A Review on Carbon Nanotubes: Preparation, Properties and Applications

Md Nur Karim[1], M.A. Sayed Patwary[2], S.M. Ashik Abedin[1], Md Riaj Hossen[3] and Md Saifur Rahman[1,*]

[1]*Department of Wet Processing Engineering, Textile Engineering College, Zorargonj, Chattogram, Bangladesh*

[2]*Department of Wet Processing Engineering, Textile Engineering College, Noakhali, Bangladesh*

[3]*Department of Wet Processing Engineering, Shahid Abdur Rab Serniabat Textile Engineering College, Barishal, Bangladesh*

Abstract: Carbon nanotubes(CNTs) have achieved attention in recent times because of their extraordinary physicochemical properties like strength, flexibility, sensors, conducting etc. Carbon nanotubes(CNTs) are known as nano-architectured allotropes of carbon, having graphene sheets which are rolled up into cylinder that forms carbon nanotubes. In the field of nanotechnology, carbon nanotubes are the one of the most unique invention. The eye-catching features of carbon nanotubes are their electronic, mechanical, optical and chemical characteristics, which open a way to future applications. Carbon nanotubes can be single walled and multi walled which can be produced in various ways. The most common techniques used nowadays are: arc discharge, laser ablation and chemical vapour deposition. In this review article,the applications of CNTs in various technologically important fields are discussed in detail.

Keywords: Nanotubes, Nanotechnology, SWCNTs and MWCNTs, Nanomedicine, Graphene, Nanocapsule.

1. INTRODUCTION

A Carbon Nanotube is a tube-shaped material, made of carbon, having a diameter measuring on the nanometer scale. Carbon nanotubes (CNTs) containing composites are very auspicious for the continuous growth of telecommunication market on account of their many idiosyncratic chemical and physical properties [1,2]. The forth coming generation computer devices, wireless LAN devices, consumer electronics, wireless antenna systems, and cellular phone systems are few portable device applications that require these composite materials, because nanocomposites have the potential to significantly surpass the physical properties of conventional bulk materials. Carbon is the chemical element with atomic number 6 and has six electrons which fill 1 s2, 2 s2, and 2p2 atomic orbital and can hybridize in sp, sp2, or sp3 forms. Nanometer size sp2 carbon bonded materials such as grapheme [3], fullerenes [4], and carbon nanotubes [5] have encouraged to make inquiries in this field. Graphene is known as 2D single layer of graphite in the list of carbon nanomaterials which is stronger material than diamond because it contains sp2 hybridisation which is stronger than the sp3 hybridisation in diamond [6].

*Address correspondence to this author at the Department of Wet Processing Engineering, Chittagong Textile Engineering College, Chittagong, Bangladesh; E-mail: sujon.btec@gmail.com

2. CARBON NANOTUBES

Carbon nanotubes (CNT) are the base of nanotechnology. Carbon with an atomic number of 6 plays a vital role in nanotechnology. They were discovered by Iijima [7]. Carbon nanotubes are made up of carbon and it is a tube shaped material which have very small diameter measured by nanoscale [8]. Graphenes which are rolled up into cylinder that forms carbon nanotubes [6]. The diameter of nanotubes is about 10 thousand times smaller than the diameter of a human hair [9]. In recent years carbon nanotubes are the most exciting areas of research [10].

The nanosized carbons (or nanocarbons) which comprise fullerenes, graphene and CNT [11]. Special priority is given to graphene and CNTs, as they play a pivotal role in current advances based on nanomaterials, including conductive and high-strength composites [12] artificial implants [13], sensors [14], drug delivery systems [15], energy conversion and storage devices [16] radiation sources [17] and field emission displays [18], hydrogen storage media [19] and nanometer-sized semiconductor devices [20], probes [21], and interconnects [22]. CNTs have excellent mechanical, thermal and electronic properties which make nanotubes ideal, not only for a wide range of applications [23] but as a test bed for fundamental

E-ISSN: 1929-5995/20

science [24]. In another area, it is thought that their massive thermal conductivity can be utilized to make thermally conductive composites [25]. Nanotubes might be used as membrane material for batteries and fuel cells, as anode for lithium ion batteries, as capacitor and chemical sensors/ filters [26]. A great amount of electrical conductivity and their relative inertness make them potential candidates as electrodes in electrochemical reactions also [27,28]. Wider surface area of nanotubes in both inside and outside, can be employed to 6 support reactant particles in catalytic conversion reactions [29]. For probe microscopies nanotube tips have also been designed as well as they also possess hydrogen storage capability [30].

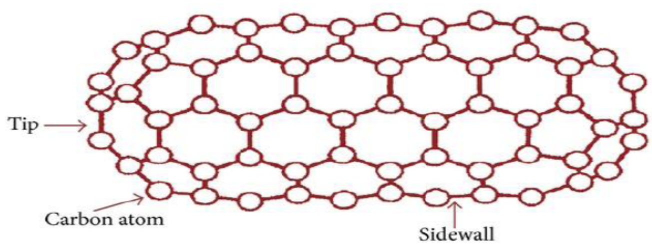

Figure 1: Structure of Carbon Nanotube.

3. CLASSIFICATIONS OF CARBON NANOTUBES

3.1. Single Walled Carbon Nanotubes (SWCNTs)

It consists of single layer of graphene and requires catalyst for its synthesis. SWCNTs are of poor purity and doesn't have any complex structure which can easily be twisted [31].

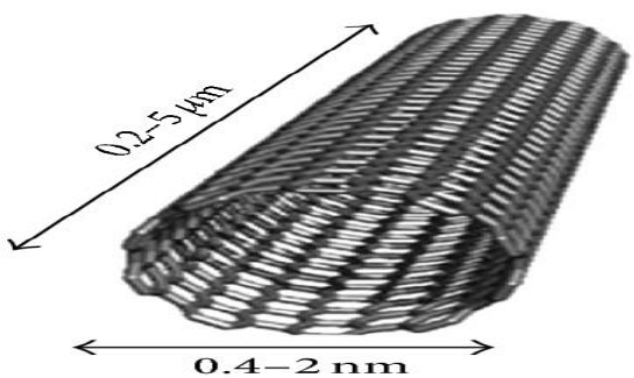

Figure 2: Single Walled Carbon Nanotube.

3.2. Multi walled Carbon Nanotubes (MWCNTs)

It consists of multi-layer of graphene and doesn't require any catalyst for its synthesis. The bigger MWCNT can contain hundreds of concentric layers which are separated by a distance of about 0.34 nm [32], wherethe measurement of length of a C–C bond in a graphene sheet of SWCNT is 0.142 nm [33]. The synthesis of DWNT was first proposed in 2003 by the CCVD technique on the gram-scale, from the selective reduction of oxide solutions in methane and hydrogen [34].

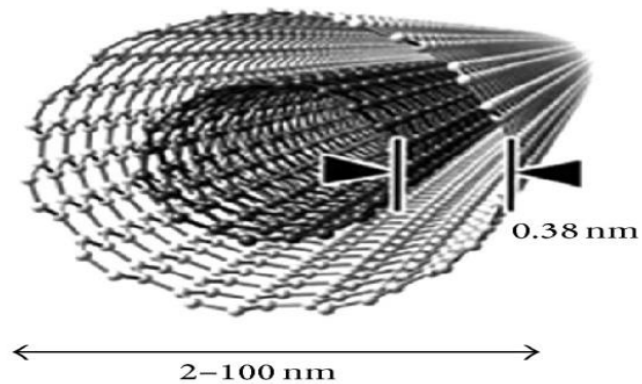

Figure 3: Multi Walled Carbon Nanotube.

Table 1: Difference between SWCNT and MWCNT [35]

SWCNT	MWCNT
It contain single layer of grapheme.	It contain multiple layer of grapheme.
It can't be produced without catalyst .	Can be produced without catalyst.
It can be easily twisted.	Can't be easily twisted.
It has simple structure.	It has complex structure.
It has less purity.	It has more purity.
It is more pliable.	Less pliable.
Bulk production is difficult.	Bulk production is easy.

4. METHODS OF PREPARATION CARBON NANOTUBES

4.1. Plasma Based Synthesis Method (Arc Discharge Method)

For best quality of nanotubes plasma based method or arc discharge method can be used which involves two graphite electrode in presence of helium and a current of 50 ampere is passed through two graphite electrodes which causes vaporization of graphite; some part of it condense on reaction vessel and some of it condense on cathode. Carbon nanotubes are deposited on cathode and If we want single walled carbon nanotubes then Co, Ni metals can be introduced in anode [8,36]. The yield of SWNTs is strongly affected bytemperature and it increases as increasing temperature. The SWNT bundles with 7-20 nm of diameters and the production of 45.3 g/h were prepared at the temperature of 600°C [37].

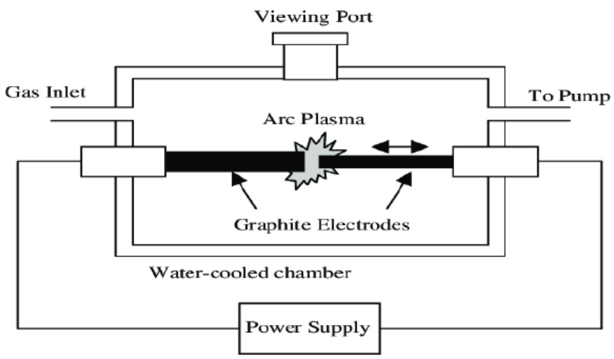

Figure 4: Arc Discharge Method.

4.2. Laser Method

In 1996 Laser was used for production of carbon nanotubes with 70% purity and Presently this method is used for production of carbon nanotubes. This process comprise of graphite rods and it contain 50:50 catalyst mixture of Co and Ni at 1200°C and argon is flowing through it for sample preparation [38] and in this method metal catalyze the growth of singlewalled carbon nanotubes and also many side products are formed. We can get nanotubes if we cool down the vaporized species [39].

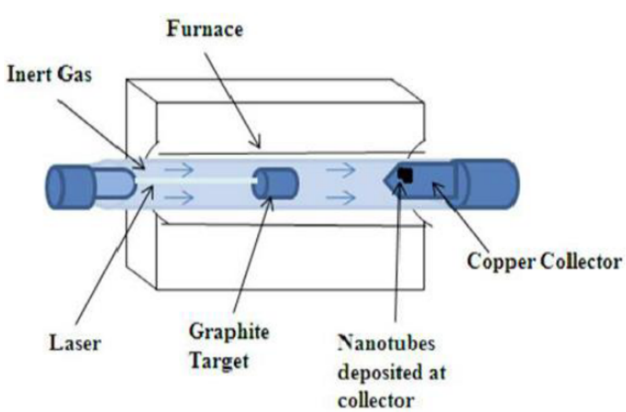

Figure 5: Laser Method.

4.3. Chemical Vapor Deposition

In the above methods, there are two major difficulties i.e. ordered synthesis and large scale production [40]. Chemical vapor deposition method was introduced in 1996 for production of carbon nanotubes [41] which is used to produce large amount nanotubes. The methods ofArc discharge and laser vaporization can be mentioned as high temperature (>3000K) and short time reaction (μs-ms) techniques, but the catalytic CVD is a medium temperature (700-1473K) and long time reaction (typically minutes to hours) technique. CNTs do not grow on a patterned or conventional substrate [42]. This method involves lower temperature and we get the well-organized carbon nanotubes [43].

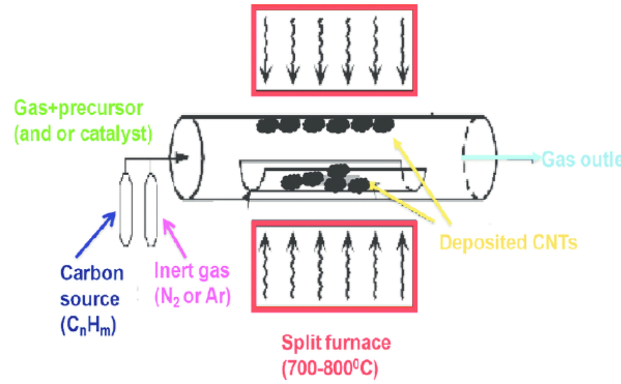

Figure 6: Chemical Vapor Deposition.

5. PROPERTIES OF CARBON NANOTUBES

CNTs have excellent electronic [44], optical [45], thermal [46], chemical, and mechanical properties [47,48]. Considering their chiral vector, carbon nanotubes containing a small diameter are either semi-conducting or metallic. The variations in conducting properties are caused by the molecular structure which results in a different band structure and thus a different band gap. These differences in conductivity can easily be derived from the graphene sheet properties [49]. The specific heat of MWNTs from 10 to 300 K [50] revealed linear dependence of the specific heat on the temperature over the entire temperature interval. By dint of the sp2 carbon-carbon bonding CNTs show high mechanical strength [51]. Young's modulus value of the nanotubes have 1000 GPa, (approximately five times higher than that of steel), are considered as the best for a variety of applications [52]. Compared to steel CNTs can have a breaking strain or tensile strength of approximately 63 GPa, which is approximately 50 times greater than steel [53].

6. APPLICATIONS OF CARBON NANOTUBES

6.1. Drug Delivery

Carbon nanotubes are used in drug delivery carriers for treatment of cancer [54] and these nanotubes are reported for targeting of amphotericin B to cells [55].

6.2. Tissue Generation

Carbon nanotubes are used for generation of tissue and in recent years carbon nanotubes are best for tissue generation because they are biocompatible, resistant to biodegradation and enhancing the organ generation [56].

6.3. Detection of Toxic Proteins

By changingthe electrical signals, the CNTs are used as a measuring platform for various toxic proteins which will immobilized on the CNTs [57]. The Scanning Electron Microscope (SEM) and the Electrochemical Chemiluminescence (ECL) are used to test the bonds of proteins with antibodies on CNTs platform.

6.4. As Bone Substitutes

Due to unique properties such as high tensile strength, CNTs can act as bone substitutes and implants when filled with calcium and shaped/arranged in the bone structure [58-59].

6.5. Preserve of Drugs

Carbon nanotubes are antioxidant in nature so they can be used to preserve drugs that are easily oxidized [60].

6.6. Gene Therapy

Carbon nanotubes are used for Gene therapy by DNA delivery to cure the gene which can Cause harmful disease by introducing DNA into cells [61-62].

6.7. As Lubricants

They can be used as lubricants or glidants in tablet manufacturing because of nanosize and sliding nature of graphite layers which bound with van der waals forces [63].

6.8. Genetic Engineering

In genetic engineering, Carbon nanotubes and Carbon nanohorns can be used to manipulate genes and atoms in the development of bioimaging genomes, proteomics and tissue engineering [63].

6.9. Diagnostic Tool

Protein-encapsulated or protein/enzyme filled nanotubes, because of their fluorescence ability in presence of specific biomolecules have been tried as implantable biosensors [64]. When nanocapsules filled with magnetic materials, radioisotope enzymes can be used as biosensors. Nanosize robots and motors with nanotubes can be used in the study of cells and biological systems [65].

6.10. Cancer Cell Identification

Nanodevices are being created that have the ability to develop cancer treatment, detection, and diagnosis andnanostructures can be so small (less than 100 nm) that the body possibly will clear them too quickly for them to be efficient in imaging or detection and so can enter cells and the organelles inside them to interact with DNA and proteins. Castillo *et al*., by using a peptide nanotube-folic acid modified graphene electrode, enhance the detection of human cervical cancer cells overexpressing folate receptors [66-72].

6.11. Biomedical Applications

The DNA sequences in the body can be identified by CNT-based nanobiosensors [73] and CNT-based pressure sensors can be used in eye surgeries, kidney dialysismachines, respiratory devices, and hospital beds [74,75]. The polymer composites based on CNTs because of their strength, stiffness, and relatively low operatingvoltage, can be used as artificial muscle devices [76]. CNTs play a vital role in the identification of cancer cells [77].

6.12. Carbon Nanotube-Based Diodes

CNTs (SWNTs) can form perfect p–n junction diodes due to their excellent mechanical and electrical properties [78]. The use of CNTs In lieu of conventional transistors and diodes significantly increases the current-carrying capability of the devices, while reducing the operational temperature. SWNT diodes exhibit excellent power conversion efficiencies when illuminated because of improved diode properties [79].

6.13. Batteries

Most portable electronic devices use rechargeable lithium-ion batteries and these batteries release charge when lithium ions move between two electrodes - one of which is graphite and the other is metal oxide. Researchers at the University of North Carolina have demonstrated that battery storage capacity can be doubled by replacing graphite with SWCNTs. CNT infused paper is used to make Ultra-thin flexible batteries [80].

6.14. Others

Applications of carbon nanotubes encompass many fields and disciplines such as medicine, nanotechnology, manufacturing, construction, electronics, and the following application can be noted: high-strength composites nanoprobes and sensors [81-87], actuators [88], energy storage and energy conversion devices [89],electronic devices [90], hydrogen storage media [91] and catalysis [92].

7. DRAWBACKS OF CARBON NANOTUBES

A Costly nanotechnology [53] and also hard to maintain high quality and lower impurities as well acumen manpower needed [93]. Huge amount of energy is required to complete the process in ARC DISCHARGE and LASER method [94].

8. CONCLUSIONS

This review paper is based on production, properties applications and limitations of carbon nanotubes. In this study we discuss about various methods of production of carbon nanotubes. Researchers taking keen interest in carbon nanotubes and likely to give more advancement in coming future and there is much about carbon nanotubes that is still unknown. More research needs to be done regarding the environmental and health impacts of producing large volume of them. There is also much effort to be done towards cheaper mass production and incorporation with other materials before many of the current applications being researched can be commercialized. There is no doubt however that carbon nanotubes will play an important role in a wide range of commercial applications in the very near future.

AUTHOR CONTRIBUTIONS

Conceptualization, M.N.K. and M.A.S.P.; methodology, M.A.S.P. and M.N.K.; formal analysis, M.S.R., M.A.S.P., M.N.K., S.M.A.A. and M.R.H.; investigation, M.S.R., S.M.A.A., M.R.H.; resources, M.N.K. and M.A.S.P.; writing-original draft preparation, M.N.K.; writing-review and editing, M.A.S.P.; supervision, M.S.R., S.M.A.A., M.R.H. All authors have read and agreed to the published version of the manuscript.

REFERENCES

[1] Rogers JA, Someya T, Huang Y. Materials and mechanics for stretchable electronics. Science 2010; 327(5973): 1603-1607. https://doi.org/10.1126/science.1182383

[2] Hu L, Pasta M, La Mantia F, Cui L, Jeong S, Deshazer HD, Cui Y. Stretchable, porous, and conductive energy textiles. Nano Letters 2010; 10(2): 708-714. https://doi.org/10.1021/nl903949m

[3] Ouyang M, Huang JL, Cheung CL, Lieber CM. Atomically resolved single-walled carbon nanotube intramolecular junctions. Science 2001; 291(5501): 97-100. https://doi.org/10.1126/science.291.5501.97

[4] Kim H, Lee J, Kahng SJ, Son YW, Lee SB, Lee CK, Kuk Y. Direct observation of localized defect states in semiconductor nanotube junctions. Physical Review Letters 2003; 90(21): 216107. https://doi.org/10.1103/PhysRevLett.90.216107

[5] Chico L, Crespi VH, Benedict LX, Louie SG, Cohen ML. Pure carbon nanoscale devices: nanotube heterojunctions. Physical Review Letters 1996; 76(6): 971. https://doi.org/10.1103/PhysRevLett.76.971

[6] Kaushik BK, Majumder MK. Carbon nanotube based VLSI interconnects: Analysis and design. New Delhi: Springer India 2015; pp. 1-14. https://doi.org/10.1007/978-81-322-2047-3_1

[7] Iijima S. Helical microtubules of graphitic carbon. Nature 1991; 354(6348): 56-58. https://doi.org/10.1038/354056a0

[8] Varshney K. Carbon nanotubes: a review on synthesis, properties and applications. International Journal of Engineering Research and General Science 2014; 2(4): 660-677.

[9] Grabowska J. Fulereny-przyszłość zastosowań w medycynie i farmacji. Gazeta Farmaceutyczna 2008; 6: 38-40.

[10] Harris PJ, Harris PJF. Carbon nanotube science: synthesis, properties and applications. Cambridge university press 2009. https://doi.org/10.1017/CBO9780511609701

[11] Rius G Technologies of Carbon Materials. Syntheses and Preparations. In Carbon for Sensing Devices. Springer, Cham 2015; pp. 15-42. https://doi.org/10.1007/978-3-319-08648-4_2

[12] Lee J, Kim T, Jung Y, Jung K, Park J, Lee DM, Kim SM. High-strength carbon nanotube/carbon composite fibers via chemical vapor infiltration. Nanoscale 2016; 8(45): 18972-18979. https://doi.org/10.1039/C6NR06479E

[13] Chua M, Chui CK, Chng CB, Lau D. Carbon nanotube-based artificial tracheal prosthesis: Carbon nanocomposite implants for patient-specific ENT care. IEEE Nanotechnology Magazine 2013; 7(4): 27-31. https://doi.org/10.1109/MNANO.2013.2289691

[14] Arunachalam S, Gupta AA, Izquierdo R, Nabki F. Suspended carbon nanotubes for humidity sensing. Sensors 2018; 18(5): 1655. https://doi.org/10.3390/s18051655

[15] Ketabi S, Rahmani L. Carbon nanotube as a carrier in drug delivery system for carnosine dipeptide: A computer simulation study. Materials Science and Engineering: C 2017; 73: 173-181. https://doi.org/10.1016/j.msec.2016.12.058

[16] Kumar S, Nehra M, Kedia D, Dilbaghi N, Tankeshwar K, Kim KH. Carbon nanotubes: A potential material for energy conversion and storage. Progress in Energy and Combustion Science 2018; 64: 219-253. https://doi.org/10.1016/j.pecs.2017.10.005

[17] Puett C, Inscoe C, Hartman A, Calliste J, Franceschi DK, Lu J, Lee YZ. An update on carbon nanotube-enabled X-ray sources for biomedical imaging. Wiley Interdisciplinary Reviews: Nanomedicine and Nanobiotechnology 2018; 10(1): e1475. https://doi.org/10.1002/wnan.1475

[18] Sun Y, Yun KN, Leti G, Lee SH, Song YH, Lee CJ. High-performance field emission of carbon nanotube paste emitters fabricated using graphite nanopowder filler. Nanotechnology 2017; 28(6): 065201. https://doi.org/10.1088/1361-6528/aa523e

[19] Zhao T, Ji X, Jin W, Yang W, Li T. Hydrogen storage capacity of single-walled carbon nanotube prepared by a modified arc discharge. Fullerenes, Nanotubes and Carbon Nanostructures 2017; 25(6): 355-358. https://doi.org/10.1080/1536383X.2017.1305358

[20] Xu JL, Dai RX, Xin Y, Sun YL, Li X, Yu YX, Ren TL. Efficient and reversible electron doping of semiconductor-enriched single-walled carbon nanotubes by using decamethylcobaltocene. Scientific Reports 2017; 7(1): 1-10. https://doi.org/10.1038/s41598-017-05967-w

[21] Choi J, Park BC, Ahn SJ, Kim DH, Lyou J, Dixson RG, Vorburger TV. Evaluation of carbon nanotube probes in critical dimension atomic force microscopes. Journal of Micro/Nanolithography, MEMS, and MOEMS 2016; 15(3): 034005. https://doi.org/10.1117/1.JMM.15.3.034005

[22] Chen S, Shan B, Yang Y, Yuan G, Huang S, Lu X, Liu J. An overview of carbon nanotubes based interconnects for microelectronic packaging. In 2017 IMAPS Nordic Conference on Microelectronics Packaging (NordPac). IEEE 2017; pp. 113-119. https://doi.org/10.1109/NORDPAC.2017.7993175

[23] Baughman RH, Zakhidov AA, De Heer WA. Carbon nanotubes--the route toward applications. Science 2002; 297(5582): 787-792. https://doi.org/10.1126/science.1060928

[24] Cao J, Wang Q, Rolandi M, Dai H. Aharonov-bohm interference and beating in single-walled carbon-nanotube interferometers. Physical Review Letters 2004; 93(21): 216803. https://doi.org/10.1103/PhysRevLett.93.216803

[25] Biercuk MJ, Llaguno MC, Radosavljevic M, Hyun JK, Johnson AT, Fischer JE. Carbon nanotube composites for thermal management. Applied Physics Letters 2002; 80(15): 2767-2769. https://doi.org/10.1063/1.1469696

[26] Peigney A. Tougher ceramics with nanotubes. Nature Materials 2003; 2(1): 15-16. https://doi.org/10.1038/nmat794

[27] Kong J, Franklin NR, Zhou C, Chapline MG, Peng S, Cho K, Dai H. Nanotube molecular wires as chemical sensors. Science 2000; 287(5453): 622-625. https://doi.org/10.1126/science.287.5453.622

[28] Srivastava A, Srivastava S, Kalaga K. Carbon nanotube membrane filters. In Springer Handbook of Nanomaterials; Springer, Berlin, Heidelberg 2013; pp. 1099-1116. https://doi.org/10.1007/978-3-642-20595-8_31

[29] Li J, Stevens R, Delzeit L, Ng HT, Cassell A, Han J, Meyyappan M. Electronic properties of multiwalled carbon nanotubes in an embedded vertical array. Applied Physics Letters 2002; 81(5): 910-912. https://doi.org/10.1063/1.1496494

[30] Che G, Lakshmi BB, Fisher ER, Martin CR. Carbon nanotubule membranes for electrochemical energy storage and production. Nature 1998; 393(6683): 346-349. https://doi.org/10.1038/30694

[31] Aqel A, Abou El-Nour KM, Ammar RA, Al-Warthan A. Carbon nanotubes, science and technology part (I) structure, synthesis and characterisation. Arabian Journal of Chemistry 2012; 5(1): 1-23. https://doi.org/10.1016/j.arabjc.2010.08.022

[32] Popov VN. Carbon nanotubes: properties and application. Materials Science and Engineering: R: Reports 2004; 43(3): 61-102. https://doi.org/10.1016/j.mser.2003.10.001

[33] Wilder JW, Venema LC, Rinzler AG, Smalley RE, Dekker C. Electronic structure of atomically resolved carbon nanotubes. Nature 1998; 391(6662): 59-62. https://doi.org/10.1038/34139

[34] Ganesh EN. Single walled and multi walled carbon nanotube structure, synthesis and applications. International Journal of Innovative Technology and Exploring Engineering 2013; 2(4): 311-320.

[35] Iijima S, Ichihashi T. Single-shell carbon nanotubes of 1-nm diameter. Nature 1993; 363(6430): 603-605. https://doi.org/10.1038/363603a0

[36] Brenner DW. Empirical potential for hydrocarbons for use in simulating the chemical vapor deposition of diamond films. Physical Review B 1990; 42(15): 9458. https://doi.org/10.1103/PhysRevB.42.9458

[37] Zhao T, Li G, Liu L, Du L, Liu Y, Li T. Hydrogen storage behavior of amorphous carbon nanotubes at low pressure and room temperature. Fullerenes, Nanotubes and Carbon Nanostructures 2011; 19(8): 677-683. https://doi.org/10.1080/1536383X.2010.515757

[38] Kaushik BK, Majumder MK. Carbon nanotube: Properties and applications. In Carbon Nanotube Based VLSI Interconnects; Springer, New Delhi 2015; pp. 17-37. https://doi.org/10.1007/978-81-322-2047-3_2

[39] Sinnott SB, Andrews R. Carbon nanotubes: synthesis, properties, and applications. Critical Reviews in Solid State and Materials Sciences 2001; 26(3): 145-249. https://doi.org/10.1080/20014091104189

[40] Mamalis AG, Vogtländer LOG, Markopoulos A. Nanotechnology and nanostructured materials: trends in carbon nanotubes. Precision Engineering 2004; 28(1): 16-30. https://doi.org/10.1016/j.precisioneng.2002.11.002

[41] Li WZ, Xie SS, Qian LX, Chang BH, Zou BS, Zhou WY, Wang G. Large-scale synthesis of aligned carbon nanotubes. Science 1996; 274(5293): 1701-1703. https://doi.org/10.1126/science.274.5293.1701

[42] Duesberg GS, Muster J, Byrne HJ, Roth S, Burghard M. Towards processing of carbon nanotubes for technical applications. Applied Physics A 1999; 69(3): 269-274. https://doi.org/10.1007/s003390051001

[43] Ibrahim KS. Carbon nanotubes-properties and applications: a review. Carbon Letters 2013; 14(3): 131-144. https://doi.org/10.5714/CL.2013.14.3.131

[44] Zhu J, Holmen A, Chen D. Carbon nanomaterials in catalysis: proton affinity, chemical and electronic properties, and their catalytic consequences. ChemCatChem 2013; 5(2): 378-401. https://doi.org/10.1002/cctc.201200471

[45] Karami M, Bahabadi MA, Delfani S, Ghozatloo A. A new application of carbon nanotubes nanofluid as working fluid of low-temperature direct absorption solar collector. Solar Energy Materials and Solar Cells 2014; 121: 114-118. https://doi.org/10.1016/j.solmat.2013.11.004

[46] Esfe MH, Saedodin S, Yan WM, Afrand M, Sina N. Study on thermal conductivity of water-based nanofluids with hybrid suspensions of CNTs/Al 2 O 3 nanoparticles. Journal of Thermal Analysis and Calorimetry 2016; 124(1): 455-460. https://doi.org/10.1007/s10973-015-5104-0

[47] Mauter MS, Elimelech M. Environmental applications of carbon-based nanomaterials. Environmental Science & Technology 2008; 42(16): 5843-5859. https://doi.org/10.1021/es8006904

[48] Thirumal V, Pandurangan A, Jayavel R, Krishnamoorthi SR, Ilangovan R. Synthesis of nitrogen doped coiled double walled carbon nanotubes by chemical vapor deposition method for supercapacitor applications. Current Applied Physics 2016; 16(8): 816-825. https://doi.org/10.1016/j.cap.2016.04.018

[49] Peng H, Alemany LB, Margrave JL, Khabashesku VN. Sidewall carboxylic acid functionalization of single-walled carbon nanotubes. Journal of the American Chemical Society 2003; 125(49): 15174-15182. https://doi.org/10.1021/ja037746s

[50] Liang J. Exploration of carbon nanotube and copper-carbon nanotube composite for next generation on-chip energy efficient interconnect applications (Doctoral dissertation, Université Montpellier) 2019.

[51] Robertson DH, Brenner DW, Mintmire JW. Energetics of nanoscale graphitic tubules. Physical Review B 1992; 45(21): 12592. https://doi.org/10.1103/PhysRevB.45.12592

[52] Yu MF, Files BS, Arepalli S, Ruoff RS. Tensile loading of ropes of single wall carbon nanotubes and their mechanical properties. Physical Review Letters 2000; 84(24): 5552. https://doi.org/10.1103/PhysRevLett.84.5552

[53] Saifuddin N, Raziah AZ, Junizah AR. Carbon nanotubes: a review on structure and their interaction with proteins. Journal of Chemistry 2013; 2013. https://doi.org/10.1155/2013/676815

[54] Zhang W, Zhang Z, Zhang Y. The application of carbon nanotubes in target drug delivery systems for cancer therapies. Nanoscale Research Letters 2011; 6(1): 1-22. https://doi.org/10.1186/1556-276X-6-555

[55] Rosen Y, Elman NM. Carbon nanotubes in drug delivery: focus on infectious diseases. Expert Opinion on Drug Delivery 2009; 6(5): 517-530. https://doi.org/10.1517/17425240902865579

[56] He H, Pham-Huy LA, Dramou P, Xiao D, Zuo P, Pham-Huy C. Carbon nanotubes: applications in pharmacy and medicine. BioMed Research International 2013; 2013. https://doi.org/10.1155/2013/578290

[57] Yang F, Jin C, Yang D, Jiang Y, Li, J, Di Y, Fu D. Magnetic functionalised carbon nanotubes as drug vehicles for cancer lymph node metastasis treatment. European Journal of Cancer 2011; 47(12): 1873-1882. https://doi.org/10.1016/j.ejca.2011.03.018

[58] Marquis FD. Fully integrated hybrid polymeric carbon nanotube composites. In Materials Science Forum. Trans Tech Publications Ltd., Zurich-Uetikon, Switzerland 2003; Vol. 437: pp. 85-88. https://doi.org/10.4028/www.scientific.net/MSF.437-438.85

[59] Bian Z, Wang RJ, Wang WH, Zhang T, Inoue A. Carbon‐Nanotube‐Reinforced Zr‐Based Bulk Metallic Glass Composites and Their Properties. Advanced Functional Materials 2004; 14(1): 55-63. https://doi.org/10.1002/adfm.200304422

[60] Pham-Huy LA, He H, Pham-Huy C. Free radicals, antioxidants in disease and health. International Journal of Biomedical Science: IJBS 2008; 4(2): 89.

[61] Bekyarova E, Ni Y, Malarkey EB, Montana V, McWilliams JL, Haddon RC, Parpura V. Applications of carbon nanotubes in biotechnology and biomedicine. Journal of Biomedical Nanotechnology 2005; 1(1): 3-17. https://doi.org/10.1166/jbn.2005.004

[62] Liao H, Paratala B, Sitharaman B, Wang Y. Applications of carbon nanotubes in biomedical studies. In Biomedical Nanotechnology. Humana Press 2011; pp. 223-241. https://doi.org/10.1007/978-1-61779-052-2_15

[63] Pai P, Nair K, Jamade S, Shah R, Ekshinge V, Jadhav N. Pharmaceutical applications of carbon tubes and nanohorns. Current Pharma Esearch Journal 2006; 1: 11-15.

[64] Ding RG, Lu GQ, Yan ZF, Wilson MA. Recent advances in the preparation and utilization of carbon nanotubes for hydrogen storage. Journal of Nanoscience and Nanotechnology 2001; 1(1): 7-29. https://doi.org/10.1166/jnn.2001.012

[65] Kuznetsova A, Mawhinney DB, Naumenko V, Yates Jr, JT, Liu J, Smalley RE. Enhancement of adsorption inside of single-walled nanotubes: opening the entry ports. Chemical Physics Letters 2000; 321(3-4): 292-296. https://doi.org/10.1016/S0009-2614(00)00341-9

[66] Shi X, Sitharaman B, Pham QP, Spicer PP, Hudson JL, Wilson LJ, Mikos AG. *In vitro* cytotoxicity of single‐walled carbon nanotube/biodegradable polymer nanocomposites. Journal of Biomedical Materials Research Part A 2008; 86(3): 813-823. https://doi.org/10.1002/jbm.a.31671

[67] Harrison BS, Atala A. Carbon nanotube applications for tissue engineering. Biomaterials 2007; 28(2): 344-353. https://doi.org/10.1016/j.biomaterials.2006.07.044

[68] Singh R, Pantarotto D, Lacerda L, Pastorin G, Klumpp C, Prato M, Kostarelos K. Tissue biodistribution and blood clearance rates of intravenously administered carbon nanotube radiotracers. Proceedings of the National Academy of Sciences 2006; 103(9): 3357-3362. https://doi.org/10.1073/pnas.0509009103

[69] Wang SF, Shen L, Zhang WD, Tong YJ. Preparation and mechanical properties of chitosan/carbon nanotubes composites. Biomacromolecules 2005; 6(6): 3067-3072. https://doi.org/10.1021/bm050378v

[70] MacDonald RA, Laurenzi BF, Viswanathan G, Ajayan PM, Stegemann JP. Collagen–carbon nanotube composite materials as scaffolds in tissue engineering. Journal of Biomedical Materials Research Part A: An Official Journal of The Society for Biomaterials, The Japanese Society for Biomaterials, and The Australian Society for Biomaterials and the Korean Society for Biomaterials 2005; 74(3): 489-496. https://doi.org/10.1002/jbm.a.30386

[71] Castillo JJ, Svendsen WE, Rozlosnik N, Escobar P, Martínez F, Castillo-León J. Detection of cancer cells using a peptide nanotube–folic acid modified graphene electrode. Analyst 2013; 138(4): 1026-1031. https://doi.org/10.1039/C2AN36121C

[72] Eatemadi A, Daraee H, Zarghami N, Melat Yar H, Akbarzadeh A. Nanofiber: synthesis and biomedical applications. Artificial Cells, Nanomedicine, and Biotechnology 2016; 44(1): 111-121. https://doi.org/10.3109/21691401.2014.922568

[73] Qiu W, Xu H, Takalkar S, Gurung AS, Liu B, Zheng Y, Liu G. Carbon nanotube-based lateral flow biosensor for sensitive and rapid detection of DNA sequence. Biosensors and Bioelectronics 2015; 64: 367-372. https://doi.org/10.1016/j.bios.2014.09.028

[74] Sinha N, Yeow JW. Carbon nanotubes for biomedical applications. IEEE Transactions on Nanobioscience 2005; 4(2): 180-195. https://doi.org/10.1109/TNB.2005.850478

[75] Joseph H. MEMS in the medical world. Sensors-the Journal of Applied Sensing Technology 1997; 14(4): 47-51.

[76] Foroughi J, Spinks GM, Aziz S, Mirabedini A, Jeiranikhameneh A, Wallace GG, Baughman RH. Knitted carbon-nanotube-sheath/spandex-core elastomeric yarns for artificial muscles and strain sensing. ACS Nano 2016; 10(10): 9129-9135. https://doi.org/10.1021/acsnano.6b04125

[77] Wu L, Qu X. Cancer biomarker detection: recent achievements and challenges. Chemical Society Reviews 2015; 44(10): 2963-2997. https://doi.org/10.1039/C4CS00370E

[78] Liu CH, Wu CC, Zhong Z. A fully tunable single-walled carbon nanotube diode. Nano Letters 2011; 11(4): 1782-1785. https://doi.org/10.1021/nl200371z

[79] Lee JU. Photovoltaic effect in ideal carbon nanotube diodes. Applied Physics Letters 2005; 87(7): 073101. https://doi.org/10.1063/1.2010598

[80] Vakhrushev AV, Vakhrushev AA, Chuckova NN, Cherenkov IA, Cormilina NV. Adsorption of Cholesterol by Carbon Nanotubes. Carbon Nanotubes and Nanoparticles: Current and Potential Applications 2019; 65. https://doi.org/10.1201/9780429463877-4

[81] Huang X, Mclean RS, Zheng M. High-resolution length sorting and purification of DNA-wrapped carbon nanotubes by size-exclusion chromatography. Analytical Chemistry 2005; 77(19): 6225-6228. https://doi.org/10.1021/ac0508954

[82] Rinzler AG, Liu J, Dai H, Nikolaev P, Huffman CB, Rodriguez-Macias FJ, Smalley RE. Large-scale purification of single-wall carbon nanotubes: process, product, and characterization. Applied Physics A: Materials Science & Processing 1998; 67(1). https://doi.org/10.1007/s003390050734

[83] Gu Z, Peng H, Hauge RH, Smalley RE, Margrave JL. Cutting single-wall carbon nanotubes through fluorination. Nano Letters 2002; 2(9): 1009-1013. https://doi.org/10.1021/nl025675+

[84] Popov VN. Carbon nanotubes: properties and application. Materials Science and Engineering: R: Reports 2004; 43(3): 61-102. https://doi.org/10.1016/j.mser.2003.10.001

[85] Baughman RH, Zakhidov AA, De Heer WA. Carbon nanotubes--the route toward applications. Science 2002; 297(5582): 787-792. https://doi.org/10.1126/science.1060928

[86] Terrones M. Science and technology of the twenty-first century: synthesis, properties, and applications of carbon nanotubes. Annual Review of Materials Research 2003; 33(1): 419-501. https://doi.org/10.1146/annurev.matsci.33.012802.100255

[87] Dai H, Wong EW, Lu YZ, Fan S, Lieber CM. Synthesis and characterization of carbide nanorods. Nature 1995; 375(6534): 769-772. https://doi.org/10.1038/375769a0

[88] Ajayan PM, Zhou OZ. Applications of carbon nanotubes. Carbon nanotubes 2001; 391-425. https://doi.org/10.1007/3-540-39947-X_14

[89] De Heer WA. Nanotubes and the pursuit of applications. MRS Bulletin 2004; 29(4): 281-285. https://doi.org/10.1557/mrs2004.81

[90] Ye XR, Lin Y, Wang C, Wai CM. Supercritical fluid fabrication of metal nanowires and nanorods templated by multiwalled carbon nanotubes. Advanced Materials 2003; 15(4): 316-319. https://doi.org/10.1002/adma.200390077

[91] Han W, Fan S, Li Q, Hu Y. Synthesis of gallium nitride nanorods through a carbon nanotube-confined reaction. Science 1997; 277(5330): 1287-1289. https://doi.org/10.1126/science.277.5330.1287

[92] Bower C, Rosen R, Jin L, Han J, Zhou O. Deformation of carbon nanotubes in nanotube–polymer composites. Applied Physics Letters 1999; 74(22): 3317-3319. https://doi.org/10.1063/1.123330

[93] Kaur R, Vatta P, Kaur M. Carbon Nanotubes: A Review Article. International Journal for Research in Applied Science and Engineering Technology. India 2018; 6(4): 5075-5077. https://doi.org/10.22214/ijraset.2018.4827

[94] Rafique MMA, Iqbal J. Production of carbon nanotubes by different routes-a review. Journal of Encapsulation and Adsorption Sciences 2011; 1(02): 29. https://doi.org/10.4236/jeas.2011.12004

Received on 03-12-2020 Accepted on 27-12-2020 Published on 30-12-2020

DOI: https://doi.org/10.6000/1929-5995.2020.09.10