likely require coordinated efforts spanning chemistry, biology, and materials engineering to establish consistent characterization standards and risk-assessment frameworks. On the energy and electrocatalysis side, continued work is needed to better understand microscopic transport mechanisms within CNT-supported catalysts and to further reduce reliance on precious metals such as platinum.^[2]

Finally, for both CNTs and their natural nanotubular analogues such as halloysite, a need-based deployment strategy—in which the degree of purification and functionalization is matched to the cost and performance requirements of the intended application, rather than defaulting to the most highly engineered material available—appears likely to offer the most realistic pathway toward large-scale, economically viable adoption.^[5]

A further cross-cutting issue is the need to evaluate CNT-based materials over their full life cycle rather than at the point of synthesis or initial application alone. For polymer composites, this includes understanding how repeated thermal cycling during additive manufacturing affects long-term dispersion stability and mechanical performance; for biomedical constructs, it includes tracking the ultimate biodegradation pathway and clearance of functionalized CNTs from the body; and for adsorbent or catalytic uses, it includes assessing regeneration energy demand and the feasibility of

secondary reuse once the primary adsorption or catalytic capacity has been exhausted.^[3,4,5] Techno-economic and life-cycle assessments of this kind remain comparatively rare in the CNT literature relative to the volume of work reporting new synthesis or functionalization strategies, and closing this gap is likely to be as important for eventual commercialization as further gains in peak performance metrics.

10. CONCLUSION

Carbon nanotubes occupy a unique place among engineered nanomaterials due to their extraordinary mechanical strength, their tunable electrical and thermal conductivity, their high surface area and their chemistry that allows for extensive functionalization. These characteristics have enabled an amazingly wide application landscape including targeted drug and gene delivery, tissue engineering, biosensing and phototherapy, fuel cells, batteries and electrochemical sensors, and lightweight, high performance composites for aerospace, automotive, construction and electronics. At the same time, the translation of CNT-based technologies from laboratory demonstration to widespread commercial and clinical application is still limited by obstacles in dispersion, reproducible functionalization, scalable and cost-effective manufacturing, and toxicological assessment. Recent work on natural nanotubular analogs such as halloysite shows that some of the same geometry and surface-chemistry design principles that make CNTs attractive can be achieved at a cheaper cost and with less environmental burden for specific applications such as carbon capture. Looking forward, progress will likely depend less on pursuing ever more elaborate CNT modification strategies in isolation, and more on matching the type and degree of material engineering to the specific performance, cost, and safety requirements of each intended application—an approach that should help carbon nanotube technologies mature from promising laboratory materials into dependable components of real-world industrial and clinical systems.

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DECLARATION OF GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES IN THE WRITING PROCESS

During the preparation of this work, the author (s) used Quillbot to improve the language, grammar and readability of the manuscript. The author(s) reviewed and edited the output as necessary and accept full responsibility for the content of the final manuscript.

Fig 1. Graphical abstract summarizing the synthesis, properties, and multidisciplinary applications of carbon nanotubes reviewed in this article.

TABLE

Table 1. Representative structural and property comparison of SWCNTs and MWCNTs.

Table 2. Comparison of the three principal CNT synthesis routes.

Table 3. Summary of major application domains reviewed, illustrative examples, and principal reported benefits.

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