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Title: **Synthesis, Properties, and Applications of Carbon Nanotubes: An Overview**

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Synthesis, Properties, and Applications of Carbon Nanotubes: An Overview

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ABSTRACT

The current study attempts to review the literature concerning the synthesis, properties, and application of carbon nanotubes (CNTs). The methods used to produce carbon nanotubes include laser ablation, electric arc discharge, chemical vapor deposition, plasma-enhanced chemical vapor deposition, pulsed laser deposition, use of low-frequency ultrasound waves, heating a bulk polymer, and bulk sputtering. CNTs have excellent mechanical and thermal properties that strongly depend upon their structure. Functionalized magnetic CNTs are involved in magnetic force microscopy used in biomedicine. The liquid and plastic limit of kaolinite can be increased by adding CNTs to it. In the medical field, CNTs have numerous applications including gene delivery to cells, cancer therapy, drug delivery, and tissue regeneration. Their antioxidant nature also enables them to be used in cosmetic products and in the field of dermatology. They are also used to purify the environment, water, and in modern food-packaging technology. The sensors containing CNTs composite pellets are sensitive to gases, such as NH_3, CO_2, and CO H_2O. CNTs are used to construct gas containers for hydrogen storage. They are also considered ideal for structural applications and their properties can be

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improved by making their composites with metals. Such metals may be introduced into the core of CNTs by different methods including solid-state reaction, arc-discharge method, and electrochemical techniques. The value of absorbed hydrogen gas in CNTs varies between 0.4 and 67 mass %. Recent advances encourage more research on CNTs to increase their clinical applications in the future.

Keywords: carbon nanotubes (CNTs), metals, properties, synthesis

1. INTRODUCTION

Carbon plays an important role in almost all fields of science and technology, especially as a source of energy [1]. Carbon nanotubes (CNTs) possess outstanding electrical and mechanical properties, which are used as an important component of flexible batteries [2]. They are hollow cylindrical structures rolled into a cylinder akin to a honeycomb lattice. The internal diameter of CNTs lies in the range of nanoscale or is 1µm in length. The history of carbon nanotubes (CNTs) started in 19th century, certainly from World War 2 when carbon fiber was first synthesized by Thomas A. Edison for electric light bulbs as a filament [3]. CNTs fall into two categories, namely single-walled carbon nanotubes (SWCNTs) and multi walled carbon nanotubes (MWCNTs). The toughness and higher thermal conductance are owed to the presence of sp^2 hybridization in CNTs. SWCNTs are insoluble in both organic and inorganic solvents, although they may be soluble after complexation and polymerization. When SWCNTs are added to aniline (organic solvent) then SWCNT-aniline charge transfer complex is formed that makes SWCNTs soluble in organic solvents and preserves their pristine nature, as proved by various analysis tools [4].

CNTs comprise graphite sheets rolled into a cylindrical pattern and have various applications in the fields of medicine and material sciences [5]. They have widespread applications in every aspect of life, such as film and coatings and also in the fields of biotechnology, electronics, environment, energy storage, and many others due to their unique higher thermal conductivities, toughness, and electrical conductivity [6].

Keeping in view the great importance of nanotechnology in various fields [7–10], the current study reviews the literature concerning the synthesis, properties, and uses of carbon nanotubes (CNTs).

2. SYNTHESIS OF CARBON NANOTUBES (CNTS)

The methods used to produce CNTs include laser vaporization, electric arc discharge, chemical vapor deposition [11], decomposition of SiC, dipping graphite in cold water, torsion of graphene layers, as well as, mechano-thermal, pyrolysis, solar energy, liquid phase, electrolysis, and heat treatment of polymers [12].

Historically, electric arc discharge was the first method used for the formation of CNTs. Arc discharge method technically resembled the laser evaporation process. Comparison between these two methods (laser evaporation process and electric arc discharge) that shows that there is a difference in the purity and quality of the obtained products. However, the most favorable and developed techniques used for the synthesis of CNTs and related to materials on a large scale, which include different types of chemical vapor deposition (CVD) and arc discharge [13]. Consequentially, CNTs were synthesized using various techniques, such as laser ablation or arc discharge. However, in present days, CVD ($<80^0$C) has replaced these techniques (laser ablation and arc discharge) because this method accurately controls the nanotube diameter, length, density, purity, orientation, and alignment [14].

2.1. Electrical Arc Discharge Method

The arc discharge method involves the vaporization of carbon by applying electric field at a high-temperature gradient. This process may be improved in the presence of numerous metal catalysts (for instance, iron, cobalt, nickel, yttrium, boron, and gadolinium) under the reduced pressure of the inert gas [15] It also creates plasma in a glass chamber due to the transfer of energy from the arc to the graphite anode doped with a catalyst. The arc discharge setup involves two graphite rods, which act as anode and cathode and have a diameter of 20 mm and 7 mm, respectively. An arc is produced when 100–200 ampere current is provided between the electrodes [16]. Generally, multi-walled carbon nanotubes (MWCNTs) are produced when no catalysts are applied. However, single walled carbon nanotubes (SWCNTs) are synthesized in the presence of a transitional metal catalyst. The high-temperature arc discharge method (above 1700°C) results in the formation of a mixture product and requires the separation of CNTs from both coal and the remaining metals (catalytic) [17]. The catalyst composed of nano-sized metal particles (such as Ni, Co, or Fe), which cause the disintegration of the precursor molecules of gaseous hydrocarbon into carbon [18]. Needle-like CNTs with approximately 1 mm of length and 4-30 nm diameter can be produced on carbon cathode by using the direct arc discharge evaporation of carbon. Lijima et al. used the pressurized chamber filled with a gaseous mixture of 40 torr argon and 10 torr methane [19]. The high yield production of CNTs depends on the concentration and nature of catalysts, gases that are composed of plasma, the pressure of inert gas, the arc current intensity, and the distance between the electrodes [17]. Figure 1 displays a 15 kW xenon short-arc lamp used in the IMAX projection system.

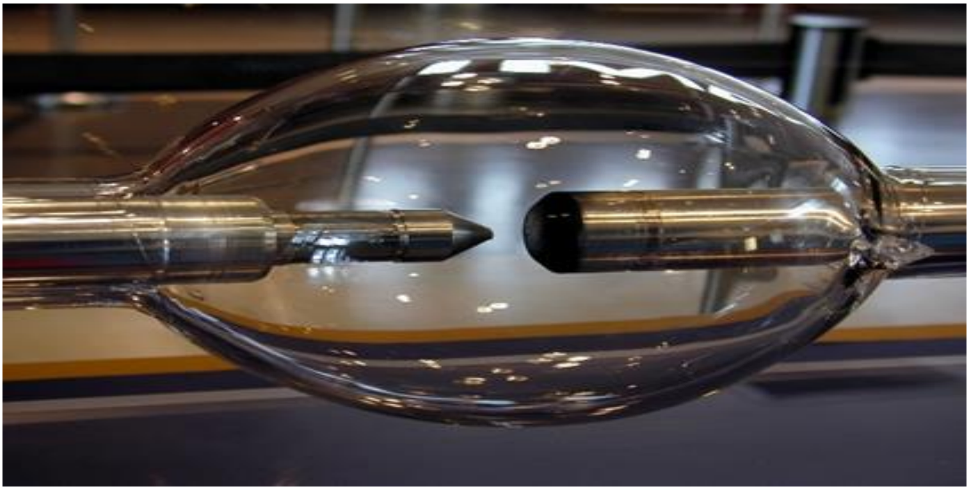

Figure 1. A 15 kW xenon Short-Arc Lamp

Source. https://en.wikipedia.org/wiki/Arc_lamp

2.2. Laser Ablation Technique

CNTs can be produced using the laser ablation method (Figure 2). Normally, a laser is directed on the targeted carbon, which vaporizes a small quantity of material inside an oven warmed up to 1200°C. The smooth beam of laser on the target is ensured by a computer control system [20]. The plasma produced by this method is usually swept by nitrogen or argon from a high-temperature gradient and deposited onto the surface of the substrate, which is cooled by the external cooling system. Pulsed or continuous laser vaporizes 1.2% of Co/Ni with 98% composite of graphite target under 500 torr of the inert atmosphere of helium at 1200^{o}C in quartz furnace. A plume forms vapors at this high temperature which rapidly expands and cools. A large cluster is formed by the quick compression of small carbon molecules or atoms to cool down the vapors [21]. The growth of nanotubes is stopped when the carbon layer cannot absorb particles anymore because the surface is already occupied and has no space for the coming particles. MWCNTs are formed by using a pure graphite target. The SWCNTs yield depends strongly on the metal catalyst type and it can be increased by increasing the temperature of the furnace, among other factors [12]. Laser ablation is the best method to grow SWCNTs with a high purity and a high quality [17].

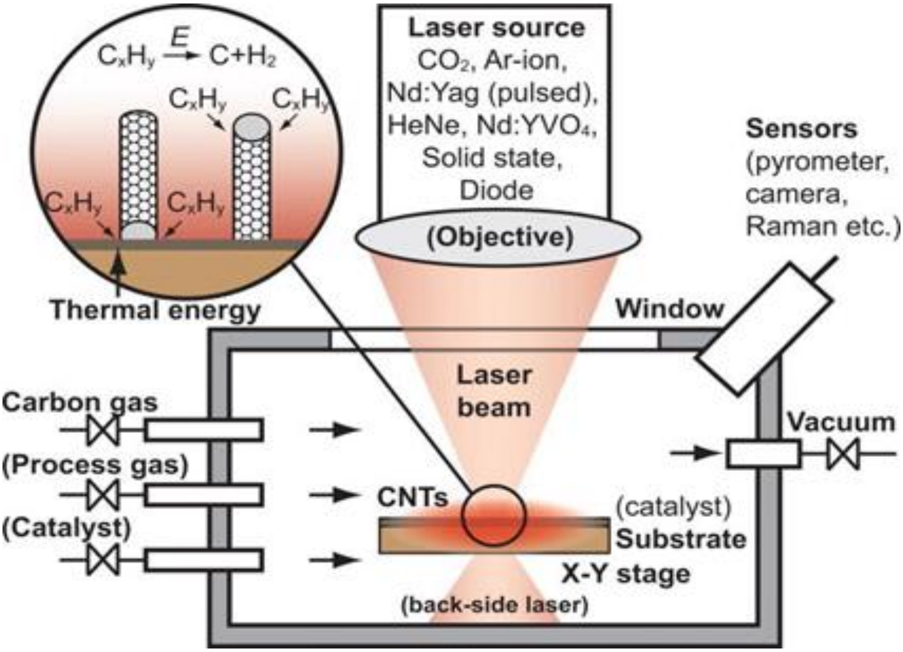

Figure 2. Laser Ablation Setup for CNT Synthesis [22]

2.3. Chemical Vapor Deposition (CVD) Method

In electronics and CMOS industry, chemical vapors deposition (CVD) is the most suitable technique for the synthesis of CNTs as compared to laser ablation and arc discharge methods. This technique can synthesize CNTs at a lower temperature [23]. CVD yields very pure and high-performance solid materials. This technique can be used to synthesize the materials in which vapor phase chemical components react at specific surfaces to form solid films [24].

CVD was first reported in 1996 for the production of nanotubes. In CVD, vacuum deposition occurs for the production of CNTs. In this process, the substrates are exposed to a volatile precursor which reacts or decompose on the surface of the substrates. This method is useful for the production of nanotubes in a high quantity and also to control the growth direction onto the substrate [25]. The synthesis of CNTs through CVD involves the sputtering of a transition metal catalyst onto the substrate. It also uses thermal annealing or chemical etching to induce nucleation in the catalyst particle. Clusters are formed on the substrate as a result of thermal annealing and nanotubes are grown [26].

In the reaction chamber, there is a gas phase in which the carbon source is placed. Then, by using an energy source such as plasma, carbon molecule or heating coil is converted to an atomic level. Carbon monoxide, methane, or acetylene can be used as a carbon source [27]. Generally, CVD utilizes a temperature range of 650–900^{o}C for the synthesis of nanotubes, with the consequent yield of about 30% [26]. MWCNTs are produced by thermal CVD methods, using acetylene or ethylene gas as the feedstock of carbon in the presence of Ni, Co, or Fe nanoparticles as a catalyst. At these temperatures, carbon atoms are dissolved into metal nanoparticles which finally become saturated and the precipitation of carbon forms CNTs. The size of the metal particles (catalysts) can help to determine the diameter of CNTs. When other elements such as Mn, Cr, and Cu are used, CNTs are formed only in minute amounts [28].

The percentage yield of CNTs varies depending upon their synthetic methodology. Table 1 gives a brief comparison between CVD, laser ablation, and arc discharge methods.

Table 1. Comparison between Different Synthesis Methods

Arc discharge method	Laser ablation method	Chemical vapor deposition
➢ With the help of the arc discharge tube method, we can synthesize up to 30% by weight of both MWCNTs and SWCNTs [29].	➢ The yield of the laser ablation method is about 70% of SWNTs with a measurable diameter, which is controlled by the	➢ For the synthesis of carbon nanotubes, CVD is known as the most widely used method [30]. ➢ The removal of catalyst by acid treatment may

Arc discharge method	Laser ablation method	Chemical vapor deposition
➢ The synthesis of carbon nanotubes requires a temperature above 1700 °C. ➢ The synthesis is performed in an arc discharge tube. This method causes less structural distortions [14].	temperature of reaction. ➢ In comparison with chemical vapor deposition, arc discharge method is much expensive [29].	cause destruction of the original structure of carbon nanotubes. ➢ The yield may be increased by the use of catalysts like MgO or Al_2O_3 [31].

2.4. Plasma-enhanced Chemical Vapor Deposition (PECVD)

PECVD is a versatile technique that is used to obtain vertically dense aligned CNTs at lower temperature, as compared to the one's used in CVD. It is a latest procedure for the selective positioning and vertical alignment of CNTs. In PECVD, the activation energy for the CVD reaction is provided not only by elevating temperature gradient but also by the energetic plasma formation in an electric field [32].

2.5. Pulsed Laser Deposition Method

The CNTs can be synthesized by the pulsed laser deposition method. This is a thin film deposition method in which the targeted material is evaporated by a pulse of laser beam and a film is deposited on the substrate surface. The furnace contains the targeted substance placed at the bottom in which the substrate is placed at the top side of the furnace. The laser beam normally used is Nd: YAG. The laser beam strikes the targeted atom and vaporize them. The vaporized atoms are called a plume. The plume is moved towards the substrate, deposited and grows as carbon nanotubes upon the substrate surface [33]. The rate of deposition and the laser beam can be collaborated to control certain parameters of the CNTs. These CNTs are deposited in the substrate surface that can be separated from the carbon nanoparticles, amorphous carbon, and other unwanted impurities. These prepared CNTs can be purified by several methods that includes gas-phase purification and liquid phase purification, which are used most commonly for the purification procedure [34].

2.5.1. Gas-phase Purification. In the gas-phase purification method, CNTs are purified by applying high-temperature oxidation, which is continued by the repeated extractions with nitric acid and HCl. In this process, the synthesized CNTs have a high purity and stability, including little impurities or residual catalyst [34].

2.5.2. Liquid phase Purification. In liquid phase purification, the CNTs are purified in several steps, which mainly include:

i. The preliminary filtration, which is done to remove the bulk residual graphite particles.

ii. Then the CNTs are dissolved in both conc., acid, and organic solvents to remove the unreacted catalyst and fullerenes.

iii. Next is the centrifugal separation of CNTs from the solution.

iv. Then microfiltration is done.

v. The final step of purification is chromatography, which is used to separate the MWCNTs and SWCNTs [34].

2.6. Modification of CNTs by Low-Frequency Ultrasound Waves

Multi-walled carbon nanotubes (CNTs) can be modified by treating with 20 kHz ultrasound in combination with dilute HNO_3 and dilute H_2SO_4 for 30 min at 12 W cm^{-2} sonication. These specified conditions prevent the aggregation of the nanotubes and allow an efficient dispersion in ethanol or in chitosan [35].

2.7. Synthesis of CNTs through Bulk Polymer

The CNTs can be synthesized by heating a bulk polymer at about 400 ^oC in the air. This can be obtained by polyesterfication reaction of ethylene glycol and citric acid. The formation of CNTs is confirmed by the number of spectroscopic analyses. The lengths of CNTs is generally less than 1 μm, whereas their diameter ranges from 5-20 nm [36].

2.8. Synthesis of CNTs through Bulk Sputtering

One of the most promising methods among all is bulk sputtering method, which may be employed for the mass production of CNTs, however, this process is overpriced[37]. During the process of sputtering, the targeted graphene is usually placed as the targeted material in the chamber. The reaction chamber is filled with an inert argon gas, which is commonly used when an inert atmosphere is required or for the production of titanium and other reactive material. The electric field is applied between the two electrodes, which accelerate the ionization process of argon gas to produce the charged particles that strike the surface of the targeted graphene material and eject the carbon atoms from the surface of graphene [38]. The CNTs are grown on the surface of the substrate. Thus, the CNTs prepared by this method are impure and can be purified by several other methods [37].

3. PROPERTIES

Carbon nanotubes (CNTs) have unique properties due to which they are found in numerous applications, which have a great impact on human health. However, some chemicals have also evolved during CNTs production and handling, which are usually inhaled during the inhalation process [39]. The tensile strength of CNTs is hundred times greater than their steel and thermal/electrical conductivities, which are comparable to copper [25]. CNTs show significant properties including physicochemical properties, metallic or semi-metallic characteristics, great mechanical and electrical characteristics, good thermal conductivity, high electrical conductivity, and a large surface area [40]. They are considered ideal for the production of next-generation composite materials due to their specific properties [41]. The properties of CNTs can be modified by doping with heteroatoms such as nitrogen and boron to tune their physicochemical characteristics for specific applications [42].

3.1. Electronic Properties

CNTs possess hollow cylinders with approximately 20 carbon atoms around the circumference of the cylinders and microns in length. They can act as semiconductors or conductors depending on their structure and possess characteristic electronic properties. CNTs have unusual electronic properties due to their high electrical conductivities as compared to copper. The symmetry of the planner system can be broken down by rolling action, which causes a specific direction with respect to the hexagonal lattice and axial directions [43]. Different theoretical and experimental works suggest that single-walled CNTs are considered as quantum wires, which have one dimension [44]. The graphene sheet is the main site for single-walled CNTs having a main electronic structure and is considered to possess metal properties with bands of conduction [45].

Moreover, carbon nanotubes are also considered as an example of ideal quantized one-dimensional conductors [46].

3.2. Mechanical Properties of CNTs

CNTs are one-dimensional materials that display the mechanical properties, such as the tensile strength and young's modulus. However, it is difficult to produce the pure form of CNTs and to control and manage their properties. Due to these properties, CNTs are considered good for polymer enforcement. The extensive mechanical characteristics of CNTs are due to the sp^2 hybridization of carbon-carbon double bond. The densities of carbon nanoparticles are very low (1.3 gcm^{-3}) as compared to stainless steel. Young's modulus of CNTs is higher than carbon fibers with larger values than that of 1TPa, which is about five times larger than steel [43]. CNTs have excellent mechanical properties that strongly depend upon their structure. There are three kinds of nanotubes (SWNTs, MWNTs, and catalytic MWNTs) studied under laboratory actions that always consist of structural defects [47]. The calculation for the stiffness constant of SWNTs can be done by adopting the elastic modulus of graphite to understand the important properties like mechanical properties of graphite of a single crystal [48].

3.3. Thermal Properties of CNTs

One of the most important properties of CNTs is thermal property, which is directly related to their small sizes and unique structures. Thermal and specific heat conductivity of bulk MWNTs can help to measure the thermal properties of carbon nanoparticles [49]. The thermal characteristics of CNTs are directly related to each other's as the size of devices (electronic or mechanical) are reduced to the micro and nanometer level. With the help of molecular modeling predictions, the studies of nano-electronic devices became very easy, however, it is quite difficult to measure the accurate thermal properties [50]. The excellent thermal conductivity of 3000 W/m K at room temperature of SWNTs makes them important for thermal applications [51]. The high thermal conductivity of nanotubes has a number of applications in thermal management such as heat sinking of silicon processors, or increasing the thermal conductivity of plastics in areas of housing for electric appliances [52]. Carbon nanotubes show greater variations in thermal conductivities and the conductivity of nanotubes is greater along the axis due to greater anisotropic property [53].

3.4. Magnetic Characteristics and Heat Generation

CNTs are widely accepted due to their fundamental properties. The basic field interest of CNTs is the magnetic functionalization, which has a wide applications as nano-scaled magnetic objects [54]. The semiconducting and metallic properties of CNTs can be predicted by both first principal calculation and tight binding that depends upon their size and helicity. Few unusual characteristics were demonstrated by many recent experiments [55]. For a magnetic field, high diamagnetic sensitivity is found in both perpendicular and parallel axis of the tube [56]. Specifically, the magnetic functionalization gives tremendous potential to CNTs that can provide a practical approach to give a stable coating for protection from degradation and oxidation. The functionalized magnetic CNTs are involved in magnetic force microscopy, which is used in biomedicine in the form of magnetic nano-vectors or spintronics [57].

3.5. Carbon Nanotubes (CNTs) Composites

Due to the magnificent physical properties of CNTs, they form a metal matrix with the metals to take the advantage of their high tensile strength and electric conductivity. They are also considered ideal for structural applications and their properties can be improved by making their composites with metals. The following techniques are used for the fabrication of CNTs polymer nanocomposite material.

3.5.1. Solvent Casting. It is an important procedure for the preparation of CNTs concentrated polymer nanocomposite materials. These solvents have a significant influence on the properties of nanocomposites. The in solvent casting of the nanotubes is facilitated by dispersion and it involves the preparation of a suspension of CNTs in the solution of a desirable polymer by energetic agitation. The process involves the dissolution of a polymer in an organic solvent and then the addition of particles (generally salts) with specific dimensions to the solution. It is followed by the shaping of consequent mixture, its final geometry a membrane that can be produced by casting it onto a glass plate or a scaffold is formed by using a three-dimensional mold. After evaporation of solvent evaporates, a composite material is produced, which contains the particles together with the polymer [58].

3.5.2. Melt Mixing Method. CNTs can also be synthesized by the melt mixing method, which is used for the thermoplastic polymers that gets soften on heating. This process involves an elevated temperature gradient to decrease the viscosity of the substrate and high shear forces to the nanotubes bundle. Templates of numerous shapes can then be obtained by various fabrication techniques, including injection molding, compression molding or extrusion formed composites of commercial polymers, such as acrylonitrile butadiene styrene (ABS) with MWCNT, polypropylene, and high impact polystyrene [59].

For the achievement of multifunction and high-performance stability, CNTs are considered to be an ideal filler for polymer type matrixes, due to their sizes in nanometers, high and well-known aspect ratio, and more specifically due to their amazing strength and high thermal and electrical conductivities [60]. Solution casting and melt blending are the most common methods that are used to produce polymer composites; inorganic fillers may also be used in making carbon nanotubes-polymer composites [61]. In recent times, fabrication of CNTs with the polymeric substances gives the characteristics synergistic effects to the host and boosts a vast interest in the development of multifunctional CNTs along with alternative materials [62].

4. APPLICATIONS OF CARBON NANOTUBES (CNTS)

Nanoparticles are found in a broad range of biological [63–66] and non-biological applications [67–70]. CNTs functional materials (CNTFMs) had shown a potential impact on the fields of science, engineering, and technology with the transformation of nanoscience towards a practical applications [71].

4.1. Carbon Nanotubes as Stabilizers

The liquid and plastic limit of kaolinite can be increased by the significant addition of CNTs to it. The resultant mixture would have lower soil strength, higher compressibility, and reduced hydraulic conductivity [72]. The presence of CNTs in construction materials increase the mechanical strength of a material. It has the capacity to increase the flexibility of a material [73]. It also decrease the breakability of a material. Soil cement itself is not a flexible material and it can be easily broken by applying stress. Consequently, materials which are made by only soil-cement can be easily breakable by applying any kind of stress. CNTs have significantly solved such type of problems [74].

4.2. CNTs Applications in the Medical Field

In the medical field, CNTs have numerous applications including gene delivery to cells, cancer therapy, drug delivery, and tissue regeneration. MWNTs and SWNTs have a greater potential to improve the traditional drug delivery to the cells [75]. CNTs as compared to other nanocarriers that can be easily modified for conjugation of bioactive compounds and ligands for the targeting process. Additionally, they also found diagnostic applications to drug delivery [76]. The use of CNTs in the nerve tissue are explained in several reports [77].

CNTs applications are also found in drug delivery, genes, cells, and cytokines. Moreover, they can also develop tissue induction and cell activation properties along with futuristic biomaterials characteristics, which are beneficial for the human body. For the self-repaired potential of the human body, it is very important to use CNTs flexibly to adapt to their environment [78]. Their solubility is applicable in biocompatibility, secretion, blood transportation, and gastrointestinal absorption. The CNTs composites are also involved in therapeutic drug delivery systems [79]. Significantly, CNT dispersions should have a uniform and stable distribution to a sufficient degree for an accurate concentration. The solubility of pristine CNTs in the aqueous solution is an important factor for their use as a practical drug carrier, which can be owed to the hydrophobic property of the graphene sidewalls and also π-π strong interaction between CNTs. There had been a prime focus on nano-carbon biomaterial research and its development over the last 15 years. However, it is strongly believed that this focus would lead to paradigm shifts and lead to major advancements in global medicine by following the road towards clinical applications [80].

Figures 3 and 4 display important applications of CNTs in the field of medical.

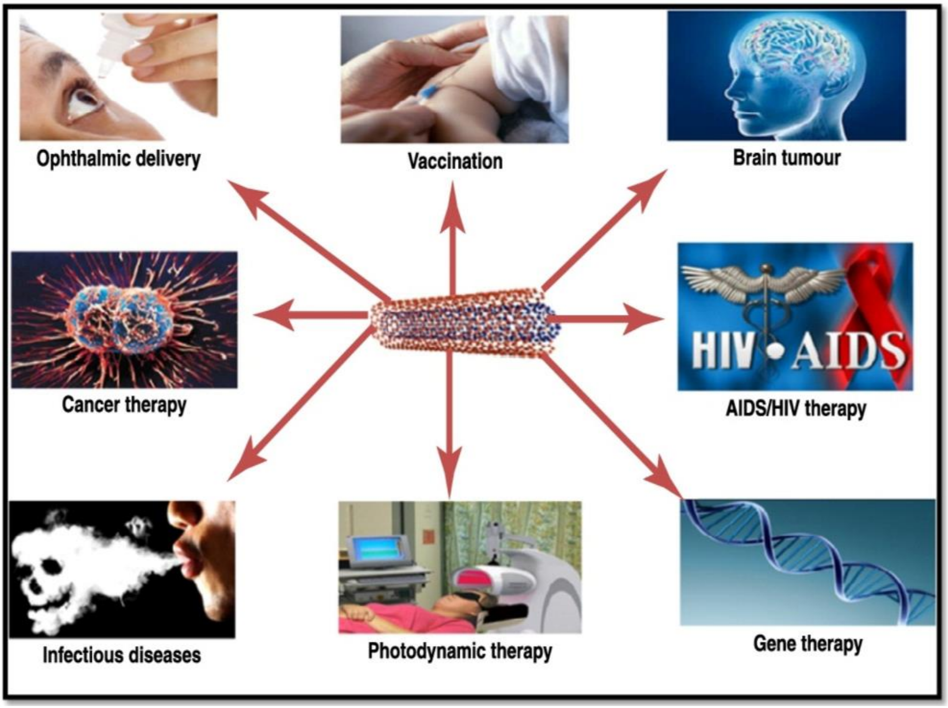

Figure 3. Application of CNT in Biomedical Field [81]

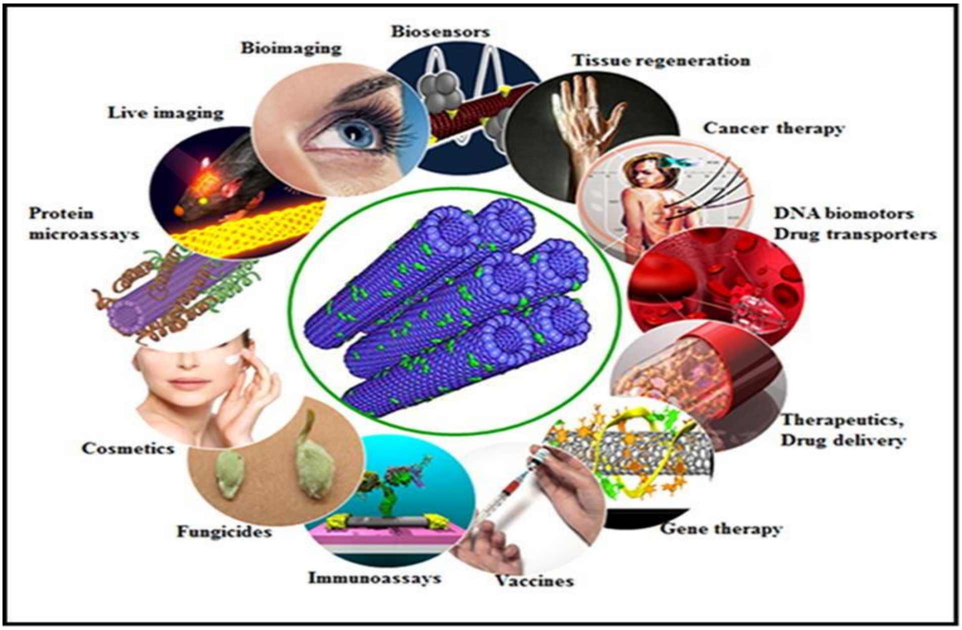

Figure 4. Application of CNT in Biomedical Field [82]

4.3. Application of Carbon Nanotubes (CNTs) as a carrier of the Anticancer Drug

Chemotherapy is usually coupled with other treatment techniques to reduce the size of the tumor in traditional methods, however, this technique also causes toxicity to the other living cells, which has adverse side effects. To reduce the side effects, a new method has been developed in which anticancer drug is delivered to tumors by CNTs [83]. To deliver the drug to the target cell, CNTs are functionalized with the chemical receptor (protein or nucleic acid), and then the anticancer drug is fixed in functionalized CNTs with the open ends; this drug along with CNTs is introduced into the animal body either by oral or injection. Finally, drug carrier CNTs pass across the nuclear membrane and cytoplasmic membrane without generating toxic effects and reach the targeted cell. There are two targeted ways through which a drug is delivered to a cell; one is non-internalization, while the second one is the internalization method. Comparatively, the second method is considered better than the first method. In the internalization method, both drug and CNTs are entered inside the cell from the intracellular environment that assists to deteriorate the drug carrier conjugate for releasing drugs into the cell. While in the method of non-internalization, the extracellular status helps to deteriorate the drug carrier to conjugate, then the drug itself penetrates across the lipid membrane to enter into the cell; here the drug is degraded before reaching the targeted cell. There are two possible mechanisms of internalization of CNTs, which include insertion and diffusion and endocytosis. The whole procedure is used for cancer therapy [84].

4.4. Carbon Nanotubes as Preservatives

Many investigations have focused on the development of novel antioxidants due to their importance in food and pharmaceutical industry [85]. CNTs and nano-horns are antioxidants in nature. They can be used in drugs to reduce the process of oxidation in the human body. Their antioxidant nature also enables them to be utilized in cosmetic products and in the field of dermatology along with zinc oxide sunscreen, which is used to avoid oxidation of vital skin constituents [86]. For convenient and processed food, aromatic organic acids are used to inhibit a vast range of fungi, molds, bacteria, and yeasts [87]. Despite this, extensive consumption of these types of preservatives in food may be harmful for human health and can cause several allergic diseases like dermatitis, hives, convulsion, and others in humans [88]. Currently, carbon nanomaterials have attracted significant attention worldwide in modern food-packaging technology due to their easy functionalization, high surface area-to-volume ratio, excellent antimicrobial activity, superb physico-mechanical and water resistance properties, strong adsorptive ability, high thermal, and electrical conductivity,. CNTs-based nano-sensors offer a better assessment of the freshness, security, safety, quality, and packaging of food products [89].

4.5. Application of Carbon Nanotubes (CNTs) as a Sensor

Sensors are mostly imported as detecting devices, which are used in different fields. There are different types of sensors such as biosensors and molecular sensors. The efficiency of sensors can be enhanced by attaching CNTs to them (Figure 5) [90]. CNTs have been employed in the sensing and detection of liver and pancreas cancer [91]. The usages of CNTs for the detection and sensing of NO_2 gas are well recognized [92]. CNTs incorporated sensors can be used to bring revolutionary changes in different sectors, especially in the biomedical industry [83]. The sensors containing CNTs composite pellets may be constructed by attaching different chemical groups onto the end; they are also sensitive to gases such as NH_3, CO_2, and CO H_2O [93]. Gas sensor are used in medical, industrial, and in commercial areas for the reduction of greenhouse gases and to monitor the environment of the combustion engine [94]. Ammonia, carbon dioxide, and oxygen gas can be detected using their conductivity and permittivity properties by multi-walled nanotubes [95].

The CNTs have unique physical, adsorption, and electrochemical properties. The strong adsorption capacity of the CNTs and their good sensitivity towards atoms and molecules adsorbed on their surface enable them to design sensors-based CNTs. Many gas sensors (detectors) based on the CNT have been reported in previous literature [96] that include:

i. Shift gas sensors

ii. Resonance frequency

iii. Capacitance gas sensors

iv. Ionization gas sensors

v. Adsorption gas sensors

Their main operating principle involves adsorption during which an adsorbed gas molecule transfers an electron to or takes it from a nanotube. This changes the electrical properties of the CNTs, which can be detected and measured. There are numerous gas sensors based on pure SWCNTs and MWCNTs modified by metals, metal oxides, polymers or various functional groups [97].

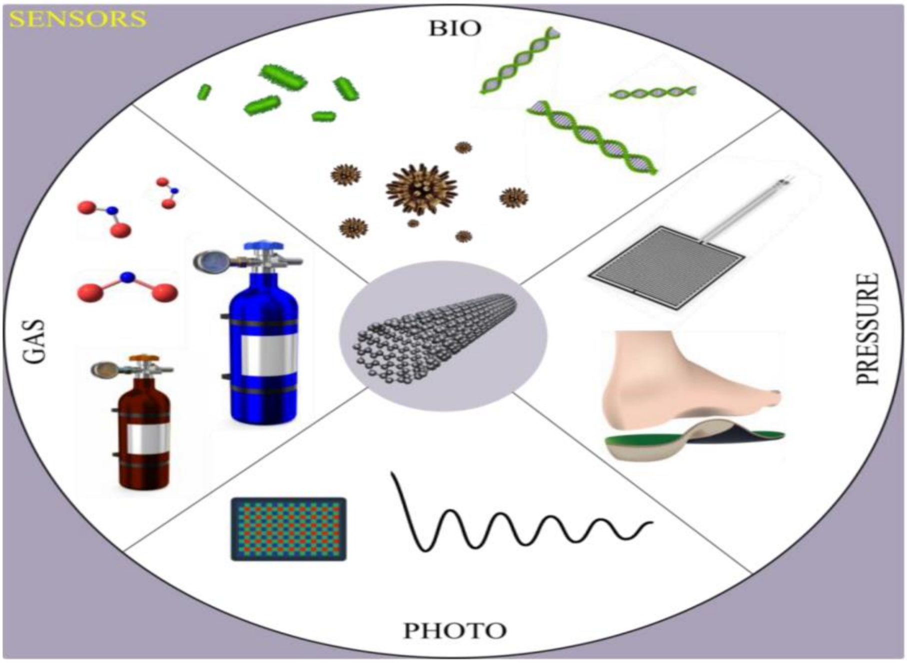

Figure 5. Application of CNT as a sensor [98]

4.6. Application of Carbon Nanotubes (CNTs) in Water Filtration and Environment

Carbon nanotubes (CNTs) find numerous applications in the purification of water [99] and the remediation of pollutants [100]. They can reduce the distillation cost by up to 75% and their membranes help in filtration. CNTs have a very small particle size, which enable smaller particles (like water molecules) to pass through them, while larger particles are blocked (they cannot pass through carbon nanotubes), such as chloride salts [101].

4.7. Carbon Nanotubes (CNTs) in Electronic Devices

In electronic devices, CNTs can be used as field emission sources, which is done by applying the potential between CNTs surface and anode.

Due to the curvature present in the form of pentagons in CNTs , electrons are discharged from their tips [102]. The use of CNTs as electron emitters is associated with several advantages, which include stable field emission, high current densities over prolonged periods, low emission threshold potential, and long lifetime of the components for the construction of field emission devices [103].

CNTs can be used in supercapacitors because they have a large surface area [104]. Therefore, by using carbon nanotubes (CNTs), the use of platinum can be reduced, which creates some problems specially in fuel cells [105].

4.8. Gas and Hydrogen Storage

Carbon nanotubes (CNTs) are used as a metal container because of their hollow cylindrical nature. Metals may be introduced into CNTs core by different methods, including solid-state reaction, arc-discharge method, and electrochemical techniques [106]. The environmental problems are rising day by day due to the overuse of fossil fuels. There are various primary energy sources, such as, wind, solar energy, thermonuclear energy, and geothermal. The best choice among all is hydrogen because of its adverse advantages. It can be easily produced, it has a high utilization efficiency and it transforms without any additional problems at the consumer end [107]. CNTs are used to construct gas containers, which are used to store hydrogen gas. Hydrogen gas is absorbed in single-walled nanotubes. The value of absorbed hydrogen gas in CNTs varies between 0.4 and 67 mass % [82].

5. CONCLUSION

Carbon nanotubes can be produced by laser ablation, electric arc discharge, chemical vapor deposition (CVD), plasma-enhanced chemical vapor deposition (PECVD), pulsed laser deposition, use of low-frequency ultrasound waves, by heating a bulk polymer and bulk sputtering etc. Chemical vapor deposition (CVD) and arc discharge are the most favorite methods for CNTs production on large scale; however, the latter is comparatively expensive. The CVD yields very pure and high-performance solid materials and has the ability to control accurately the nanotube diameter, length, density, purity, orientation, and alignment. Plasma-enhanced chemical vapor deposition (PECVD) is a latest technique for the selective positioning and vertical alignment of CNTs.

The laser ablation is the best suitable method to grow single-wall nanotubes with high purity and high quality. The CNTs prepared by pulsed laser deposition require either gas- or liquid-phase purification. CNTs show characteristic metallic/semi-metallic, mechanical, electrical, thermal and electrical properties which are improved by making their composites with metals. They can improve the mechanical strength and flexibility of a construction material. CNTs find applications in diagnosis, drug delivery, gene delivery to cells, cancer therapy, drug delivery, tissue regeneration, biomedicine, cosmetic products, dermatology, environmental science, water purification, modern food-packaging technology, electronic devices, gas sensors and in construction of gas containers for hydrogen storage.

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