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A Review of Carbon Nanotubes and Alloys Synthesized by the Laser Ablation Technique

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ABSTRACT

Carbon nanotubes (CNTs) with a nanostructure have revolutionized the field of nanotechnology. They are promising candidates for a wide range of potential optoelectronic and medical applications. Carbon nanotubes can be classified into carbon nanofibers, single-walled nanotubes, and multiple-walled nanotubes. This paper reviews the various synthesis (like arc discharge, laser ablation, and chemical vapour deposition) with a special focus on laser ablation, and characterization methods for carbon nanotubes (CNTs) used to meet the extensive demands owing to their distinctive properties, including exceptional strength and elevated thermal and electrical conductivities. Despite the significant demand for carbon nanotubes (CNTs), their cost remains the primary concern due to the temperature-sensitive synthesis processes and substantial set-up expenses. The laser ablation (PLA) method is the sole technique for decreasing the cost of CNTs. It additionally outlines the advantages and challenges of PLA in the production processes and applications of CNTs. CNTs and their alloys are advanced materials that can address these challenges. They are examined in applications such as sensors, batteries, detectors, and the medical field. However, since it is still challenging to identify comprehensive and reliable parameters and conditions to control their properties, the review suggests more research on laser ablation for CNT production.

Keywords: *Synthesis methods, Nanotubes, CNTs-alloys, Characterisation*

1. INTRODUCTION

In recent years, the research has focused on nanotechnology and nanocomposites. The word “nano” is from the Greek, meaning dwarf (small); nanotechnology refers to scientific treatment performed at the nanoscale (atomic level) using specialized scientific equipment, which has become a well-known field in the last three decades [1]. Norio Taniguchi of Japan first used the term "nanotechnology" in 1974. An individual atom's or molecule's separation, consolidation, and distortion are the primary processing processes in nanotechnology [2]. Because of its novel nature, nanotechnology has sparked a great deal of interest among researchers in their electrical, mechanical, chemical, and physical properties. Consequently, nanomaterials have shown interest in several fields, including medicine, gas sensors, water filtration, chemical sensors, solar cells, and light-emitting diodes, among many others. In recent times, dyes and other industrial byproducts, along with human and commercial effluent, have been major contributors to water contamination. To deal with the pollutants, sophisticated and traditional methods like thrombosis, adsorption on activated carbon, chemical deposition, and separation can be employed. Metal oxide nanoparticle-based nanomaterials have emerged as crucial elements in applied nanotechnology across various domains, including gas sensors, batteries, magnetic storage media, solar cells, catalysis, energy conversion, medicine, food, agriculture, cosmetics, and optoelectronics, significantly improving performance regarding sensitivity and detection limits to the level of single molecule detection [3]. This is because these materials are very effective, inexpensive, stable, and non-toxic. Nanomaterial synthesis can be accomplished using a variety of methods, including sol-gel, hydrothermal, physical, chemical vapour deposition, microwave, and many more. There are two main schools of thought regarding the underlying principles of these methods: top-down and bottom-up. Collecting materials one molecule or atom at a time is known as the bottom-up strategy. The material must first be minced to produce nanoparticles using the top-down method. One common top-down method for creating nanoparticles is laser ablation. Laser ablation in liquid, or LAL, is a technique that produces nanoparticles by directing the laser beam onto a target that is submerged in liquid. This process is not only easy, affordable, and environmentally friendly, but it also doesn't create any byproducts, which is a huge plus. The properties of metal and semiconductor nanoparticles are significantly influenced by their size. Therefore, studies are now being conducted to determine whether these materials can be produced in a liquid medium for use in a variety of applications [4]

2. CARBON NANOTUBES

Since 1991, carbon nanotubes (CNTs) have been known for their exceptional thermal, morphological, electrical, physical, and magnetic properties [5]. The widespread use and mass production of carbon nanotubes allow for a novel approach to nanomaterials and nanodevices. CNTs, sometimes referred to as buckytubes, are cylindrical carbon molecules with unique properties that could make them useful in a range of applications. These include applications in nanoelectronics, materials science, and optics. In addition to their remarkable strength, CNTs have remarkable mechanical, electrical, and thermal properties. Fullerenes, which were identified by Kroto et al. [6], are round structures with a buckyball shape that are carbon nanotubes. The term "CNT" comes from the fact that a nanotube's diameter is only a few nanometers. Iijima [7] first produced multi-walled carbon nanotubes (MWNTs) in 1991 using a simple arc-evaporation method. However, carbon nanotubes (CNTs) were discovered long before researchers even thought that carbon could exist in such a diverse allotropic form. In 1952, Radushkevich and Lukyanovich [7] found carbon structures that looked like worms. They observed these while researching the soot that is produced when iron particles are exposed to carbon monoxide (CO) at 600°C. The authors determined that the produced substance was composed of lengthy carbon crystals, either needle-like or filamentary, with diameters of approximately 50 nm, based on many experiments, TEM pictures, and other characterization methods. The discovery of nanotubes was largely unacknowledged at the time, as is the case with many other fields, both before and after nanotechnology[8].

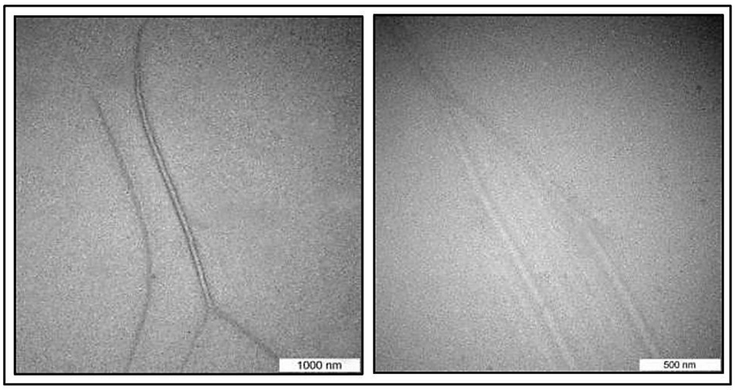

Figure 1. TEM image of two adhered carbon nanotube CNT prepared by 1064 nm Nd: YAG laser ablation of graphite target in de-ionized water at 13 J.cm^{-2} laser energy density for 400 pulses. Adapted from [9].

A rare observation obtained of two adhered carbon nanotubes are obtained by laser ablation of graphite target at laser energy density of 13 J.cm^{-2} for 400 pulses as shown in Fig.1. This can be attributed to the van der Waals forces that bind the nanotubes together [9]. CNTs possess exceptional optical qualities, high thermal properties, and remarkable mechanical qualities. Applications for carbon nanotubes (CNTs) include lithium-ion batteries, data storage devices, and the administration of medications in medical settings. Carbon nanotubes (CNTs) represent safer and more effective alternatives to prior drug delivery methods. High dosages, however, have the potential to build up in tissues, causing oxidative stress and harming healthy cells [10, 11]. For drug delivery applications, CNTs can be made biocompatible and efficient with the right surface functionalization, regulated size, optimized dosage, and suitable administration routes [12].

The network of polymers and carbon nanotubes is also present in gas flow for a number of applications, including in the electronics industry. The amount of impurities, controlling the growth of nanotubes, and mass-producing CNTs are some important issues that need to be addressed [9].

3. CARBON NANOTUBES (CNT) AND IT ALLOYS

Multiwalled carbon nanotubes (MWCNTs) possess great surface area, solid mechanical properties, and excellent electron conductivity. These factors make MWCNTs the preferred material for solid-phase separations involving organic and inorganic materials when adsorbed onto the surface of ZnS NCs. However, MWCNTs' high electronic conductivity can enhance photocatalytic activity by preventing photo-corrosion of charge carriers on photocatalyst surfaces, reducing charge recombination of electron/hole pairs, and increasing interfacial electron transfer from photocatalyst surfaces to MWCNTs [13].

Among the more modest approaches is the combination of TiO_2 with an adsorbent substance [14]. There are a lot of future uses for multi-walled carbon nanotubes (MWCNTs) in the industrial and scientific fields due to their excellent mechanical, physical, electrical, chemical, and electromagnetic properties. For instance, MWCNTs show great promise for usage in nanoelectronics, nanodevices, medicine, field emission displays, hydrogen storage, and other fields. Due to its many desirable qualities, MWCNT is being considered as a potential replacement for more traditional nanofillers in nanocomposites [15]. Additionally, MWCNTs are an excellent foundation for heterostructures composed of various other nanoscale materials due to their high specific surface area [16].

Among the various composite components, TiO_2 and carbon nanotubes (CNTs) attracted a lot of attention due to their remarkable optical, photoelectrochemical, and electrical properties. Mixed-phase TiO_2-based composites exhibit higher photo-reactivity than pure materials because of the formation of solid-solid interfaces, which can (i) enhance spatial separation and charge transfer and (ii) lessen electron-hole recombination and interface defective sites, which act as catalytic "hot spots". High photoactivity is ensured, charge recombination is reduced, and electron transit through the TiO_2 network is accelerated when carbon nanotubes (CNTs) are added to a TiO_2 matrix, increasing the material's conductivity [17].

Furthermore, it is commonly used to alter the band gaps of photocatalysts to improve their absorption capacity in the visible light region, which makes up around 45% of the solar light spectrum [18]. FTIR spectra for TiO_2 nanoparticle suspensions in deionized water at 120 mJ with 100 pulses and for TiO_2 NPs doped with 8, 16, and 25% MWCNTs at 100 mJ with 25 pulses are displayed in Fig. 2. [19]

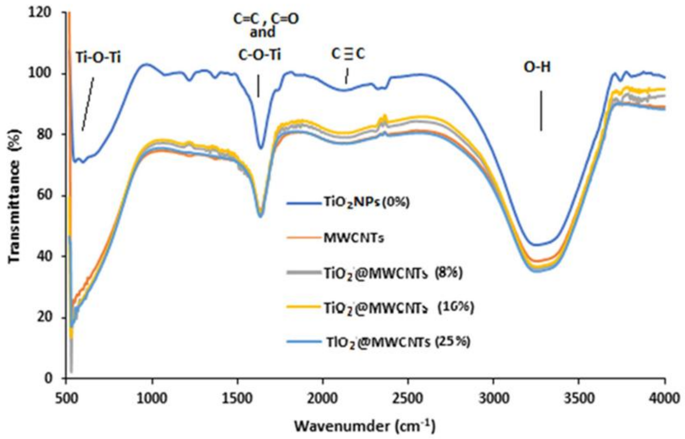

Figure 2. FTIR Spectra of MWCNTs, TiO_2 nanoparticles and TiO_2 doped with different concentration ratios (8, 16, 25) % of MWCNTs prepared at a laser energy of 100 mJ for 25 pulses. Adapted from [19].

Among the fascinating properties of carbon nanotubes (CNTs) are their exceptional thermal and electrical conductivities, high tensile strengths, and massive electron storage capacity. Their ability to use semiconductor metal oxides at the nanoscale to form homogenous composites is excellent [20, 21]. Zinc oxide and carbon nanotube composites have been found to have important applications in a wide range of industries, such as photocatalysis, microelectronics, coatings, optical devices, and drug and gene delivery [22, 23]. CNTs create a hybrid nanocomposite with a layer of crystalline ZnO on top, which is widely used as an essential part of nano-sensors, nanogenerators, and nano-resonators. It has been discovered that a ZnO-SWCNT nanocomposite can increase the stability and efficiency of an organic solar cell. Additionally, CNTs are essential as electron acceptors and transporters in nanocomposites containing semiconductor oxides like ZnO. They also significantly speed up the conduction of light-generated electrons, improving photocatalytic performance. This phenomenon reduces the likelihood of photogenerated electron-hole pairs recombining while increasing catalytic efficiency [24-26].

In vivo in animal models, the use of produced carbon and composite carbon doped with iron oxide nanoparticles enhanced wound healing activity. Metal oxide-CNT matrix nanocomposites and metal-CNT matrix nanocomposites have been developed and studied to improve their properties [27]. Yogeswaran and Chen reported creating a composite film with MWCNTs and polyethylene blue to enhance and distinguish the electroanalytical response of catecholamine and ascorbic acid [28]. Metal oxides have many desirable qualities, including a high surface-to-volume ratio, outstanding selectivity, and high sensitivity. A lot of research has gone into making MWCNT-metal oxide nanocomposites for applications such biosensors, electrochemical capacitors, supercapacitors, and lithium-ion batteries [29]. Bismuth oxide (Bi_2O_3) is an important semiconducting metal oxide material with a room temperature energy gap between 2.36 and 3.96 eV [30]. The electrical and optical characteristics of Bi_2O_3 nanoparticles are appealing; these include a high dielectric permittivity, refractive index, and energy band gap, and they also exhibit noteworthy photoconductivity and photoluminescence. The numerous applications made possible by Bi_2O_3's exceptional features include gas sensors, optoelectronics, optical coatings, and more [31, 32]. Fig. 3 shows SEM images of Bi_2O_3NPs and Bi_2O_3NPs-decorated MWCNTs at two magnifications [33].

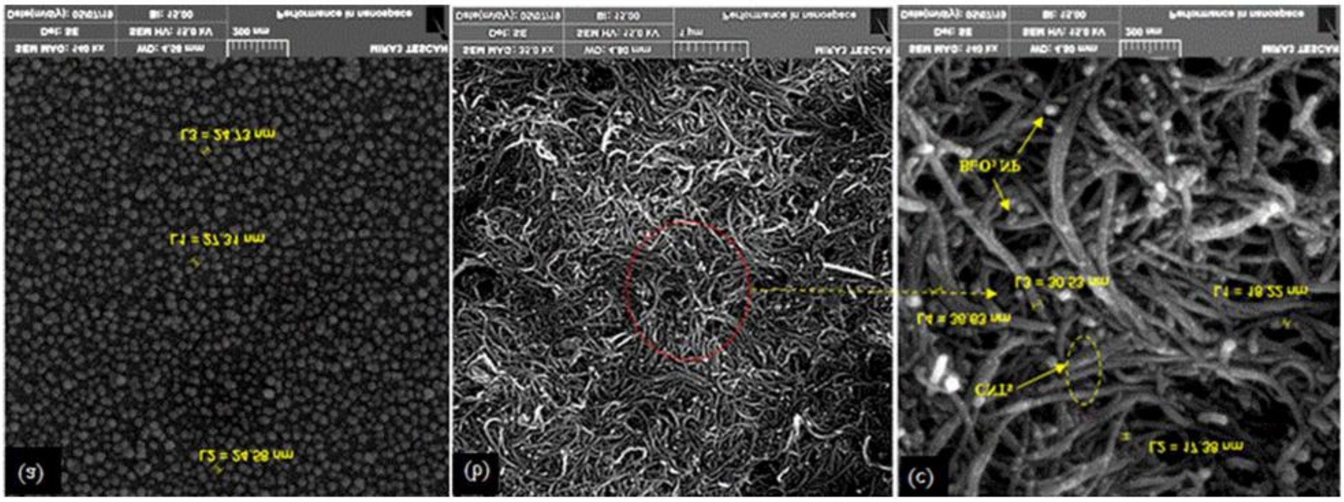

Figure 3. SEM image of a) Bi_2O_3NPs, b) low magnification of Bi_2O_3 NPs-decorated MWCNTs c) high magnification Bi_2O_3 NPs-decorated MWCNTs. Adapted from [33].

CNTs are used for many applications including catalysis [34], nanoelectronics [35], biosensors [36], antibacterial [37], and sensors [38] due to their special physical and chemical properties. The numerous reported and characterized applications of MOs-carbon nanotubes and carbon nanotubes-MOs nano composites have made them interesting [38-40]. For instance, Kohli et al. prepared In_2O_3/MWCNTs sensors [41]. Berki et al. [40] prepared and characterized MWCNT–In_2O_3/Si composites as promising gas sensors and catalysts. Zhang et al. [42] reported that copper oxide was doped with carbon nanotubes as a catalyst. Sun et al. [43] examined the hydrogen-sensing properties of SnO_2 coated MWCNTs at room temperature. Khashan et al. [44] synthesized and studied novel TiO_2/CNTs nanocomposite produced by laser ablation method. Abdul-Redaa et al. decorated MWCNT with In_2O_3 using laser ablation in two-steps for photodetector applications. Fig. 4 shows TEM images and the size distribution histograms of In_2O_3NPs and In_2O_3-MWCNTs colloidal synthesized with 17.5 J/cm^2 for 100 pulses [45].

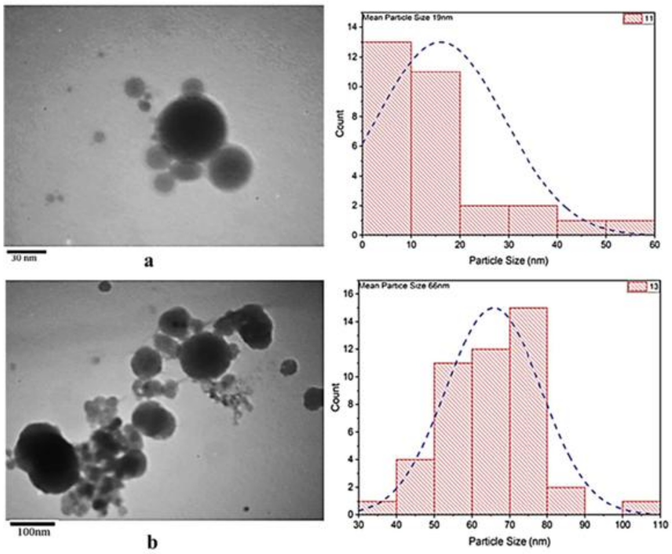

Figure 4. TEM images and distribution histogram of (a) In_2O_3NPs and (b) In_2O_3-MWCNTs nanostructure produced with 17.5 J/cm^2. Adapted from [45].

4. METHODS OF CARBON NANOTUBES SYNTHESIS

The synthesis of SWCNTs and MWCNTs is customized to satisfy particular needs, ranging from very small-scale requirements, such as CNTs needed for laboratory studies, to very large-scale needs, such as CNTs for industrial applications. Local methods can be used to create these CNTs, but they will not be perfect and may have various issues. In industrial settings, such as those involving heat, electricity, and mechanics, carbon nanotubes (CNTs) must be perfect and unaltered. As such, they require an extremely accurate synthesis procedure; for example, the plasmaaccelerated chemical vapor decomposition method was used to investigate the parameters affecting the properties of MWCNTs [46]. The well-known chemical vapor deposition method is one of several methods that can start the growth of CNTs (CVD). laser ablation method [47] and electric arc discharge method. Graphite powder in a solution of nitric acid, sulphuric acid, and potassium chlorate can also be used to develop CNTs locally and at room temperature.

4.1 Laser Ablation Method

The laser ablation method was first reported in 1995 [48]. As shown in Fig.5, the procedure involves exposing a graphitic target (containing a catalyst) to a laser beam in order to cause its vaporization. The localized and intense heating creates a cloud at the point of incidence where carbon ions and a metallic cluster of catalyst atoms come together to form the graphitic walls of carbon nanotubes (CNTs). The catalyst encourages the growth of CNTs, especially SWCNTs [49]. By following this procedure, SWCNTs with a minimal number of flaws can be manufactured while achieving excellent control over characteristics including length, chirality, and diameter. Since there are more productive options, this approach is rarely utilized to synthesize MWCNTs. The following variables have been investigated to optimize the process and perhaps modify the properties of SWCNTs:

1. The source of the laser beam (wavelength, pulse width, and intensity)
2. The reactor's temperature, which can range from room temperature for certain lasers to as high as 1200ºC for the most used laser (Nd: YAG)
3. Gas composition of the atmosphere and pressure
4. The target is typically formed by mixing the catalyst with graphite.

Munoz et al. [50] researched the impact of laser ablation on SWCNT production as a function of gas and pressure. They found that argon and nitrogen work well in this process, but helium gas is inappropriate. This is explained by the physical properties of helium, specifically its high thermal conductivity and low atomic mass, which lead to the rapid cooling and diffusion of carbon species, thereby creating an environment that is less conducive to the synthesis of SWCNTs. However, because of their larger atomic masses and lower thermal conductivities, nitrogen and argon provide better conditions for maintaining the temperature and concentration of carbon species needed for effective SWCNT growth [50] . In addition, it was discovered that the laser-formed vapor cloud has a low carbon ion density and that the reactor's yield decreases at low pressure.

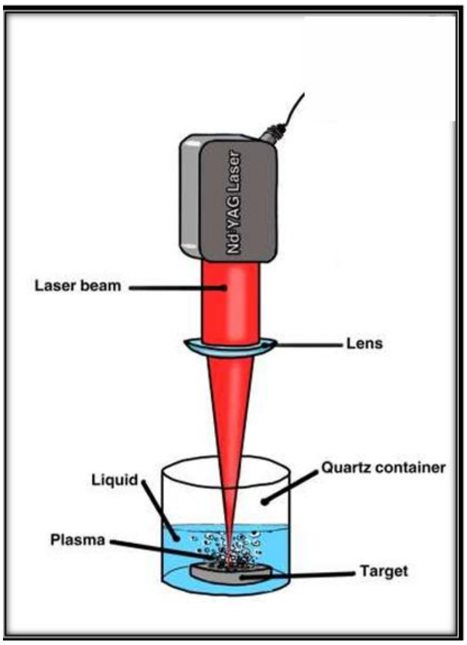

Figure 5. Laser ablation set-up for CNT synthesis. Adapted from[9].

5. COMMON CHARACTERIZATION TECHNIQUES FOR CNTS

Common characterisation methods for CNT include X-ray photoelectron spectroscopy (XPS), transmission electron microscopy (TEM), atomic force microscopy (AFM), contact angle calculations, thermogravimetric analysis (TGA), and XRD. The structure and chemical content of CNTs are characterized using techniques such as XPS, FT-IR, and Raman spectroscopy (Table 1). Teimuri-Mofrad et al. [51], by using FT-IR spectra, verified that the functionalization of CNTs with chitosan (Cs)-ferrocene (Fs) moieties. X-ray photoelectron spectroscopy (XPS) studies on SWCNTs doped with phthalocyanines have shown a strong interaction between macrocyclic complexes and CNT sidewalls. It was discovered that the transition metal spectra in complexes bound to zigzag-shaped nanotubes represented one oxidation state [52]. TEM images of

CuO/ZnO/CNT thin films verified the existence of a densely packed, nanocrystalline microstructure [53]. The analysis of single monolayers showed that CNT proliferation was independent of temperature.

Recently, Li et al. [54] reported that when carbon-based materials undergo deformation, the Raman shift causes the G band to expand and split. Raman spectroscopy on carbon nanotubes (CNTs) can identify structural defects such as cracks, edges, and grain boundaries. In most cases, characterization devices are used for various CNT research; for example, tensile testing is used to evaluate Young's modulus. A crucial property for CNTs in biomedical applications is their solubility in water, which has been achieved through functionalization. Determine the surface reactivity and dispersibility of carbon nanotubes (CNTs) by employing the Fourier transform infrared spectroscopy (FT-IR) method. The chirality and concentration of CNTs are measured using techniques like UV-Vis in order to analyze certain features of their dispersion. The growth mechanisms and purity of CNTs can be evaluated via HRTEM analysis. Furthermore, TEM can show the structure and distribution of pore sizes in CNTs, including the exterior diameter and accessibility of the inside pores.

Table 1 Common characterization techniques for CNTs

Technique	Strengths	Limitations	Best Suited For
FTIR	Determines the functional groups	Low carbon backbone sensitivity	The detection of functionalization [55, 56]
TEM	Defect imaging and high-resolution morphology	Costly, damage to the beams	Walls, crystallinity, defects, and diameter [57, 58]
XPs	Analysis of surface elements	Nohydrogen; morphology is absent	Doping, oxidation states, and surface chemistry [59]
AFM	Profile height and topography	Convolution of tip and bundling problems	CNT surface morphology and dispersion [57, 60]
XRD	Both crystallinity and graphitization	Unnoticed overlapping amorphous peaks	Order in graphite and bulk crystallinity [58, 61]
TGA	The composition, thermal stability	Lack-of morphology information	Purity and loading of functionalization [62, 63]
Contact Angle	Wettability At the surface	Roughness-affected, no nanoscale information	Changes in surface energy as a result of modification [64]

6. APPLICATIONS OF CNTS

Nanotechnology is one of the most innovative and exciting areas of study and development. It has the potential to produce new materials with improved properties. Nano-medicine, energy, environmental protection, and sensor technologies are just a few of the numerous possible fields in which nanotechnology could be used [2, 65]. Carbon nanotubes (CNTs) hold the most promise among the many fields that make up nanotechnology, and new materials are always being discovered for use. There have been a lot of studies on nanotechnology and carbon nanotubes (CNTs) as fillers because researchers have spent a lot of time and effort developing new properties and expanding new applications in a variety of fields, such as materials science, medicine, electronics, and energy storage [66] . Applications for carbon nanotubes (CNTs) that require conductivity and high absorption capacity, such as high-strength composites, fuel cells, energy conversion devices, field-emission devices, hydrogen storage devices, semiconductor devices [67, 68], and other applications, may become more appealing . Furthermore, the use of CNTs for wastewater treatment is a rapidly expanding topic for those interested in adsorption studies [69]. The primary drawbacks of carbon nanotubes are their high cost and nonrenewable nature. The goal of current research is to figure out how to prepare CNTs while keeping costs low. We will discuss some of the most important and promising applications of CNTs below.

6.1. Sensors

In many modern contexts, sensors play an essential role. CNTs can be attached to molecular and biosensors to enhance their performance. Wong et al. [70] developed the first methods utilising chemical force microscopy to show the detection of functional chemical groups attached to CNT ends. Due to their widespread use in sensors, nanotube composite pellets are ideal for gas sensing applications, such as identifying chemical plant leaks. Researchers Collins et al. [71] found that SWNTs are highly sensitive to air and vacuum conditions after conducting work in a related field. This was based on their observations of significant variations in the electrical resistance levels of their SWNT samples. They mentioned another advantage of MWNTs as a sensor for CO, H2O, NH_3, and CO. The researchers Varghese et al.[72] observed changes in CNT resistance and capacitance levels in response to subtle environmental changes. In 2002, microwave-resonant sensors that used either SWNTs or MWNTs to detect NH3 were developed; these sensors were very sensitive and responded quickly [73]. Carbon nanotubes (CNTs) and composites made of them have several potential applications beyond gas sensing, such as environmentally sensitive pressure sensors

[74]. Beyond gas sensing, carbon nanotubes (CNTs) and their composites have several possible uses, including as environmentally sensitive pressure sensors. Wood and Wagner observed that CNTs are particularly vulnerable to liquid immersion or polymer embedding processes because the nanotubes somewhat distort in the presence of different liquid media[75].

6.2. Batteries (Lithium Ions Batteries)

Lithium (Li) offers special appropriateness due to its low electronegativity and ease of electron donation, making it a valuable element. It is therefore the best material to use when creating lightweight and effective batteries. However, despite these advantages, Li's high reactivity limits its application since it reduces the metal's efficiency. This issue can be resolved by combining carbon nanotubes (CNTs) and lithium (Li) by intercalating Li ions inside CNTs. This enables the transfer of lithium ions from a graphite anode to a cathode. A medium, usually polyolefin, is required to keep the anode and cathode apart. When intercalated with CNTs, the theoretical Li storage capacity is expected to be 372 mAh/g. The rates of Li^+ intercalation and de-intercalation control the phenomena of charge and discharge in these batteries[2].

6.3. CNTs as Fillers

The use of carbon nanotubes (CNTs) as fillers in different materials to produce nanocomposites is one of the most cutting-edge applications of nanotechnology. Scientists interested in nanocomposites have conducted a number of filler experiments on carbon nanotubes (CNTs). The main purpose of adding carbon nanotubes (CNTs) to different materials, such as polymers, is to improve their characteristics. This results in mechanical, electrical, and thermal properties that are almost flawless. Garcia-Gutierrez et al. [76] developed melt-processed, injection-moulded polybutylene terephthalate (PBT) nanocomposites and graphene oxide (SWNTs). The SWNTs affected the PBT material's crystallization behavior as well as the orientation of the polymer during shearing.

Researchers Soichia et al. [77] discovered that adding it to a nanocomposite containing SWNTs and polyimide enhanced the yield strength and tensile modulus. They demonstrated how fine dispersion improved the mechanical characteristics of polyimide. Bhattacharyya et al. [78] used a conical twin-screw extruder to create SWNTs encased in melt-mixed styrene maleic anhydride (SMA) with a PA12 matrix. Increased SWNT dispersion caused by SMA copolymer encapsulation improves the interfacial adhesion between PA12 and SMA-modified SWNT. The result is a better mechanical product. Both Saeed and Park [79] produced SWNTs encased in melt-mixed styrene maleic anhydride (SMA) with a PA12 matrix using a conical twin-screw extruder. The interfacial adhesion between PA12 and SMA-modified SWNT is improved by increased SWNT dispersion brought on by SMA copolymer encapsulation. The result is an improved mechanical product. Saeed and Park synthesized MWNT/PP and MWNT/PP-g-MA nanocomposites using a range of techniques, and they examined their morphological, mechanical, and rheological characteristics at different MWNT concentrations. Their results showed that MWNTs disperse more evenly in PP-g-MA than in PP, and that the combination of the two materials has better adhesion and interfacial strength than MWNTs/PP because of the former's higher mechanical properties and improved rheological percolation threshold. Zhang et al. [80] used poly(adipic acid-hexamethylene diamine) (PA66) to create F-MWNTs. Amino MWNTs were used in the fabrication process, and after PA66 functionalization, the dispersion of the A-MWNTs in formic acid (HCOOH) was improved. The PA66 materials are grafted onto the surface of the A-MWNTs. The findings demonstrated that, in contrast to the pure PA66 composite, the addition of A-MWNTs to PA increased the thermal breakdown temperature, reduced the chain length of the PA, and enhanced the storage modulus.

6.4. Scanning Probe Tips

A scanning probe microscope features a sharp probe tip at the end of a cantilever, which enables scanning the surface of specimen and creation of nano-scale images of surfaces and structures. Probe tips are crucial because they allow for the acquisition of higher-resolution pictures. Earlier results could be improved upon by using a scanning probe bound with MWNTs instead of a regular probe, leading to higher picture resolution [81]. Daiken Chemical Company and Seiko Instruments are currently attempting to commercialise these probes. It is possible to use chemically modified nanotube tips to create sensors that can detect specific chemical and/or biological groups [82]. These sensors are crucial for identifying additional or even prohibited substances. Through experimentation, Kim and Lieber [71] found that two nanotubes could be attached to a probe tip, enabling the creation of nanotube tweezers. This nano-tool is created by the electrostatic contact of two carbon cylinders

6.5. Electronic Devices Using CNTs

CNTs are important nanomaterials that can be used in electronic devices to improve their properties. Tans et al. [86] created a SWNT-based gadget with three switchable terminals. Connected to metal nanoelectrodes, the SWNT molecule exhibited semi-conductivity. At low capacitance levels, excellent performance was observed. Due to the notoriously challenging nature of working with nanotubes, researchers developed a new method for manipulating their electrical properties and length: scanning tunnelling microscopy (STM nanostructure)[87]. The potential use of AFM to construct SWNT bends and crossings was covered by Postma et al.[88]. The technique makes it possible to shorten nanotubes by applying a controlled voltage at the tips of scanning tunnelling microscopes (STMs), which makes it possible to fabricate tiny nanotube devices. Future uses for these devices could include the manufacturing of nanoscale circuits, molecular machinery, and other nanoelectronics materials [87, 89].

Research suggests that carbon nanotubes (CNTs) can have current densities as low as 109 A/cm², which is far lower than the values found in metals (105 A/cm²)[90]. Bachtold et al. [91] and Huang et al.[92] were the first to accomplish room-temperature operation, a high on-off ratio, and a highly favourable gain in field-effect transistors. The researchers can demonstrate a variety of digital logic operations using circuits with one, two, and three transistors. A static RAM cell, an inverter, an AC ring oscillator, and a logic NOR are a few examples. Using the same technique, a Harvard University team that used crossed nanowire p-n junctions and junction arrays to build critical OR and NOR logic-gate structures saw a significant improvement. They will soon be useful in the creation of sophisticated computer systems. Derycke et al. confirmed the feasibility of using carbon nanotubes (CNTs) in a field-effect transistor (FET) in 2007 [79]. Furthermore, they demonstrated that doped nanotubes exhibit n-type behavior as opposed to pure CNTs' invariably p-type behavior. The two classes could be combined to create voltage-converting inverters.

Even though it can be difficult to control the chirality of the tubes with their electrical properties, Javey et al. [80] demonstrated that arrays of p- and n-type nanotube field-effect transistors (FETs) can be used to create logic rings and NOR and OR logic gates. Collins et al. [93] demonstrated that MWNTs produced by arc discharge can have their outer layers peeled back until the outer shell's desired electronic characteristics are achieved. Further research into the use of controlled development to produce specific chiralities is required for more electrical applications. A similar theory was applied in previous studies by Blase et al. [94], which showed that using the electrical properties of carbon nanotubes (CNTs) in polymer materials could result in the desired electrical applications.

6.6. Medical Applications of CNTs

The field of nanomedicine has grown at the fastest rate due to the higher profits associated with medical technology related to gene therapy, cancer treatments, and creative new solutions for life-threatening diseases [83-85]. Because of CNTs' special qualities and traits, researchers can explore new frontiers in nanomedicine. Researchers have already demonstrated that SWNTs and MWNTs are safer and more efficient substitutes for earlier drug delivery techniques. They can pass through membranes and reach their intended substrate targets deep within the cell to deliver nucleic acids, therapeutic drugs, and vaccines. They are ideal non-toxic carriers that occasionally increase the drug's solubility, boosting both its efficacy and safety. All things considered, recent studies on carbon nanotubes have shown that their use in medicine has a very promising future [86].

6.7. Gas and Hydrogen Storage

Carbon nanotubes (CNTs) are effective gas and metal containers because of their hollow cylindrical shape. Numerous techniques have been found for introducing important chemical species into CNT cores. These approaches include (a) chemical treatments, arc-discharge procedures, solid-state processes, and electrochemical techniques. The introduced species can include metals, metal carbides, and oxides [95]. However, the primary issue with these techniques stems from CNTs' incapacity to encapsulate gaseous compounds. According to recent studies, MWNTs and SWNTs can store hydrogen and arsenate, respectively.

Terrones et al. [96] demonstrated experimentally that gaseous nitrogen injection into MWNTs can be accomplished in a single step. According to their study, ferrocene and benzylamine solutions can be spray pyrolysed to load MWNTs. The work of Trasobares et al. [97] is similar, even though ferrocene and camphor were pyrolysed in powder form in an ammonia-filled environment [89]. Carbon nanotubes (CNTs) have the potential to be useful in the manufacturing process because they can be used to store chemical species in fuel cells, which are primarily used to power electric vehicles. However, there is some controversy surrounding the storage of hydrogen at high pressure. Carbon nanotubes (CNTs) can store between 0.1 and 66 weight percent of hydrogen[98, 99]. Hirscher et al. [100] showed that the previously observed 7% uptake levels could be explained by trace amounts of contaminants added during CNT production. Using density functional theory, the theoretical hydrogen storage capacity of carbon nanotubes has been established. Carbon nanotubes (CNTs) can absorb hydrogen molecules in several ways, including chemisorption, adsorption at interstitial sites, and the expansion of the nanotube array. Although more research and calculations are required to interpret these results, it is clear from the aforementioned examples that CNTs may not be the best material for storing hydrogen [101,102]. It has recently been demonstrated that carbon nanotubes and carbon on foams can absorb other gases, including He, NH_3, N_2, and SF_6.

7. CONCLUSION

This review revealed that PLA processes have the potential to be as competent as, or even better than, conventional methods in the production of CNTs and their alloys. Laser ablation in liquid offers a promising alternative for carbon nanotube synthesis, providing high purity, controlled morphology, environmental sustainability, versatility, and rapid production. Although it may not currently be appropriate for extensive industrial production due to specific constraints, its benefits render it a significant method for research and specialized applications. This is due to its ability to produce high-quality CNTs with versatile properties, making them ideal for cutting-edge industrial applications such as energy storage, biomedicine, and nanoelectronics. CNTs synthesized using the PLA technique provide a means to address challenges associated with other methods, eliminating the necessity for complex equipment that may adversely impact life and the environment. The selection of carbon precursors and the design of CNT production processes must be devoid of contamination to effectively and sustainably tackle the challenges without causing adverse effects on the environment. In addition, advanced characterization techniques such as TEM, Raman spectroscopy, XPS, AFM, FTIR, and TGA are essential for investigating and analyzing carbon nanotubes (CNTs). Each method offers a unique perspective on different aspects of CNT characteristics. The synthesis of carbon nanotubes (CNTs) and their alloys through laser ablation in liquid (PLAL) shows great potential for the future. However, there is a lack of comprehensive studies on how to effectively control the synthesis and concentration of CNTs, as well as the profiles of the alloys. Therefore, more research is needed to ensure that the quality of CNTs is not compromised and that the production capacity is viable for large-scale use. Moreover, the integration of CNT with various nanomaterials and the adjustment of laser ablation parameters could enhance the efficacy of the functional device derived from these nanomaterials.

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