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Recent Advances In Carbon Nanotubes For Biomedical Application And Nanotechnology

Miss Gaikwad Shruti balasaheb, Miss Dagade Shruti Mahadev, Miss Dhavale Shruti bapurao Miss Datir Shivani Hanumant ,Miss Barbade Vaishnavi

Abstract:

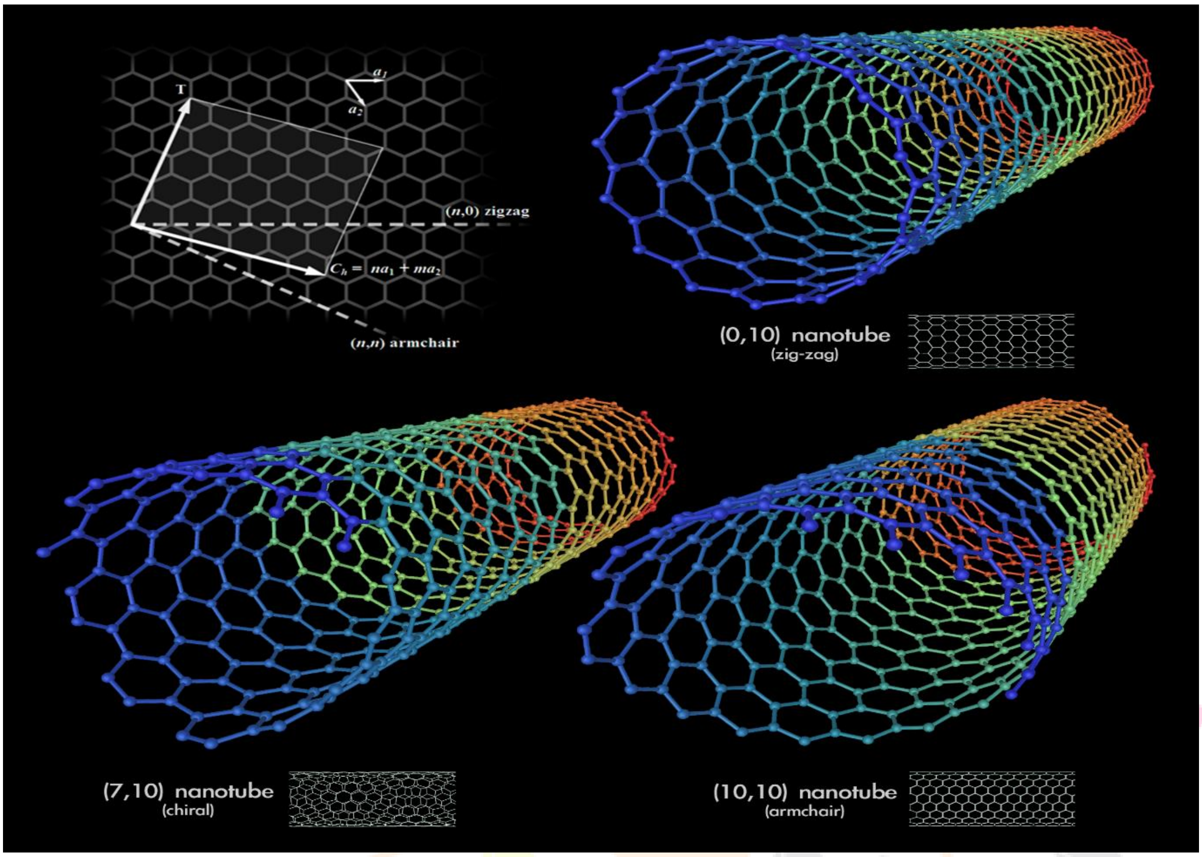
Carbon nanotubes(CNTs), indeed stand as one of the major game changer in the landscape of nano-technology especially recent advances made on such synthetic device for biomedical applications and Nano-scale engineering. This has led to recent advances, such as improved drug delivery systems, precision oncology and detection of biological compounds. From selectively targeting cancer cells to improved diagnostic accuracy, functionalized carbon nanotubes have opened the gates for novel nano-constructs that are multifunctional in nature. These technological advancements are changing the way diseases get diagnosed, treated and monitored. F1000Review is a structured, Citeable review and presentation of this industry-breaking paper: The most exciting work on the applications of carbon nanotubes in biomedicine and nanotechnology. C: Carbon nanotubes (CNTs) are tube-like materials that contain carbon and have a diameter measured in linear angstrom, when it comes to tens of naoms. They are basically made up of a graphite sheet, and these sheets look like when you have rolled up an unendingly endless breakage non-breakable hexagonal shape mesh structure with carbon molecules present on the apexes (peak points) of those hexagon structures. Carbon nanotubes, depending upon the number of carbon layers can be single-walled carbon nanotubes (SWCNTs), double-walled carbon nanotubes (DWCNTs),multi-walled carbon nanotubes (MWCNTs)The main three ways of building carbon nanotubes (CNTs) are chemical vapor deposition, electric arc method and laser deposition method. Further, because of the interesting properties including high elasticity, low density and great thermal conductivity to name a few it was also reported that carbon nanotubes have found significant applications in areas like nanotechnology electronic materials science optics among many other fields as well. Applications of carbon nanotubes are used for drug delivery, sensing and water treatment etc.

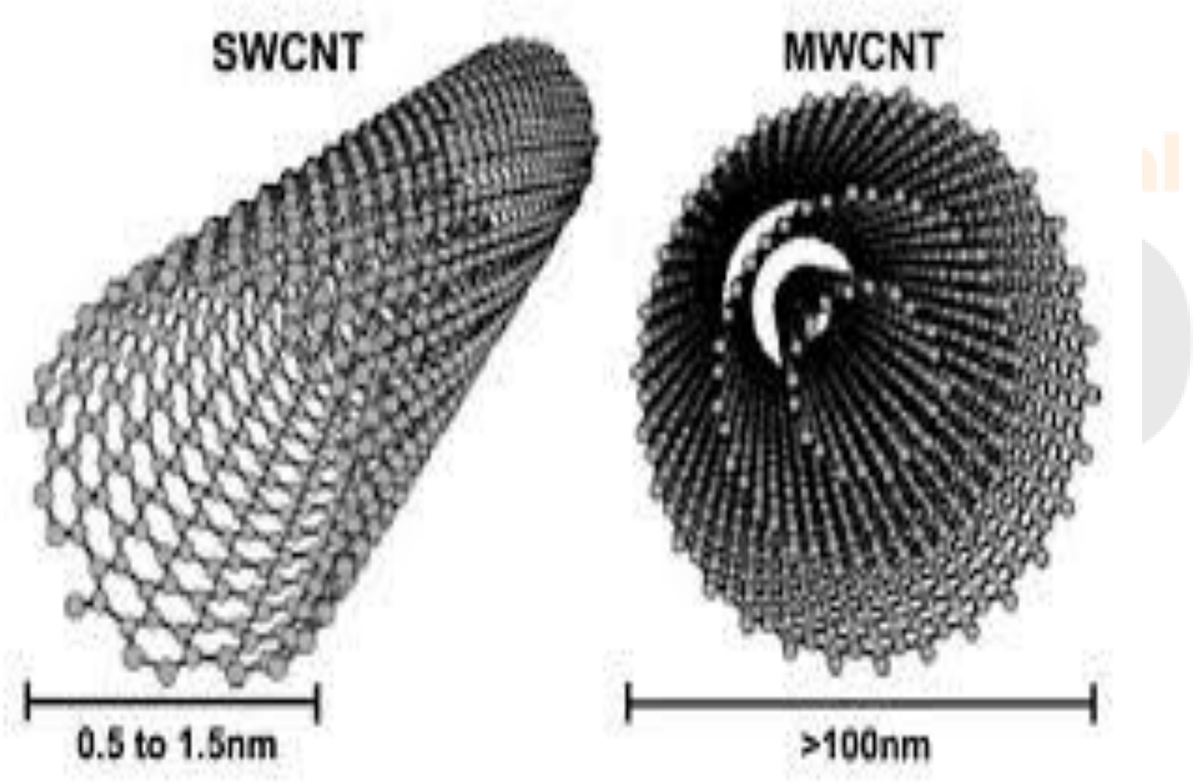
Keywords:

Carbon nano horns (CNHs),Fullerenes ,Functionalized CNTs , Graphene oxide (GO), Metal-organic frameworks (MOFs), Multi-walled carbon nanotubes (MWCNTs), Nanodiamonds, Quantum dots , Reduced graphene oxide (rGO), Single-walled carbon nanotubes (SWCNTs).

Introduction

carbon-based quantum dots [3, 4], graphene oxide, and nanotubes and their derivatives, including nanodiamonds [2]. Carbon nanotubes (CNTs), which Iijima discovered in 1991, are regarded as the most notable creation in nanotechnology [5, 6] because of their exceptional electrical, optical, thermal, and mechanical capabilities. Because of its sp, sp2, or sp3 hybridization, carbon is one of the most flexible elements, having several allotropes and structures with different characteristics. These characteristics make it possible to create a variety of structures that range in size from a few nanometres to hundreds of millimetres. The ability to create and characterize carbon compounds at the nanoscale has made them a hot topic in the field of nanotechnology. One of the special characteristics of carbon nanomaterials is their large specific surface area strong electrical conductivity, flexibility, optical transparency, and high carrier mobility; as a result, they are used in many different fields, including tissue engineering, medication administration, biosensing, and molecular imaging [1]. Carbon nanomaterials can be molded into a variety of shapes, including nanowires, 2D films, and even 3D structures. Graphene, fullerenes, and carbon are examples of carbon-based nanomaterials. Layers of carbon atoms arranged in a hexagonal pattern on top of one another in a rolled tube make up carbon nanotubes (CNTs). Sp2 hybridized carbon atoms are arranged in CNTs with an interatomic spacing of 1.4 Å. Buckytubes, which are hollow tubes with sizes in the nanometer range, are another name for carbon nanotubes. Based on the quantity of carbon layers they contain, CNTs are often classified into two categories. With sizes ranging from 0.4 to 2 nm, single-walled carbon nanotubes (SWCNTs), which are made up of a single layer of graphene, are typically found in hexagonally packed bundles. Two areas of the SWCNTs have different chemical and physical characteristics. The two areas are the tube's end cap and sidewall [7]. The intricate structure of multi-walled carbon nanotubes (MWCNTs) is composed of two or more cylinders (about fifty), each of which is composed of graphene sheets. The sizes fall between 1 and 3 nm [8]. The concentric arrangement of several SWNTs is another way to describe them. High frequency semiconducting devices, light-emitting diodes (LEDs), microelectronic devices, wearable and textile-based electrodes, large-area printed electronics, radio-frequency identification (RFID) tags, circuits, humidity sensors, catalysis, and flexible sensors for bio-signal measurement, including electroencephalography, electrocardiogram (ECG), and electromyography, are just a few of the many applications for MWCNTs [9]. Mostly found as a fluffy black and granular powder, MWCNTs exhibit superior mechanical and physical properties, such as a high modulus of elasticity (≥ 1 TPA), a tensile strength of 65–93 GPa, twice the thermal conductivity of diamond, a high aspect ratio in the range of 100–2,50,000, and excellent electrical conductivity. Despite having a fairly basic chemical makeup and atomic bonding arrangement, carbon nanotubes (CNTs) exhibit a remarkable diversity and richness in their topologies and structure–property relationships. The length and diameter of CNTs can affect their properties. Trivalent or pentavalent impurities can be readily added to the structure of carbon nanotubes to change their electrical characteristics. These dopants may fill the cylindrical holes in SWCNTs or the inter shell gaps in MWCNTs [10]. Because of the strength of the atomic connections, CNTs have an extremely high thermal conductivity, which can range from 3000 to 6000 W/m.K. at 300 K [11]. It is capable of withstanding temperatures as high as 750 °C under normal conditions and 2800 °C at vacuum atmospheric pressure. CNTs possess a high specific heat (425 Cp (J kg^{-1} K^{-1})), tensile strength (22.2–63 GPa), and density ($\rho < 1600$ kg/m3). Its internal temperature and the temperature around it both affect its thermal conductivity. CNTs have a Young's modulus of 1.4 TPa and a maximum tensile strength of about 100 GPa, making them stiffer than diamonds [12]. There are some differences between SWCNTs and MWCNTs. MWCNTs have several graphene layers and are challenging to twist, whereas SWCNTs only have one layer and are easily twisted. SWCNTs require a catalyst to be manufactured, whereas MWCNTs do not. MWCNTs are more pure than SWCNTs and are easier to synthesize in bulk. Compared to MWCNTs, SWCNTs are denser [13,14]. Table S1 (Supplementary Information) provides examples. Because CNTs are hydrophobic, many of their industrial uses are restricted. They are insoluble in water and difficult to dissolve in other solvents. Because CNTs can conjugate with a variety of molecules with varying chemical structures, they may find use in the biomedical industry [15–16].Since CNTs increase the drug's ability to enter cells and have a better effect, they are being investigated for use in drug delivery. Surface functionalization is used to achieve selective targeting in anti-cancer therapy. CNTs are used in tissue engineering to enhance the mechanoelectrical properties of scaffolds, allowing chemical processes to occur inside the cells and sensation to occur in the cell's microenvironment [17]. Function-alized CNTs in biosensors have the ability to readily infiltrate individual cells and cross biological barriers. CNTs are of interest in biosensors due to their internalization mechanism and cell release [18]. Presenting the use and production methods of carbon nanotubes (CNTs) in light of environmental concerns and upcoming developments in the biomedical field is the review's main goal. In the next section, several functionalization methods have been explained. There has been discussion and a summary of the current state of five primary biomedical uses of carbon nanotubes (CNTs): drug delivery, biosensors, bioimaging, tissue engineering, and cancer treatment. The main obstacle to using CNTs in biomedicine is their toxicity, which is thoroughly examined and a potential remedy is offered. The economics of the current market, its main manufacturers, and costs have all been discussed in this review.





Classification of CNTs:

Properties	SWNTs	MWNTs
Organoleptic property appearance	Granular or fluffy black powder sometimes with a shiny metallic appearance	Mostly granular and fluffy black powder
Appearance on electron microscopy Qualitative analysis using Raman spectroscopy	Appearance as aggregated bundles gives characteristic peaks	Aggregate bundles there are no such characteristic peaks observed
Solubility study	Soluble in water and ethanol, form aggregate soon after sonication	Quite soluble in water but form slightly transluscent dispersions
Electrical property	Good electrical conductivity	Bad conductors of electricity

Method of preparation of CNTs

The major synthesis techniques used for SWCNTs and MWCNTs are arc discharge method, laser ablation method, chemical vapor deposition (CVD) method, spray pyrolysis, and flame synthesis method CNTs are widely accepted nanocarriers in the field of drug delivery and in biomedical application. For pharmaceutical use, the CNTs produced must be of good quality, free from impurities and carbonaceous matter and should not have damaged structures.[19] CNTscanbesynthesized naturally by heating carbon black and graphites in a controlled flame environment. However, nanotubesproducedbythismethodaremostlyirregularinsize, shape, mechanical strength, quality and purity because of the uncontrollable natural environment.[20] Nowadays CNTs are synthesized by artificially developed methods of considerable interest to the pharmaceutical scientist, which include electric arc discharge (EAD), laser ablation technique (LA) and catalytic chemical vapour deposition (CVD) methods. The major synthesis techniques used for SWCNTs and MWCNTs are arc discharge method, spray pyrolysis, and flame synthesis method In addition, several other techniques such as plasma enhanced chemical vapour deposition (PE-CVD)[21] and high pressure carbon mon oxide disproportionation process (HiPCO) technique are of recent interest. The HiPCO technique can be used for the catalytic productionofSWNTsinacontinuous-flowgasphase, using carbon monoxide (CO) as the carbon feedstock and Fe(CO)5 (iron pentacarbonyl) as the iron-containing catalyst precursor. The size and diameter distribution of the nanotubes can be roughly selected by controlling the pressure of the CO. This process is promising for bulk production of CNTs.[22] Different methods of preparation produce CNTs with different physical and mechanical properties. The type of CNTs pro duced, solubility, mechanical properties, quality, purity and yield usually differ from one method to another (Table 2). In the electric arc discharge method, two different types of electrodes (anode and cathode) are used. CNTs are produced at the end of the anode, which consists of pure graphite. The nanotubes are produced by high voltage beams (around 100 amp) of electrons produced by the electric arc, which bombards the graphite surface. The electric arc is a plasmon setup made across CNTs resulting in the formation of CNTs on a substrate.[20,23,24] In the laser ablation technique, the nanotubes are produced by allowing a specific spectrum of laser beam to strike on the graphitic target using transition metal as catalyst, which produces both SWNTs and MWNTs. This method uses two different laser sources, as primary laser and secondary laser beam. The initial bombardment is done with the primary laser followed by a secondary laser beam to finally produce CNTs of high quality. This method has the advantage of producing nanotubes desired for particular applications.[25,26] However, this method has the drawback of being time consuming and costly. The catalytic chemical vapour deposition (CVD) tech nique works on a principle completely different from the above methods. Here, the feed material used is present in the form of a mixed vapour phase (vaporized carbon along with an inert gas). This feed material is passed through a hot furnace where it decomposes to give CNTs deposited on the surface of a substrate. The substrate is made by embedding nanometre-sized nickel or cobalt particles, or a combination of both, as a catalyst on its surface and is generally heated to approximately 700°C.[27,28,29] The variables, including nano tube diameter and tensile strength, depend on the size of the metal particles. These can be controlled by masked deposition of the metal, by annealing or by plasma etching of a metal layer. For commercial production, the nano-sized metal particles are mixed with MgO or Al2O3 to increase catalyst support and increase the surface area for higher yield.[30]Addi tionally, several newer techniques namely plasma-enhanced chemical vapour deposition (PECVD), CoMoCat process, thermal CVD, laser-assisted CVD and high pressure CVD have been developed for high quality CNT production.[31,32] The flame synthesis process is autothermal and provides an opti mal temperature for obtaining the preferred conditions for synthesis. It involves the growth of CNTs by the introduction of a catalyst. The catalyst can be in the form of solid support or in the gas phase (floating catalyst). The flame provides energy and chemical species in the synthesis of CNTs [34, 25, 26, 28]. Spray pyrolysis is a method for forming thin films and synthesizing thin films of metals, metal oxides sulfides, and nitrides. This method has an edge over others as by this method we can produce large-sized CNTs on a commercial scale [35, 33–34]. The different methods of synthesis of CNTs are summarized with their advantages and disadvantages and listed in Table S2 (Supplementary Information).

APPLICATIONS:

Recent advancement in carbon nanotubes have a significantly impacted both biomedical applications and nanotechnology. Their unique properties ,such a high electrical and thermal conductivity ,mechanical straight ,and large surface area ,make them highly versatile for various innovative applications .The unique qualities of carbon nanotubes (CNTs), such as their high strength, electrical conductivity, thermal stability, and light weight, have made them suitable for a wide range of applications in several sectors.Here area few noteworthy uses:

1.Electronics and Semiconductors:

CNTs are being used to make integrated circuits and transistors that are faster, smaller, and consume less energy than conventional silicon-based transistors. This has the potential to transform the semiconductor sector and provide smaller, faster electronics.

Flexible Electronics:

Because CNTs are pliable, they can be incorporated into circuits that are bendable or stretchable, opening the door to the creation of wearable technology, flexible displays, and medical sensors.

2.Energy Conversion and Storage

Lithium-ion batteries and supercapacitors incorporate carbon nanotubes (CNTs) in their electrodes to

increase their capacity, charge/discharge rates, and general efficiency. They are perfect for improving energy storage systems because of their conductivity and surface area.

Solar Cells:

By enhancing the absorption and conversion of sunlight into electricity, carbon nanotubes (CNTs) are being used to increase the efficiency of photovoltaic cells, resulting in more effective solar energy solutions.

3.Applications in Medicine and Biomedicine

Drug Delivery:

By functionalizing CNTs, medications can be delivered straight to certain cells, increasing the accuracy of therapies like chemotherapy, reducing side effects, and improving patient outcomes.

Biosensors:

CNTs are perfect for creating biosensors that can identify certain biomolecules or alterations in biological circumstances because of their large surface area and sensitivity. This may result in the early detection of conditions like diabetes or cancer

Tissue engineering:

CNTs are being incorporated into scaffolds to encourage tissue regeneration and cell proliferation, opening up new avenues for the restoration of injured organs or tissues.

4.Composite and Structural Materials

Composites that are lightweight, robust, and resistant to damage are made possible by the incorporation of carbon nanotubes (CNTs) into polymers and other materials. These materials are used to make parts for sports equipment, automobile bodywork, and airplane wings in the construction, automotive, and aerospace sectors.

Wear-resistant Coating:

To increase the longevity of tools, machinery, and infrastructure, CNT-based coatings are applied to surfaces to increase their resistance to wear, corrosion, and severe temperatures.

5.Applications in the Environment

Water Purification:

CNTs are being utilized to create membranes and filters that are more efficient than conventional materials at removing impurities from water. In rural or disaster-affected locations, this offers alternatives for access to clean water by removing heavy metals, organic contaminants, and bacteria.

Air Filtration:

CNTs can improve air quality and preserve the environment by capturing pollutants including particulate matter and hazardous gasses from industrial emissions.

6. Wearables and Textiles

Smart Textiles:

CNTs are used with textiles to provide materials with electrical conductivity and environmental change detection capabilities. As a result, intelligent apparel is being created that can track health, adapt to temperature fluctuations, and even produce energy through movement.

Self-cleaning and antibacterial Fabrics:

CNTs can be added to textiles to give them these qualities, which are useful for outdoor, military, and medical applications.

7.Aerospace and Defense-

Spacecraft Materials:

CNTs' great strength and low weight make them perfect for use in spacecraft, where strength and weight reduction are crucial. They are employed in radiation shielding and structural components.

Ballistic Armor:

Because CNT-based materials can absorb and dissipate energy, they are being investigated for application in ballistic Armor, which would provide better defence against bullets.

8.Quantum computing

Quantum Devices:

The potential of carbon nanotubes (CNTs) to produce quantum bits, or qubits, the fundamental building blocks of quantum computers, is being investigated. They are promising candidates for this new technology because of their distinct mechanical and electrical characteristics.

9. Thermal Management Electronic Heat Dissipation:

Because carbon nanotubes (CNTs) are so good at transmitting heat, they are perfect for use in thermal management systems. High-performance electronics like CPUs and GPUs can benefit from their capacity to disperse heat, which reduces overheating and increases dependability. These usage demonstrate how carbon nanotube technology has the potential to revolutionize a variety of industries, and research is now being conducted to find even more creative applications.

Biomedical Applications of Carbon Nanotubes

1. Drug Delivery Systems:

CNTs are being developed as nanocarriers to deliver drugs directly to specific cells or tissues, improving efficacy while minimizing side effects. Functionalized CNTs (surface-modified) are used to target cancer cells and deliver chemotherapeutics. For example, CNTs functionalized with antibodies or peptides can specifically target tumor cells, improving the precision of cancer treatment.

2. Tissue Engineering:

CNTs are also used in scaffolds for tissue regeneration, particularly in bone and neural tissues. Their ability to support cell adhesion and proliferation, combined with their mechanical strength, makes them promising for repairing damaged tissues. CNT-based scaffolds for neural regeneration can help restore functions in spinal cord injuries by encouraging neuron growth.

3. Biosensors:

Carbon nanotubes are employed in biosensors for detecting biomolecules like glucose, cholesterol, and even pathogens. They enhance sensor sensitivity due to their electrical conductivity and large surface area. CNT-based glucose sensors, for instance, allow for continuous and more accurate monitoring of glucose levels in diabetic patients.

4. Cancer Treatment:

CNTs are being explored for use in photothermal therapy, where they absorb near-infrared light and convert it into heat to kill cancer cells selectively. This method targets and destroys tumor tissues with minimal impact on surrounding healthy cells.

Nanotechnology Applications of Carbon Nanotubes

1. Electronics and Semiconductors:

CNTs are increasingly used in transistors and integrated circuits, particularly in creating CNT field-effect transistors (CNT-FETs), which could outperform traditional silicon transistors. They are also being researched for flexible electronics like bendable displays, thanks to their mechanical strength and conductivity.

2. Energy Storage:

CNTs are making strides in energy storage, particularly in supercapacitors and batteries. Their ability to enhance electrical conductivity and increase surface area makes them ideal for improving the performance of lithium-ion batteries and supercapacitors. For instance, CNT-based anodes in batteries can provide faster charge-discharge cycles and increased energy density.

3. Water Purification:

CNT membranes are being utilized for water purification and desalination. Due to their high surface area and hydrophobicity, CNTs can filter out contaminants like heavy metals, organic pollutants, and microorganisms from water. This makes them particularly valuable for developing nanofiltration systems in areas facing water scar

4.Nanomedicin city.

4e and Imaging:*

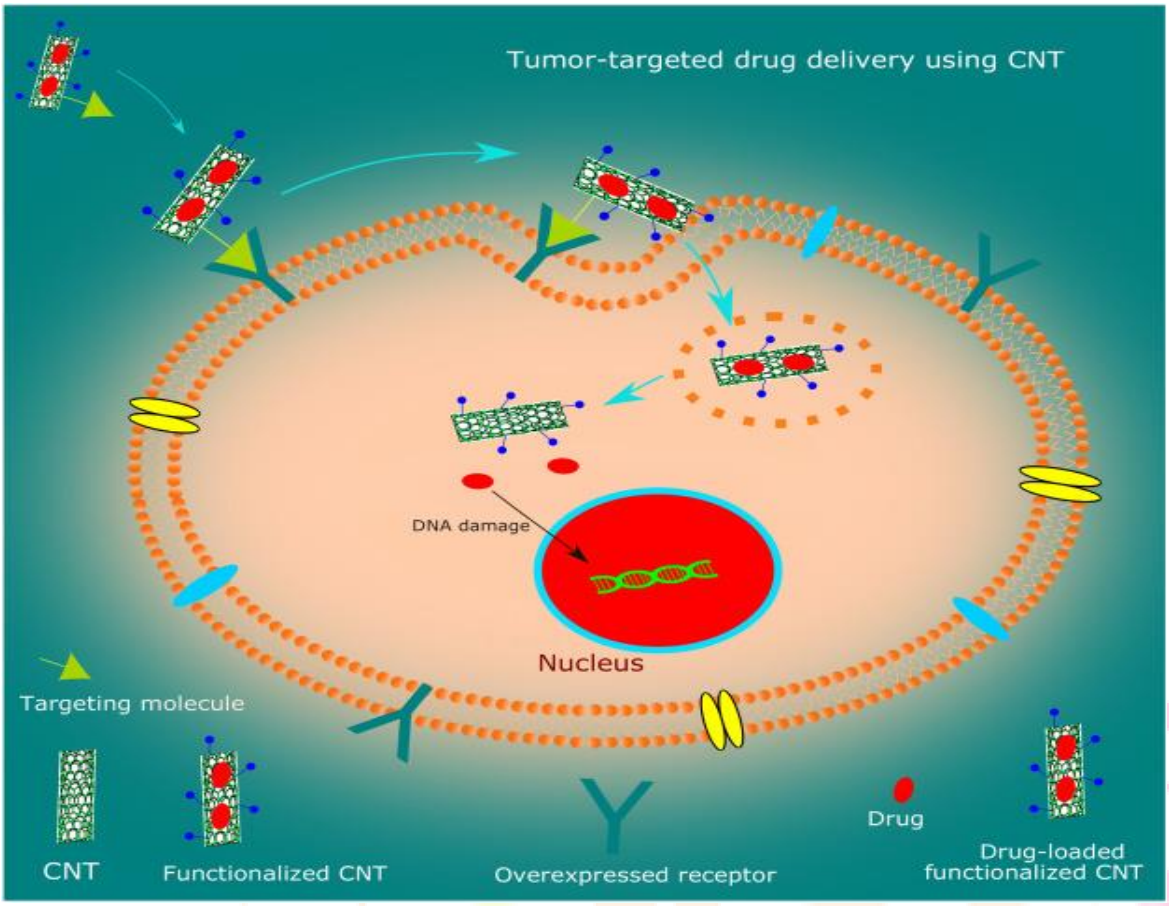
CNTs are being researched for use in bio-imaging and diagnostic tools. Their ability to absorb and emit light at specific wavelengths, particularly in the near-infrared region, makes them ideal for non-invasive imaging techniques like photoacoustic imaging. This helps in the early detection of diseases, including cancers and cardiovascular conditions.

CANCER THERAPY:

The malignant cells are hard to treat or get rid of completely without damaging healthy ones. [35] In addition to also killing normal cells, chemotherapy thus destroys more than 99% of all cancer cells. This causes serious side effects. That's where nanotubes come into play: with their help, cancer cells can be treated both safely and effectively.[36,37] If delivered together with CNTs, chemotherapeutic agents can produce a better uptake in malignant cells, while avoiding unaltered tissues. [38] As a result, nanotubes may well have the advantage of decreasing the dose required to take effect against a disease at its tumour cell source only. In addition to chemotherapy, NTs can also be utilized to carry genes and target cells with

carcinoma treatment. Stanford University recently revealed the more recent practical benefits of carbon nanotubes (CNTs), which have the ability to cure cancer on their own. [39] The findings demonstrated that nanotubes exposed to an infrared (IR) light source have a tendency to heat up to 70°C to 160°C in a relatively short period of time (less than 120 s). When positioned at a tumor site, they readily destroy malignant cells of a particular population and appear to have tumoricidal properties. Because of their rapid infrared absorption capabilities, MWNTs specifically made via the CoMoCAT technique are of great interest for application in chemotherapy. In particular, CoMoCAT nanotubes that have a small absorption peak at 980 nm and a consistent size of roughly 0.81 nm make excellent candidates for this innovative strategy. Such nanotubes were linked to folic acid, a tumor marker, in order to improve targeting ability. Folic acid coupled to its particular folate receptor, and a 980 nm laser's precise wavelength of radiation induced malignant cells to die on purpose. This cancer treatment method is referred to as "photothermal therapy for cancer treatment" in a number of publications. [39,40] In an experiment involving MWNTs, Levi-Polyachenko and colleagues [41] shown that nanotubes exposed to infrared light for less than two seconds could cause hyperthermia, or the heating of the cellular environment, up to 42°C. In order to cure colorectal cancer, this study demonstrated that MWNTs exposed to intense infrared wavelengths (700–1100 nm) produced hyperthermia (42°C) in peritoneal cells for up to two hours.which helps in the treatment of colorectal carcinoma. When fed to colorectal cancer cells, medications such as mitomycin C or oxaliplatin effectively reduce the number of malignant cells because hyperthermia increases drug uptake by increasing cell membrane permeability. Similarly, Torti et al. [42] found that when exposed to an infrared beam, MWNTs doped with nitrogen gas cause thermal ablation, which kills cancer cells. The kidney tumor cells are treated using this method. It was determined that heat transduction, which causes cellular cytotoxicity, may be the cause of CNTs' anti-tumor efficacy. MWNTs coated with DNA had superior tumoricidal effect compared to non-DNA-encased MWNTs, which is consistent with the data above. Guenzel [43] investigated the tumoricidal effect of DNA-coated nanotubes on 12 mice with prostate cancer that were treated separately with MWNTs with and without a laser beam, non-DNA-encased MWNTs, and DNA-encased MWNTs. The findings demonstrated a higher tumor cure rate using DNA-encased MWNTs within 70 s from a 3 W laser beam for a maximum of six days. The underlying fundamental mechanism may be that malignant cells die when their heat production increases by two to three times the threshold. Because DNA-encased nanotubes have a selective tumoricidal effect, this method of treating human tumors has an edge over straightforward radiation and heat therapy. functionalized SWNTs are the most effective at slowing the course of human myeloid leukemia, according to Wang and colleagues [44]. The condition is typically brought on by the key mediator cyclin A 2, which is present in human body cells at a higher level in tumor cells and is essential for interfering with transcription, DNA replication, and cell cycle regulation. Leukemia is one of the cancers that develops as a result of cyclin A 2 overexpression. Therefore, lowering or suppressing the body's amount of cyclin A 2 is advised as a way to stop tumor growth. Functionalized SWNTs delivering tiny interfering siRNA into K562 myelogenous leukemia cells demonstrated high apoptosis, cell proliferation suppression, and cyclin A 2-dependent leukemia development inhibition. In addition to treatment for chronic myeloid leukemia, this opens up a new area of use for nanotubes in the fight against multidrug resistance during chemotherapy for a number of diseases. Recent research reports that nanotubes are used in radiation to cure cancer by accelerating the rate of oxygen uptake to cancerous cells relative to the normal rate of uptake, in addition to their usage in delivering drugs and nucleic acids to cancerous cells.
This increases the effectiveness of the radiation treatment. [45,46] In addition to CNTs, research is currently being done on carbon nanohorns (CNHs) to see if they may be used in chemotherapy. Anti-cancer drugs, such as doxorubicin given intratumorally to mice bearing human non-small cell lung cancer cells (NCI-H460), have been delivered using water-soluble CNHs. These CNHs have demonstrated a notable

reduction in tumor growth linked to extended doxorubicin retention in the tumor cavity. [47,48]



TOXICITY OF CNTs:

Because of their higher surface area to size ratio, nanoparticles offer some noteworthy properties when compared to comparable bulk materials. Because of this characteristic, carbon nanotubes are more poisonous and reactive. Like haptens, carbon nanotubes alter the architecture of proteins and increase their antigenicity, which raises the possibility of autoimmune reactions. The primary causes of carbon nanotube toxicity are their decreased size, which increases their total surface area and ideally suggests that the contact area with cellular membranes has grown, or else the absorption and transportation of toxins has been significantly improved [49]. Another factor is the production of superoxides and reactive oxygen species [50]. Both in vitro and in vivo techniques are used to assess the toxicity of CNTs. Mice and rats are the main subjects of in vivo toxicity investigations. However, there are also reports of research conducted on guinea pigs. Studies on biodistribution and toxicity to particular organs are frequently used. Microbes including bacteria and yeast as well as animal cell lines can be used for in vitro toxicity investigations. Reactive oxygen species (ROS) generation assays, apoptosis detection assays, cell proliferation/viability assays, and superoxide dismutase measurements are all highly helpful in vitro techniques for evaluating the toxicity of CNTS [51-52].

The hazardous effects of carbon nanotubes (CNTs) are influenced by their physical characteristics, including their length and type, mode functionalization, presence of metal impurities, and solubilizing agents [53]. Oxidative stress, membrane damage, and CNT genotoxicity are the main causes of carbon nanotube toxicity [54]. Certain in vitro investigations have shown that the concentration of SWCNTs is responsible for the oxidative stress, which is caused by either increased formation of reactive oxygen species (ROS) or decreased levels of antioxidants [55]. By subjecting the highly pure MWCNTs to mouse macrophages, the impact of membrane damage in producing cytotoxicity has been investigated [56]. By directly interacting with DNA or by releasing reactive oxygen species (ROS) from inflammatory cells, which can then interact with the genetic materials to produce genotoxicity, CNTs can both directly and indirectly cause genotoxicity [57]. The ef-fect of catalyst residue formed after the synthesis of carbon nanotubes is a better reason for the toxicity. The synthesis of carbon nanotubes re-quires certain metal catalysts which are themselves toxic [58]. The ROS formed due to the free radical generation creates oxidative damage to cells and membranes. Certain post-fabrication treatments also induce toxicity. The fiber shape, length, and aggregation of CNTs could produce immune responses and cause their deposition in the tissues [54]. MWCNTs with a small size conjugated with polyethylene glycol are showing a lower toxicological profile since the size and functionalization with biocompatible materials can significantly affect the toxicity of CNTs [59]. Figure 1 illustrates the many cellular reactions to CNT that result in toxicity.

DNA damage or mutation, inflammatory reactions, oxidative stress, malignant transformation, interstitial fibrosis, and granuloma are all examples of CNT toxicity [60]. Mice used in a toxicological trial with both pure and metal-doped SWCNT showed signs of pulmonary toxicity, including lung granulomas, peribronchial inflammation, and necrosis. Furthermore, some investigations have demonstrated that CNTs are cytotoxic and negatively impact the reproductive and cardiovascular systems [61]. Because CNTs can cause genotoxic stress, they may be carcinogenic. To identify the genotoxicity of CNTs, the gene expression profiles of untreated and SWCNT-treated human normal lung cells were examined, and this microarray analysis revealed notable variations in gene expressions [62]. Despite all of these traits, they have been successful in their biomedical applications through various functionalization techniques since they lessen their harmful effects, which increases their use.

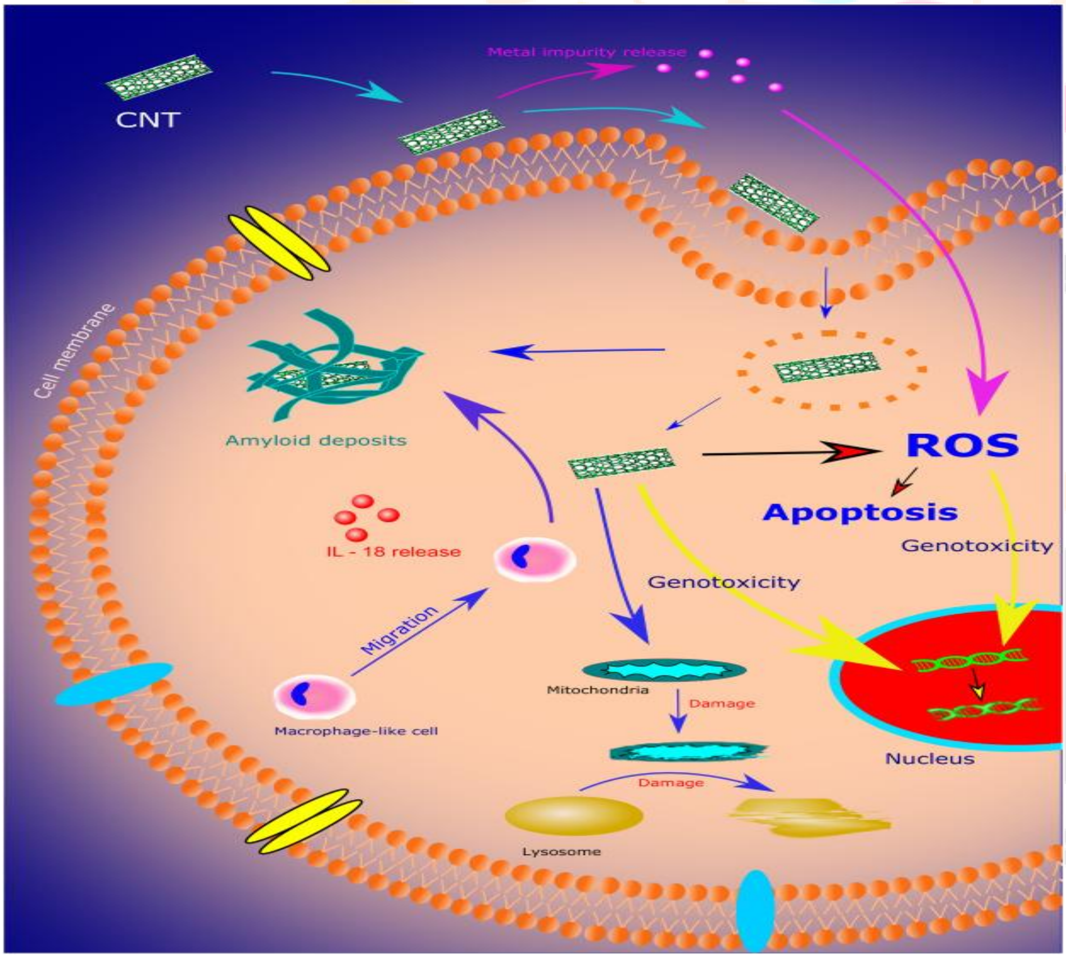


FIG2:various cellular responses to carbon nanotubes CNTs leading to toxicity. CNT induces reactive oxygen species (ROS) which leads to apoptosis. Macrophages like cell migrate to the to CNT, release interlukin 18 (IL-18),and produce amyloid deposite CNT can directly produce genotoxicity or through the induced ROS. CNT can induce mitochondrial damage which subsequently results in lysosomal damage. Metal impurities present in CNT, such as iron, induce ROS and results in cell damage.

Examples of Specific Advancements:

Smart Drug Delivery: CNTs can be functionalized with stimuli-responsive molecules, allowing them to release drugs in response to changes in pH, temperature, or other specific conditions. This makes them ideal for treating diseases like cancer, where the tumor microenvironment differs from healthy tissues.

CNT-Based Nerve Conduits: Researchers have developed *CNT-incorporated conduits for nerve repair, which facilitate neural regeneration by promoting the growth of neurons across the damaged area, potentially restoring lost sensory and motor functions.

These examples highlight the potential of CNTs to revolutionize both medical and technological fields through innovative, highly effective solutions. However, there are ongoing concerns about the safety and biocompatibility of CNTs, and further research is needed to address these issues for their broader implementation.

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