Characteristics of carbon nanotubes and their nanocomposites

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PART 3: Properties of carbon-based nanomaterials

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CHAPTER 5

Characteristics of carbon nanotubes and their nanocomposites

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Chapter Outline

1. Introduction

The carbon atom is one of the important elements in the periodic table. It can form sp^3, sp^2, and sp hybridizations [1−3]. There are different allotropes of carbon based on its arrangements, such as diamond, graphite, graphene, carbon nanotubes (CNTs), and fullerene [3]. These allotropes have a wide variety of physical and chemical properties [1−4]. Diamond is made of sp^3-hybridized carbons arranged in a tetrahedral lattice. On the other hand, graphite has a planar arrangement of sp^2-hybridized carbons [3,5]. The sheaths of the graphite are attached only by van der Waals interactions. Because of this structural arrangement, graphite is softer than diamonds [5]. A single layer of graphite is known as graphene. Buckminster fullerene, commonly known as fullerene, has a spheroidal

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arrangement like graphene [6,7]. The structures of different allotropes of carbon are shown in Fig. 5.1. Among these allotropes, CNTs are one of the most important members of carbon. It is the most exciting addition of the carbon family. CNTs lye between fullerenes and graphite as a new member of carbon allotropes. CNTs have a nanometer-sized diameter and a length of up to several micrometers [1–4]. A rolled structure of the graphite sheath is called CNTs. It is arranged in a hexagonal pattern with an arrangement similar to that of the structure of graphite [8,9]. CNTs are considered to be a graphitic cylinder 1 nm in diameter closed at the ends with caps containing carbon pentagons and hexagons. They can be either semiconducting or metallic [10,11]. CNTs have high electrical conductivity, chemical stability, a surface area, and high thermal stability [11]. They have a variety of applications in the fields of physical science, material science, biological science, pharmaceuticals,

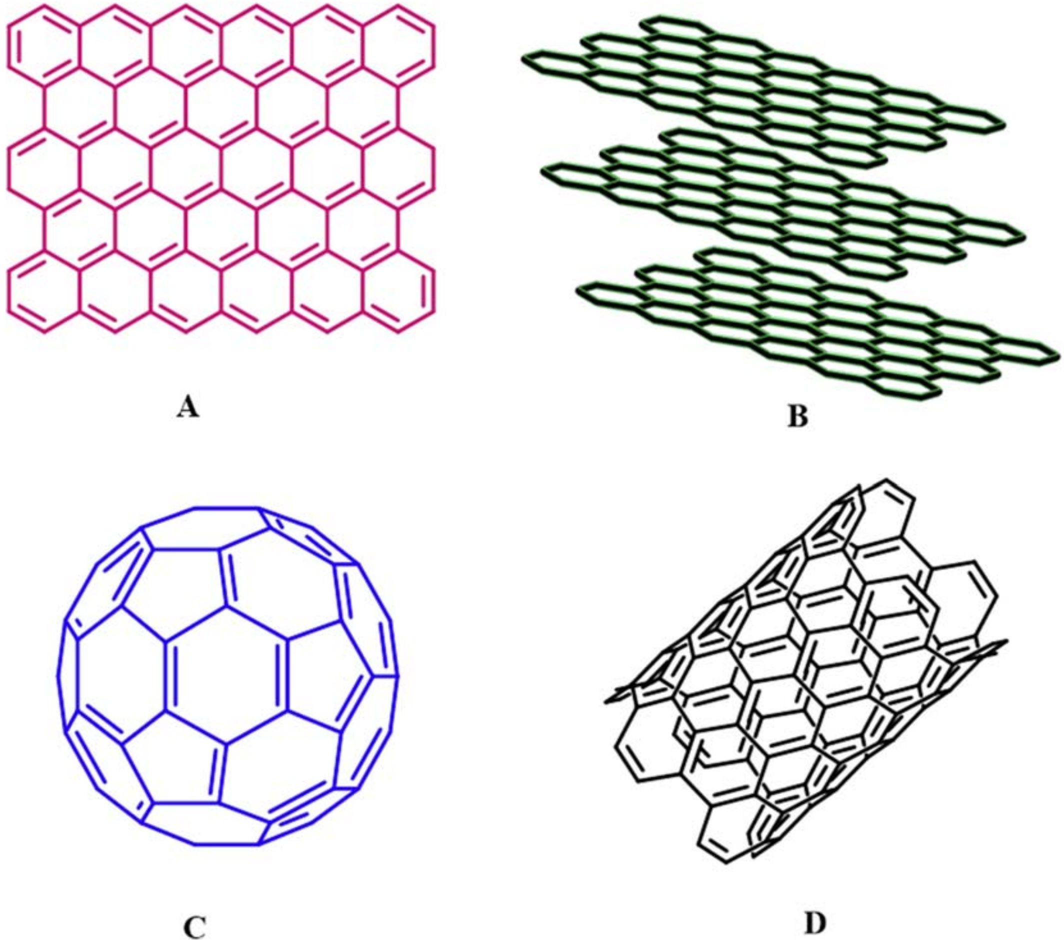

Figure 5.1
Different types of carbon allotropes (A–D) and their crystallographic arrangements: (A) graphene, (B) graphite, (C) fullerene, and (D) carbon nanotubes.

medicine, drug development, and so on [11−13]. They can be used in diodes, supercapacitors, medicine, electrocatalysts, nanocomposites, catalyst supports, and more [6,13,14]. They are also used as an electrocatalytic support material for the development of electrochemical sensors for toxic chemicals, pesticides, pollutants, drugs, and so forth [4,6,15]. In this chapter, the characteristics of CNTs and their nanocomposites, characterization tools, and applications are briefly discussed.

1.1 History of carbon nanotubes

The discovery of CNTs has created controversy in the scientific community. The most cited research articles suggest that CNTs were first discovered by Japanese scientist Sumio Iijima in 1991 [3,16,17]. However, some evidence supports the discovery of CNTs before Iijima's report [3,18]. More recent investigations indicate the discovery of multiwalled carbon nanotubes (MWCNTs) in the early 1950s. The discovery of hollow carbon filament (with a diameter as high as the nanometer range) in 1952 provides support for the discovery of MWCNTs in the early 1950s [18]. The systematic study of Iijima was significant for the discovery of MWCNTs. but we cannot neglect the earlier scientific contributions. On the other hand, single-walled carbon nanotubes (SWCNTs) were first reported independently by Iijima and Ichihashi [19] and by Bethune et al. [20]. The discovery of SWCNTs is more fundamental than MWCNTs. It has a significant number of theoretical predictions and interpretations. After the discovery of CNTs, scientists explored the characteristics, properties, and applications of CNTs. The most important progress in the field of CNTs and its nanocomposites is discussed in the following sections.

1.2 Types of carbon nanotubes

CNTs are categorized based on the orientation of the graphene sheath. There are three types of CNTs: chiral (n,m), zigzag (n,0), and armchair (n,n), where m and n are an integer value between two extremes for chiral vector C [3,17,21]. Two atoms in a planar graphene sheath are chosen and one is used as the origin. Vector C points the first atom toward the second one, as is shown in Fig. 5.2 [21]. These arrangements of carbon atom in CNTs may behave as metallic or semiconducting. These special characteristics of CNTs open up new dimensions for the development of functional materials [12].

Based on the number of concentric cylinders, CNTs are classified into different categories: SWCNTs, double-walled carbon nanotubes, triple-walled carbon nanotubes, and MWCNTs [11,22]. The schematic structures of SWCNTs and MWCNTs are shown in Fig. 5.3 [3]. In SWCNTs, the thickness of the cylindrical layer is 0.2−2 nm and the length is up to several micrometers. The structures of SWCNTs are conceptualized by wrapping a single layer of graphene into a cylinder. The exceptional electronic properties of SWCNTs make them outstanding compared with other forms of CNTs [23,24]. On the other hand,

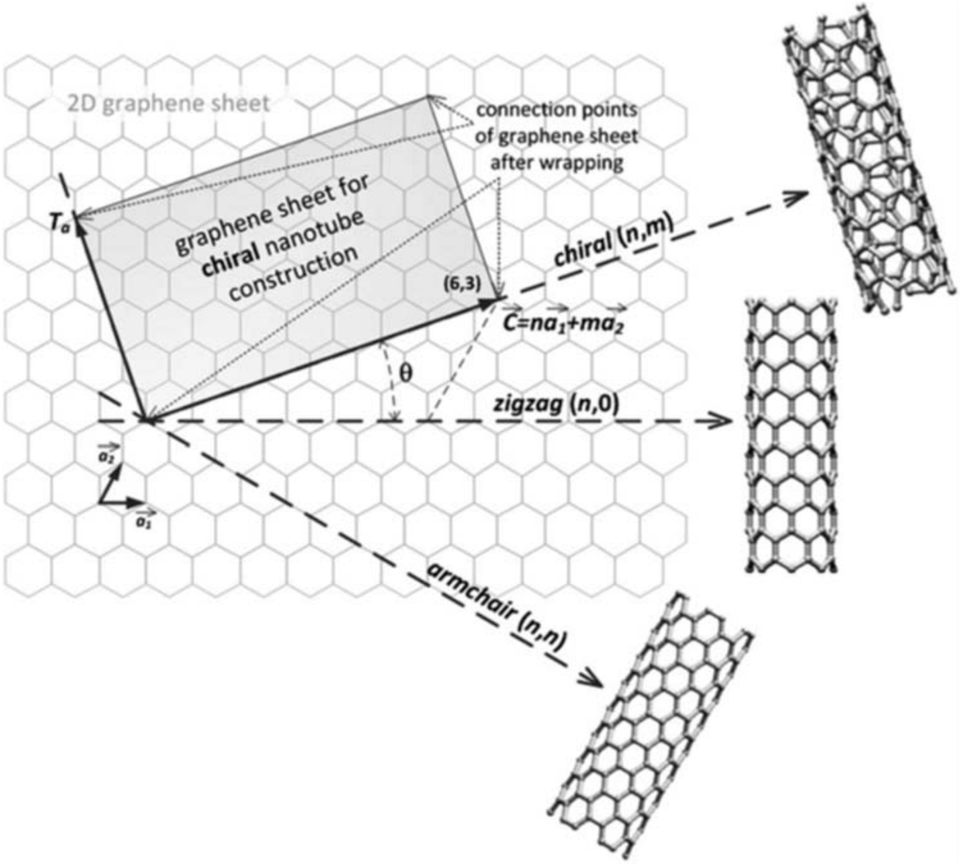

Figure 5.2

Growth of carbon nanotubes from graphene sheath along with chiral vector C. *Reproduced with permission from J. Prasek, J. Drbohlavova, J. Chomoucka, J. Hubalek, O. Jasek, V. Adam, R. Kizek, Methods for carbon nanotubes synthesis, J. Mater. Chem. 21 (2011) 15872–15884.*

the inner diameter of MWCNTs ranges from 1 to 3 nm and the outer diameter is 2–100 nm [3,25]. The inner diameter of MWCNTs is wider than that of SWCNTs. MWCNTs have a tube-like structure with multiple layers of graphite rolled to form a tube-like arrangement [25].

1.3 Physical properties of carbon nanotubes

CNTs have unique structural, electrical, and mechanical properties that make them an outstanding and attractive material for researchers [26,27]. The excellent mechanical properties, exceptionally high-tensile strength, and stiffness have stimulated interest and promoted research with CNTs [26,28]. These properties make the CNTs suitable for high-

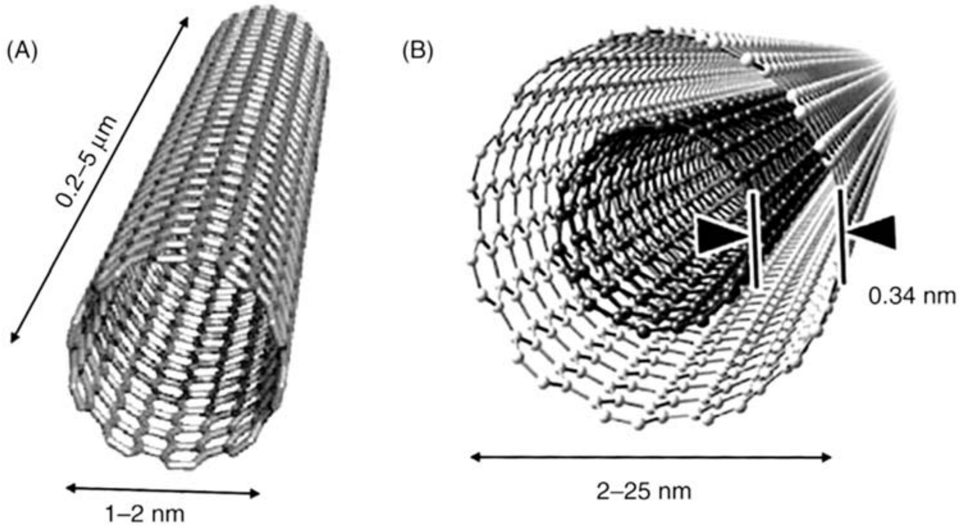

Figure 5.3
Structure of (A) single-walled carbon nanotubes and (B) multiwalled carbon nanotubes with a representation of their dimensions. *Reproduced with permission from R. Ghasempour, H. Narei, CNT Basics and Characteristics, Carbon Nanotube-Reinforced Polymers, Elsevier (2018) 1—24.*

performance structure materials, electromagnetic interference shielding, wave absorption, optical limiting, supercapacitors, and polymer-based light-emitting devices [26—28].

1.3.1 Electrical conductivity

CNTs have outstanding electronic properties. They have a nanometer diameter and a symmetric structure of two-dimensional (2D) graphene sheet that provides extraordinary electronic conduction of a 1D CNT structure [28]. Theoretical calculations and experimental measurements show conducting features of SWCNTs as quantum wires, CNTs bundles, and conduction in MWCNTs [3,29]. Theories regarding the electronic properties of SWCNT's suggest that the conductivity of SWCNTs is influenced by the helicity of tubes and their diameter. It depends on the indices (n,m) [30]. The electrical conductivity of SWCNTs and MWCNTs lies in the range 10^2—10^6 and 10^3—10^5 S/m, respectively [8,28,31—33]. The exceptional electronic properties and nanotube structure of CNTs provide significant applications in nanoelectronics. The diameter-influenced energy gap of CNTs provide special characteristics as a semiconducting material [34]. In addition, SWCNTs are used in field-effect transistors, which have a huge advantage over conventional transistors. The 1D nature of SWCNTs make them a key component in a single-electron transistors. The high electronic conductivity of SWCNTs make them a useful material for memory devices [34].

1.3.2 Mechanical properties

The mechanical strength of CNTs is highly influenced by the distribution and types of defects present in nanotubes [26]. These defects also affect the thermal and electrical properties. Different synthesis processes such as laser ablation, arc generation, and chemical vapor deposition (CVD) modulate the nature of the defects in the CNTs [26]. The mechanical strength of CNTs is measured in terms of the tensile strength. It is a difficult task to measure the tensile strength of CNTs. Yu et al. measured the tensile strength of SWCNT bundles varying from 13 to 52 GPa [35]. The tensile strength of the MWCNTs measured by Yu et al. ranged from 11 to 63 GPa [36]. Furthermore, the tensile strength of MWCNTs prepared by CVD was measured by Pan et al.; they reported a low tensile strength of 1.72 ± 0.64 GPa [37]. Generally, prepared CNTs are not a single SWCNT or MWCNTs. Initially, they may be either agglomerated SWCNTs or MWCNT bundles [38]. The high tensile strength and stiffness of a single SWCNT may not be the same in the CNT nanostructure. The high tensile strength, stiffness, tensile load, and lower density indicate the extraordinary mechanical properties of the CNTs. Hence, it is useful for developing strong composite materials.

1.3.3 Thermal properties of carbon nanotubes

The thermal conductivity and thermal expansion of the CNT are significant properties owing to its fundamental and technical importance. The small size and unique configuration directly affect the thermal behavior of CNTs [27,39]. Because of these special characteristics, CNTs may be considered an ideal material for the thermal management and investigation of low-dimensional phonon physics. Pyrolytic graphite represents high in-plane thermal conductivity. However, type II-a diamond represents extremely high thermal conductivity [39]. The thermal conductivity of graphite across the plane is extremely low because of the weak interaction of van der Waals forces. According to molecular dynamics and experimental studies, the thermal conductivity of single or bundled SWCNTs and MWCNTs are 20–6000 W/mK [40]. The thermal conductivity of a single MWCNT measured by Samani et al. is 2586 W/mK [40]. The outstanding mechanical, thermal, and electrical properties of the CNTs are useful for developing various electronic devices and composite materials. The general physical properties of the SWCNTs and MWCNTs are summarized in Table 5.1 [8,28,31–33].

The formation of CNT composites with epoxy enhances thermal conductivity 6 to 10 times higher. Gardea et al. reported increased electrical and thermal conductivity owing to the formation of CNT–epoxy composite materials [34]. It is well-documented in the literature that electrical, thermal, and mechanical properties can be enhanced owing to the formation of an appropriate composite of CNTs: for example CNT–bismaleimide composites [41], polyamide–MWCNT nanocomposites [42], polyimide–CNTs fabricated by in situ polymerization [43], MWCNTs and epoxy composites [44], well-dispersed

Table 5.1: Physical characteristic of single-walled carbon nanotube (SWCNTs) and multiwalled carbon nanotube (MWCNTs).

Characteristics	MWCNTs	SWCNTs
Nanotube diameter	0.2–2 nm	2–100 nm
Nanotube length	Up to several micrometers	Up to several micrometers
Concentric nanotubes, n	More than 2	1
Specific area	$(0.4-0.9) \times 10^3$ m^2/g	$(0.2-0.4) \times 10^3$ m^2/g
Conductivity (thermal)	$(3-6) \times 10^3$/Wm/K	$(2-3) \times 10^3$/Wm/K
Bulk specific gravity	0.8–1.3 gcm^{-3}	1.8–2.6 gcm^{-3}
Young's modulus	~1.0 kPa	~1.0 kPa
Conductivity (electrical)	$(1-10{,}000) \times 10^2$ Scm^{-1}	$(1-100) \times 10^3$ Scm^{-1}
Specific surface area	$(4-9) \times 10^2$ m^2/g	$(2-4) \times 10^2$ m^2/g
Stability (thermal) in air	550–650°C	550–650°C

Data for the characteristics of CNTs were taken from Ghasempour and Narei [3], Cao et al. [8], Meyyappan [28], Xie et al. [31], Ma et al. [32], and Díaz et al. [33].

SWCNT–polystyrene composites [45], MWCNT-reinforced carbon matrix composites [46], polybenzimidazole with CNT–graphene oxide hybrids [47], CNT-reinforced Al matrix composites [48], and so forth [49–51].

2. *Functionalization of carbon nanotubes*

The properties of CNTs can be enhanced by the insertion of unique functional groups. Two main are used for the functionalization of CNTs: noncovalent and covalent functionalization [52–54]. This functionalization of CNTs was carried out using different chemical functional groups and molecules. In the noncovalent functionalization of CNTs, aromatics, peptides, polymers, nucleic acids, surfactants, and oligomers were bound to CNTs with noncovalent interactions [52,55]. Noncovalent interactions include several aspects such as van der Waals forces, hydrophobic interaction, and π-stacking [54]. According to some reports, the electrical conductivity and aromatic structure of CNTs can be retained during noncovalent functionalization [6,9]. Without doubt, the noncovalent interactions provide weak strength to CNTs, which makes them unstable or less stable functionalized moieties [54].

In covalent functionalization; CNTs can be functionalized from ends, defects and side walls. The ends and defects method have high specificity for the reactions compare to side walls [56–58]. Functionalized CNTs can be prepared by covalent bonding between the surfaces of CNTs and compatible functional groups. In these ways, the surface of CNTs has been functionalized by different methods [57,58]. These variations provide a suitable platform for the functionalization of CNTs. During functionalization, the side walls of CNTs are damaged and increase the other features of CNTs. CNTs can be functionalized with concentrated sulfuric acid and nitric acid treatment [56,59]. Treatment of these acids provides the carboxylic group at the point defect of the carbon skeleton. Carboxylic acid functional groups increase the hydrophilicity of CNTs [59]. Hence, because of the covalent functionalization of the carboxylic acid group, CNTs become more water-soluble [56]. In addition, stable CNTs functionalization can be prepared by covalent bonding or coupling, which makes it more appropriate for drug delivery [58]. Different types of CNTs functionalization are summarized in Fig. 5.4 [60].

Different types of CNT functionalization are available in the literature: for example, electrochemical functionalization of SWCNTs with phosphorus and nitrogen species [61], MWCNTs functionalized with bathocuproinedisulfonic acid [62], organic functionalization of CNTs [63], sidewall functionalization of CNTs [64], CNT functionalization using a silane coupling agent [65], functionalization of CNTs with polystyrene, functionalization of CNTs with amines and enzymes [66], and so on [58,67–69]. Large numbers of CNT functionalized composites have been documented in the literature [58,70,71]. These functionalized CNTs and composite materials are useful in various applications such as electrochemical energy storage, sensing, material development, drug delivery, and pharmaceuticals [7,12,14,28].

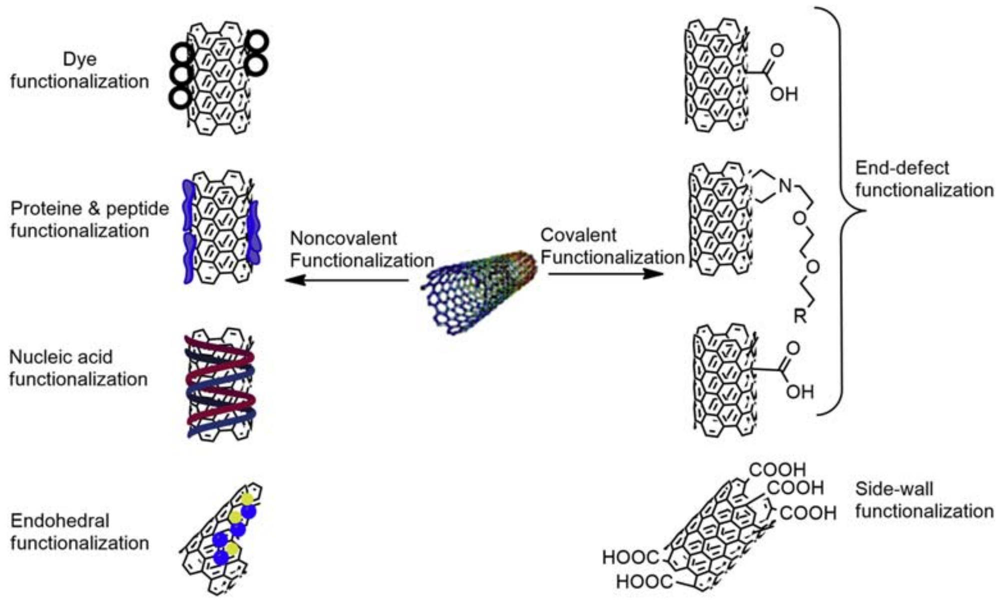

Figure 5.4

Covalent and noncovalent functionalization of carbon nanotubes. *Reproduced with permission from B. Singh, S. Lohan, P.S. Sandhu, A. Jain, S.K. Mehta, Functionalized Carbon Nanotubes and Their Promising Applications in Therapeutics and Diagnostics, Nanobiomaterials in Medical Imaging, Elsevier (2016) 455–478.*

3. Characterization tool for carbon nanotubes and their nanocomposites

The general physical properties of CNTs were discussed earlier in this chapter. However, CNTs and their composites can be characterized using spectroscopic and microscopic methods. A brief discussion is provided here for microscopic characterization using a scanning electron microscope (SEM), transmission electron microscope (TEM), energy dispersive X-ray analysis (EDAX), EDAX mapping, and atomic force microscope (AFM). In the spectroscopic methods, we will discuss only Raman spectroscopy for the characterization of CNTs and their composites. The other spectroscopic and characterization methods are beyond the scope of this chapter.

3.1 Microscopic analysis

SEM analysis is an important tools for characterizing CNTs and their composite materials. SEM images of SWCNTs and MWCNTs generally appear as fibers. The appearance of the fibrous bundle indicates the CNTs. Any small change in the tubular structure can be identified using this technique. SEM images of the SWCNTs and MWCNTs are shown in Fig. 5.5 [72,73]. The structure of SWCNTs (A) and MWCNTs (B) is clearly tubular in the SEM image.

The SEM images of the CNTs show the clear appearance of the nanotubes [72,73]. However, TEM analysis shows the high-resolution images. Even the layers of CNTs can also be visible in high-resolution TEM images. The TEM images of SWCNTs and

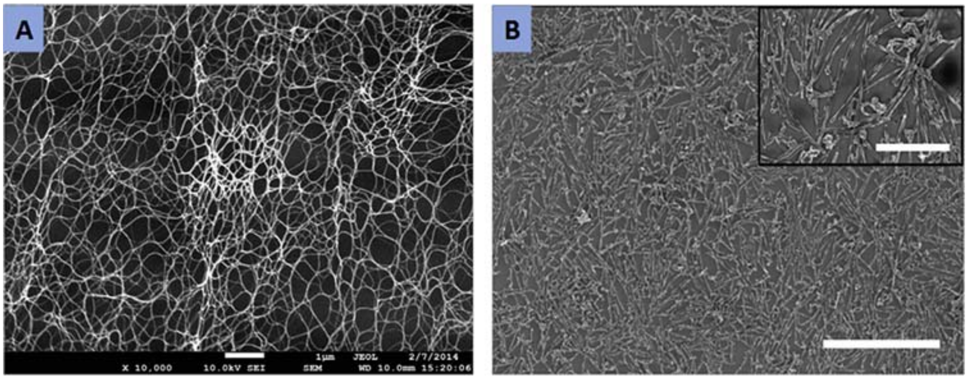

Figure 5.5

Scanning electron microscope image of (A) single-walled carbon nanotubes and (B) multiwalled carbon nanotubes. *Reproduced with permission from A. Tonkikh, V. Tsebro, E. Obraztsova, K. Suenaga, H. Kataura, A. Nasibulin, E. Kauppinen, E. Obraztsova, Metallization of single-wall carbon nanotube thin films induced by gas phase iodination, Carbon, 94 (2015) 768–774, K. Kedzierski, K. Rytel, B. Barszcz, A. Gronostaj, Ł. Majchrzycki, D. Wróbel, Unusual conductivity temperature dependence of multiwalled carbon nanotube thin film, Chem. Phys. Lett., 712 (2018) 144–148, respectively.*

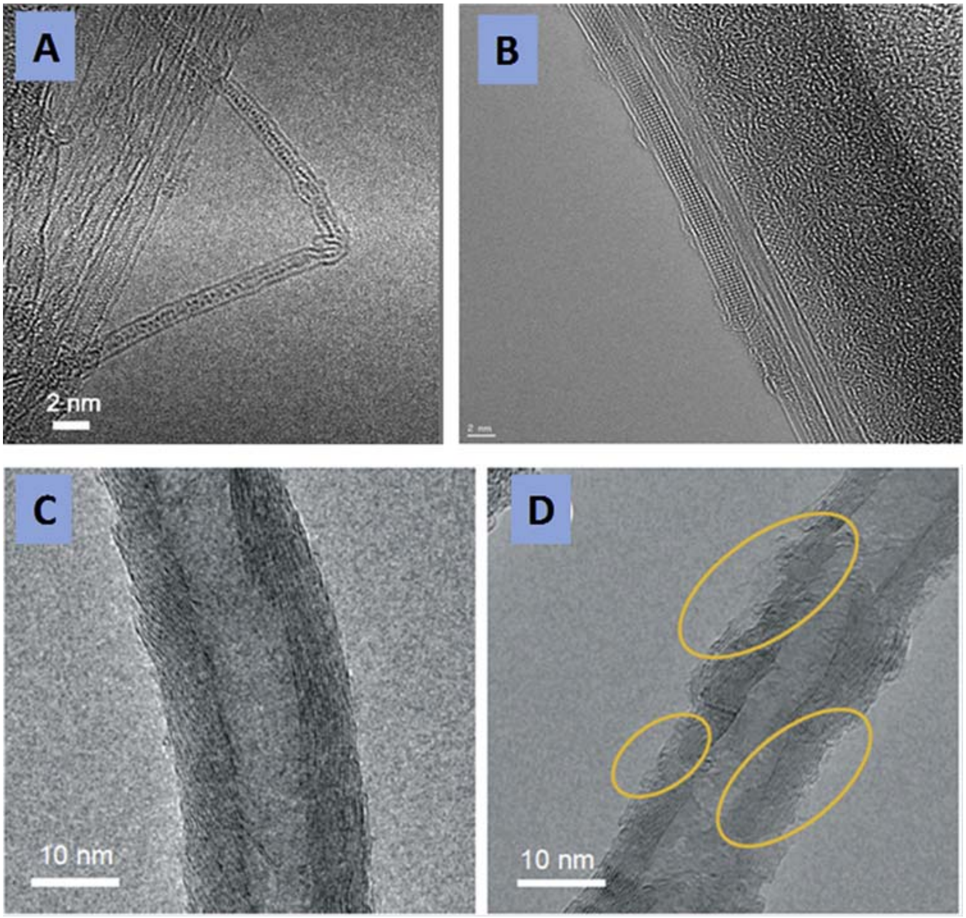

Figure 5.6

Transmission electron microscope images of single-walled carbon nanotubes filled with iodine from a gas phase at different magnification (A, B) and acid-purified multiwalled carbon nanotube (MWCNTs) (C) and acid-functionalized MWCNTs (D). The *circle* in (D) represents the rupture of the tube wall owing to acid functionalization. *Reproduced with permission from A. Tonkikh, V. Tsebro, E. Obraztsova, K. Suenaga, H. Kataura, A. Nasibulin, E. Kauppinen, E. Obraztsova, Metallization of single-wall carbon nanotube thin films induced by gas phase iodination, Carbon, 94 (2015) 768–774, S. Sweeney, S. Hu, P. Ruenraroengsak, S. Chen, A. Gow, S. Schwander, J.J. Zhang, K.F. Chung, M.P. Ryan, A.E. Porter, Carboxylation of multiwalled carbon nanotubes reduces their toxicity in primary human alveolar macrophages, Environ. Sci. Nano 3 (2016) 1340–1350 respectively.*

MWCNTs are shown in Fig. 5.6 [72,74]. Generally, composites of CNTs represent some nodules with dark shading of layering on the nanotubes [9,75]. Modification of CNTs with functional groups, enzymes, biomolecules, drugs, or other moieties can be identified with the help of SEM and TEM analysis [10,72,73].

In addition, EDAX and EDAX mapping also provide support to these characterization tools [4,6]. The EDAX technique provides the presence of elements in the samples. EDAX coupled with SEM or TEM enables elemental identification of selected regions in the microscopic images [76]. The EDAX spectra of the SWCNTs and MWCNTs show the presence of carbon and oxygen atoms in the elemental composition [4,9]. The incorporation of any functional groups or foreign molecules on the CNTs can easily be identified with this technique.

The characterization of CNTs and their composites are generally performed with the collective interpretation of these techniques. For example, nickel salophen immobilized MWCNTs are shown in Fig. 5.7 [4].

Here, incorporation of nickel salophen was visible in the SEM and TEM images in the form of the dark lining and spots. In addition, the presence of nickel salophen was identified using the EDAX study. EDAX shows the presence of nickel as an indication of nickel salophen [4].

The elemental distribution of the constituent elements of CNTs and their composites can be visualized using EDAX mapping. Fig. 5.8 shows EDAX and EDAX mapping of

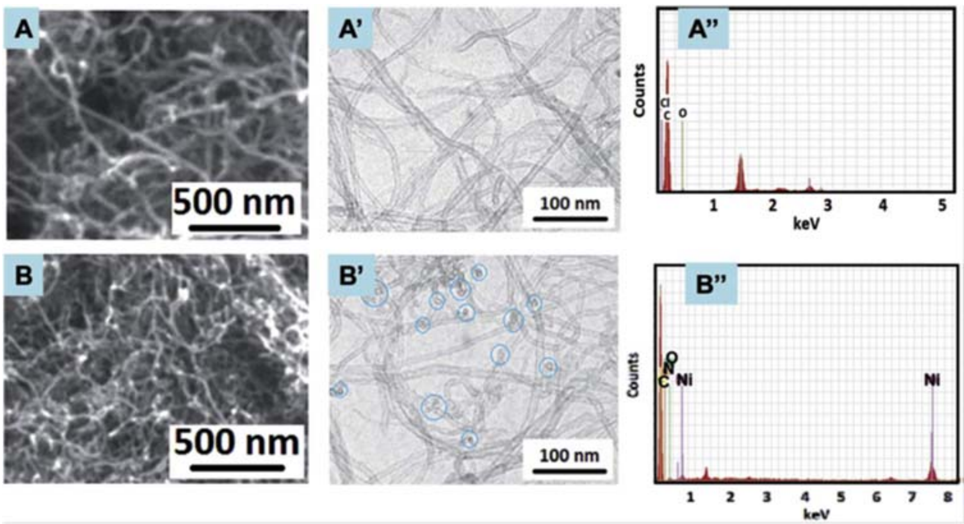

Figure 5.7
(A, B) Scanning electron microscope images, (A′, B′) transmission electron microscope images showing the morphology, and (A″, B″) energy dispersive X-ray analysis of (A, A′, and A″) multi-walled carbon nanotubes (MWCNTs) and (B, B′, and B″) MWCNT–nickel salophen composite. *Reproduced with permission from P.K. Sonkar, V. Ganesan, S.A. John, D.K. Yadav, R. Gupta, Non-enzymatic electrochemical sensing platform based on metal complex immobilized carbon nanotubes for glucose determination, RSC Adv. 6 (2016) 107094–107103.*

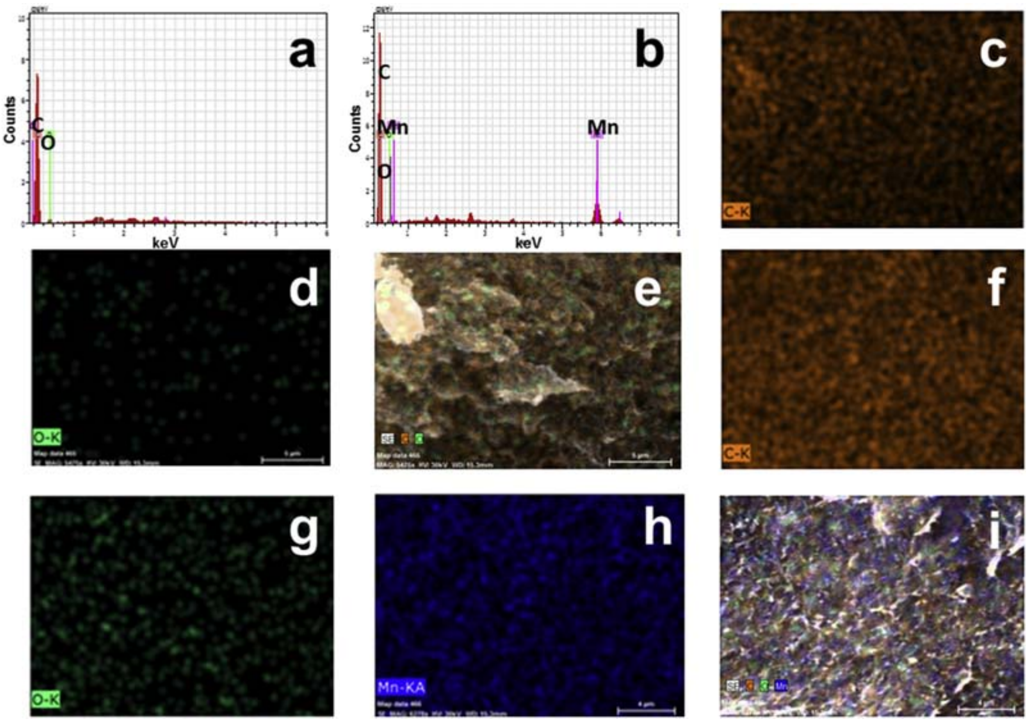

Figure 5.8

Energy dispersive X-ray analysis (EDAX) spectra of (A) multiwalled carbon nanotube (MWCNTs) and (B) MWCNT-manganese salen composite. (C—I) EDAX mapping of MWCNTs. (F—I) MWCNT-manganese salen composite. *Reproduced with permission from P.K. Sonkar, V. Ganesan, S.K. Sen Gupta, D.K. Yadav, R. Gupta, M. Yadav, Highly dispersed MWCNTs coupled manganese salen nanostructure for simultaneous electrochemical sensing of vitamin B2 and B6, J. Electroanal. Chem. 807 (2017) 235—243.*

MWCNTs and an MWCNT-immobilized manganese salen composite [6]. The presence of manganese in the composite material indicates immobilized manganese salen [6]. Combined microscopic and EDAX mapping provides strong support for the characterization of CNTs and their composites.

AFM analysis provides additional support for the interpretation of surface morphology [77,78]. The roughness of the thin film of nanotubes in the form of the root mean square surface, mean surface, or average surface can be determined using AFM [77,78]. In addition, the tube diameter, height profile, particle size, and other physical properties can be interpreted using AFM analysis [75,79]. The AFM analysis of SWCNTs and an SWCNT-oxovanadium(IV) salen composite is shown in Fig. 5.9. The variation in roughness and the change in height profile indicate the presence of nickel salophen in the composite material [75].

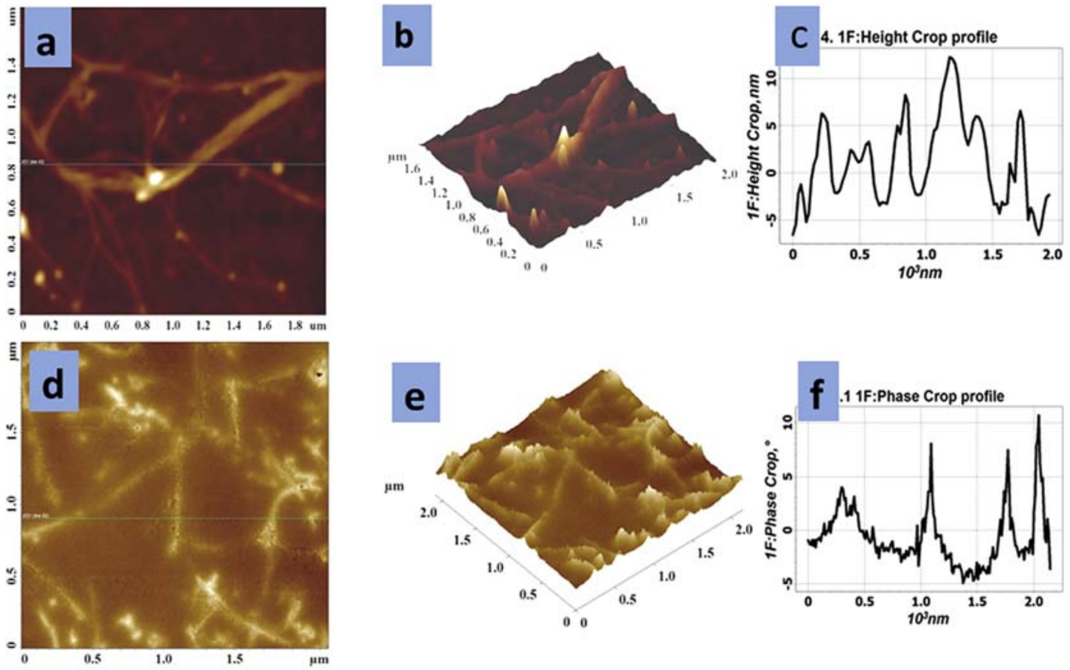

Figure 5.9
(A—C) Atomic force microscope images of single-walled carbon nanotubes (SWCNTs), (D—F) SWCNT-oxovanadium(IV) salen composite, and with corresponding (A, D) two-dimensional image, (B, E) three-dimensional image, and (C, F) section analysis, respectively. *Reproduced with permission from P.K. Sonkar, V. Ganesan, D.K. Yadav, R. Gupta, Dual electrocatalytic behavior of oxovanadium(IV) salen immobilized carbon materials towards cysteine oxidation and cystine reduction: graphene versus single walled carbon nanotubes, ChemistrySelect, 1 (2016) 6726—6734.*

Without doubt, different microscopic techniques such as AFM, SEM, TEM, as well as EDAX and mapping provide strong characterization tools for the morphological study of CNTs. The characterization of CNTs and CNT-based composites with their microscopic details have been discussed: CNT-hybridized carbon fiber composites [80], polycarbonate CNTs composites [81], CNT—polymer composites [82], alumina-coated CNTs [83], hybrid materials with CNTs [84], polycarbonate with MWCNTs [85], well-dispersed SWCNTs polyaniline composites [86], MWCNT-manganese salen composites [6], and so on [9,87,88].

3.2 Raman spectroscopy

Raman spectroscopy is one of the most powerful tools for characterizing CNTs and their composite materials [89,90]. It is based on vibrational spectroscopy with numerous applications. It gives useful information regarding the electronic and phonon behavior of samples [3,89]. A low-energy photon as a probe is used in Raman spectroscopy. Because of this, it is a noninvasive and nondestructive technique. Raman spectroscopy provides a unique identity to CNTs because of the high optical response of the 1D nanotube confinement of phonon and electronic states [3,89,90]. The Raman spectra of CNTs show the radial breathing mode (RBM) in the range of 100–500 cm^{-1} [3,91]. It is a unique phonon mode and arises only in the Raman spectra of CNTs. Thus, it is recognized as the fingerprint of the CNTs. The diameter of the CNTs shows an inverse relation with the RBM frequency. Hence, real-time monitoring of CNTs during its separation makes Raman spectroscopy more attractive. Defects in the nanotubes of CNTs can be recognized using the D-band, which appears at around 1300 cm^{-1}. The planar vibration of carbon present in the nanotube skeleton shows the G-band. The G-band appears for CNTs at around 1500–1600 cm^{-1} [3,92]. The G-band provides the difference between metallic and semiconducting SWCNTs. Two peaks of G-band appear in SWCNTs. The Lorentzian line shape G-band appears in semiconducting SWCNTs. However, a Breit–Wigner–Fano line shape G-band structure is observed in metallic SWCNTs [92]. A G′-band for CNTs appears at the Raman shift of 2450–2650 cm^{-1} based on the diameter and chirality of the CNTs. Raman spectra of the CNTs also show the M-band and iTOLA (second-order mode) [92]. These bands have less significance in the characterization of the CNTs. Raman spectra of SWCNTs and modified SWCNTs are shown in Fig. 5.10 [93].

Composite or functionalized CNTs can be identified using Raman spectroscopy by observing the change in D- and G-bands. For example, silver nanoparticles incorporated in CNTs show the change in Raman intensity compared with CNTs (Fig. 5.11A) [89]. The

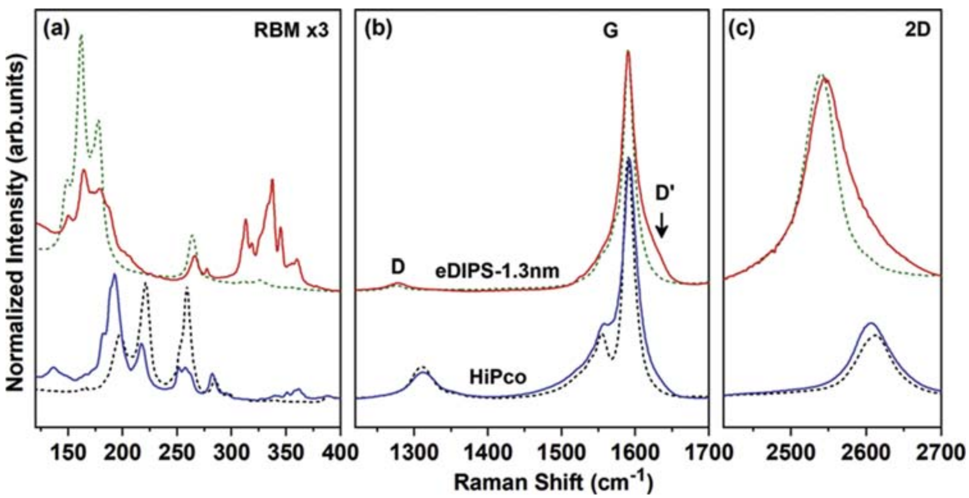

Figure 5.10

Raman spectra of pristine (*dashed lines*) and annealed (*solid lines*) enhanced direct injection pyrolytic synthesis with 1.3 nm–diameter (eDIPS-1.3 nm) (excited at 1064 nm) and high-pressure carbon monoxide (HiPco) single-walled carbon nanotubes (excited at 633 nm). (A) Radial breathing mode (RBM), (B) D- and G-bands, (C) Two-dimensional band. *Reproduced with permission from L. Shi, J. Wei, K. Yanagi, T. Saito, K. Cao, U. Kaiser, P. Ayala, T. Pichler, Templated direct growth of ultra-thin double-walled carbon nanotubes, Nanoscale 10 (2018) 21254–21261.*

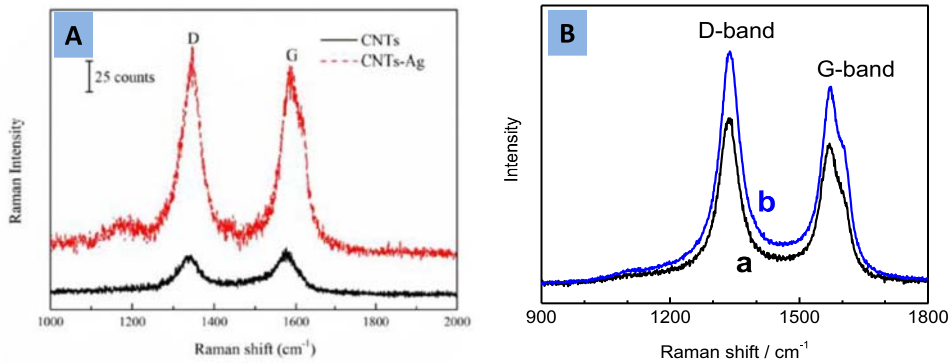

Figure 5.11
(A) Raman spectra of carbon nanotubes (CNTs) and silver nanoparticle–incorporated CNT composite. (B) Raman spectra of multiwalled carbon nanotube–manganese salen composite. *Reproduced with permission from P.K. Sonkar, V. Ganesan, S.K. Sen Gupta, D.K. Yadav, R. Gupta, M. Yadav, Highly dispersed multiwalled carbon nanotubes coupled manganese salen nanostructure for simultaneous electrochemical sensing of vitamin B2 and B6, J. Electroanal. Chem., 807 (2017) 235–243, X. Zhang, J. Zhang, J. Quan, N. Wang, Y. Zhu, Surface enhanced Raman scattering activities of carbon nanotubes decorated with silver nanoparticles, Analyst 141 (2016) 5527–5534, respectively.*

Raman peak of D- and G-bands at 1343 and 1576 cm^{-1}, respectively, confirms the presence of CNTs. The change in Raman intensity of silver nanoparticle-incorporated CNTs increases about 21 and 26 counts for D- and G-bands, respectively [89]. This change in Raman intensity confirms the formation of composite material. Similar studies were observed in manganese salen-incorporated MWCNTs (Fig. 5.11B) [6]. It is clear from this discussion that a composite material can be identified using Raman spectroscopy.

4. Applications of carbon nanotubes and their composites

CNTs have a wide range of applications in various fields. They are significant for nanoelectronics, nanodevices, hydrogen storage, electrochemical sensors, biosensors, electrocatalysis, and more [12,13,15]. CNTs and their composite materials are useful in drug delivery, pharmaceuticals, and bio-nanomaterials [7,12]. They are useful for the lithium-ion batteries of computers, notebook, mobile phones, and other electronic appliances, which is the reason for the major commercial success of CNTs [14,94,95]. In addition, CNTs and their composites are used in fuel cells and solar cells as catalyst support, which reduces the cost of these cells [12,14,96,97]. CNTs are also used in water purification [98,99]. We have discussed the application of CNTs only briefly. For the detailed application of CNTs, readers are directed elsewhere [100–104].

5. Summary

CNTs are an important allotrope of carbon. The nanotubes of the CNTs are composed of sp^2-hybridized carbon atoms. They are an attractive material owing to their significant properties, such as a high surface area, high tensile strength, stiffness, high thermal stability, and remarkable thermal conductivity. The functionalization or composite formation alters the physical properties of CNTs. The tensile strength and thermal stability can be enhanced by the formation of composite materials. Generally, epoxy groups provide more strength to CNT composite materials. A brief discussion was provided for the characterization of CNTs and their composites materials using SEM, TEM, AFM, EDAX, EDAX mapping, and Raman spectroscopy. These characterization tools provide the key to recognizing CNTs and their composite materials. For sure, CNTs and their composites are significant materials with a wide range of applications in almost every branch of science and technology.

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