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A Critical Review on Synthesis and Sensing: Implications of Carbon Nanotube Development for Future Technologies

Md Ashraful Alam[1], Md. Al-Amin[2], Md. Ariful Islam[3]
[1] Graduate Research Assistant Tuskegee University Alabama, USA
[2] Graduate Research Assistant, University of Massachusetts Lowell, Massachusetts, USA
[3] Graduate Student, American International University-Bangladesh, Dhaka, Bangladesh

Abstract:- Researchers from various disciplines have shown great interest in carbon nanotubes (CNTs) due to their exceptional nanostructures and distinct electronic, mechanical, and optical characteristics. Carbon nanotubes (CNTs) have shown great potential in various fields, including nanocomposites and biomedicine, making them particularly advantageous in the domain of sensing technologies. This review provides a critical analysis of the progression of carbon nanotube (CNT) synthesis techniques, starting from arc discharge and progressing to chemical vapor deposition. The focus is on the inherent trade-offs that exist between the yield, purity, and cost associated with these methods. Furthermore, the review examines a diverse array of sensing applications, encompassing glucose, pH, and quaternary ammonium compounds (QAC) sensors, among others. Considerable emphasis is placed on the prospective capacity of carbon nanotube (CNT) sensors to significantly transform analytical methodologies by providing enhanced sensitivity, specificity, and the potential for downsizing. This review seeks to offer insights into the opportunities and challenges associated with carbon nanotube (CNT)-based sensing technologies by conducting a thorough analysis of existing literature. Additionally, it aims to provide a forward-looking perspective on the future potential of these technologies. If these nanostructures are successfully developed, they possess the potential to initiate a novel phase of technological progress, thereby transforming our quality of life in unprecedented manners.

I. INTRODUCTION

Carbon nanotubes (CNTs) are increasingly recognized as a fundamental element in the field of nanotechnology, with the potential to revolutionize technological progress, similar to the transformative impact of silicon-based technologies on contemporary society [1]. Imagine a hypothetical scenario where the implementation of space elevators utilizing exceptionally durable cables, hydrogen-fueled vehicles attaining unparalleled efficiency, and artificial muscles enhancing human capacities are realized [1]. The feasibility of such innovative applications can be considered within the domain of carbon nanotube (CNT) research.

However, it is important to approach the optimistic perspective on carbon nanotubes (CNTs) with a certain level of prudence [2]. By drawing a parallel to the historical narrative of fullerenes, which are molecular counterparts of carbon nanotubes (CNTs), valuable insights can be gained regarding the effective management of expectations [3]. The year 1985 marked the discovery of fullerenes, which generated a significant amount of excitement and ultimately led to the Nobel Prize in Chemistry being awarded in 1996 for their discovery [1]. Despite the initial excitement, the practical use of fullerenes in commercial applications has been relatively limited [4]. This observation highlights the need for caution when making predictions about the potential applications of carbon nanotubes [1].

The anticipated transformative impact of carbon nanotubes (CNTs) on the electronics industry is a significant factor contributing to the prevailing optimism surrounding them [5]. With the approaching limitations of Moore's law, which is an empirical observation that predicts the doubling of transistors in a dense integrated circuit every two years, there is an increasing need to investigate new avenues for achieving further miniaturization [6]. Carbon nanotubes present a compelling alternative due to their distinctive electrical properties and capacity to expand the limitations of traditional silicon technologies [6].

The remarkable electrical [5], mechanical [7] [8], optical [8], and thermal properties [6] of carbon nanotubes (CNTs) serve as a source of inspiration for numerous innovative applications. These encompass a wide range of advancements, including next-generation electronics, innovative materials, sustainable energy solutions, power quality improvement 30 and revolutionary medical technologies [6] [31]. Hence, with a conscientious emphasis on maintaining a judicious equilibrium between optimism and pragmatism, the present review endeavors to offer a thorough examination of the historical progression of carbon nanotubes, a critical evaluation of their synthesis techniques, and an exploration of the diverse range of potential applications that lie ahead. Deep learning [32] also can be employed to design and optimize CNT-based energy storage materials, predicting their properties and performance.

II. THE GENESIS OF CNTS: INNOVATIONS AND METHODOLOGIES

A: Vapor-Growth Methods

Vapor-growth methods are one of the most scalable and cost-effective ways to make carbon nanotubes [4]. Chemical Vapor Deposition dominates vapor-growth methods [9]. Carbon-containing gases like methane or ethylene are heated to 700–1000°C in a CVD furnace. CNTs grow on silicon wafers or alumina plates with a metal catalyst like iron, nickel, or cobalt [9] [4].

CVD releases carbon atoms by heating carbon-containing gases to decompose [9]. CNTs form when these atoms precipitate on metal catalyst particles. Temperature, gas flow rate, and catalyst choice can greatly affect CNT yield, purity, and morphology [9]. Recently developed CVD methods like Plasma Enhanced Chemical Vapor Deposition (PECVD) allow CNT growth at lower temperatures, expanding its applicability [9].

Another vapor-growth method is Vapor Phase Growth (VPG) [10]. A tube furnace thermally decomposes a carbon source under inert gas flow to grow CNTs, which are collected downstream [10]. VPG is less common than CVD. The lack of a metal catalyst distinguishes this method [10].

Recently published literature suggests that Vapor-Liquid-Solid (VLS) growth methods are becoming popular [11]. A liquid catalyst dissolves the carbon source and precipitates nanotubes in this process. This method may improve CNT dimensions and orientations.

These vapor-growth methods produce high-quality CNTs efficiently and allow for further CNT property customization for applications like glucose, pH, and quaternary ammonium compound sensors [11].

B: Arc-Discharge Method

The Arc-Discharge Method is one of the oldest and simplest ways to make carbon nanotubes [11]. This method traditionally involves creating an electric arc between two graphite electrodes submerged in helium or argon [9]. One electrode is anode and one cathode. High temperature (~4000 K) from the electric arc vaporizes the anode surface, forming a carbon-atom plasma [4]. As vaporized carbon atoms condense on the cathode, they form multi-walled (MWNTs) and single-walled carbon nanotubes [9].

Arc-Discharge Method is simple and cost-effective, but it has drawbacks. CNT heterogeneity is the main drawback [11]. MWNTs, SWNTs, amorphous carbon, and fullerene structures are often produced by the method. To increase SWNT yield and quality, nickel or cobalt catalyst particles are added to the anode, but they can contaminate the nanotube sample [7].

Post-synthesis purification can improve Arc-Discharge Method CNT purity, but it adds complexity and cost [7]. Despite these drawbacks, the method is preferred for specialized applications that require CNTs with minimal structural defects because the high-temperature environment helps form nanotubes with fewer defects than CVD [9].

Recent advances have optimized parameters like the inert gas, arc current and voltage, and electrode composition to improve the Arc-Discharge technique [9]. These optimizations produce CNTs with specific diameters, lengths, and chirality, expanding their use in sensing, energy storage, and nanocomposites [11].

III. ADVANCES IN SYNTHESIS TECHNIQUES

A: Electric-Arc Discharge

The Electric-Arc Discharge method is a staple in CNT synthesis due to its simplicity and high yield [12]. A direct current arc discharge between two graphite electrodes in helium or argon is used. Electric arcs heat the anode to over 4000 K, vaporizing graphite [6]. As carbon atoms approach the cathode, they recondense into CNTs and other allotropes [6]. This method produces high-quality CNTs with fewer structural defects, which is important for applications requiring superior electrical and mechanical properties. However, this method has drawbacks. It produces a heterogeneous mix of single- and multi-walled CNTs, amorphous carbon, and fullerenes [13]. Post-synthesis purification improves purity but increases complexity and cost. Nickel and cobalt catalysts are used to increase SWNT yield but can contaminate the product [13]. Despite these challenges, Electric-Arc Discharge is essential for specialized applications that require CNT quality.

B: Laser-Based Methods

After mid-1990s work by the Richard Smalley group, laser-based CNT synthesis became popular [13]. This method uses high-energy laser pulses to irradiate a graphite-metal target in argon or helium [14]. Laser interaction with target material vaporizes carbon atoms, which condense on a copper substrate to form CNTs [15]. The homogeneity of laser-based synthesis, especially high-quality single-walled carbon nanotubes, is remarkable [15].

C: Chemical Vapor Deposition (CVD)

CVD is a popular method for synthesizing carbon nanotubes (CNTs) due to its scalability, versatility, and cost [15]. Hydrocarbons like methane or ethylene are introduced into a reactor chamber with a metal catalyst substrate in this process [16]. Hydrocarbon gas decomposes and releases carbon atoms when heated to 600°C to 1200°C. CNT growth on the substrate begins when these atoms interact with the metal catalyst [16].

Finally, tuning process parameters like hydrocarbon gas, catalyst material, temperature, and pressure controls CNT morphology, quality, and yield [7]. For instance, iron, nickel, and cobalt catalysts affect nanotube diameter and wall structure [16]. CVD innovations like the High-Pressure Carbon Monoxide (HiPco) method produce specific CNTs [6]. Despite its many benefits, CVD can produce impurities that require purification. However, its adaptability makes it the preferred method for CNT research and industrial production.

IV. FUTURE POTENTIALS

A: Advanced Composite Materials

These papers collectively highlight the growing popularity and applications of advanced composite materials (ACMs) in various industries. Liu 2013 [17] defines ACMs as materials with high-strength fibers and weaker matrices, exhibiting properties such as light weight, high stiffness, and temperature resistance. Overall, these papers demonstrate that ACMs offer benefits such as lightweight construction, high tensile strength, corrosion resistance, and thermal stability, making them increasingly popular in aerospace, automotive, construction, and renewable energy sectors [33].

Popular ACMs include Fiber Reinforced Polymers (FRPs). Carbon, glass, and aramid fibers in a polymer matrix provide strength and flexibility [17]. The study conducted by Sattar in 2015 examines the enhancement of mechanical, thermal, and electrical characteristics of carbon fiber reinforced polymers (CFRPs) by incorporating carbon nanotubes (CNTs) into thermoplastic polyurethane composites. In the study conducted by Han in 2017 [18], an investigation was carried out to examine the application of nanofillers in order to augment the multifunctional properties of CFRP laminates, encompassing enhancements in thermal and electrical conductivity [18]. The article by Spitalsky (2010) [19] provides a comprehensive examination of the chemistry, processing, and properties of composites consisting of carbon nanotubes and polymers. The author highlights the crucial importance of achieving a uniform dispersion of carbon nanotubes within lightweight matrices [19]. Finally, Udupa (2012) [20] examines the prospective uses of functionally graded composite materials reinforced with carbon nanotubes (CNTs), emphasizing their potential applications in diverse sectors including aerospace, defense, and medicine. In general, the aforementioned papers provide evidence of the enhanced mechanical, thermal, and electrical characteristics exhibited by carbon fiber-reinforced polymers (CFRPs) when incorporating carbon nanotubes as reinforcements. This renders them well-suited for applications requiring exceptional performance. Nanoparticle- or nanotube-containing nanocomposites have improved tensile strength, flame retardancy, and conductivity over traditional composites [20]. These materials are used in advanced electronics, catalysis, and targeted drug delivery devices.

This field is vast, so a comprehensive review [34] would cover resin transfer molding and filament winding, reinforcement and matrix effects, cost and recyclability, and future trends like IoT integration into smart composites for real-time monitoring.

B: Sensor Development:

Multipurpose Platforms for Environmental and Medical Monitoring. Carbon nanotubes (CNTs) have demonstrated immense promise in the realm of sensor development, capable of detecting a wide array of substances and conditions with high sensitivity and selectivity [21]. Recent advancements have led to the development of sensors based on carbon nanotubes (CNTs), ranging from glucose [22] to quaternary ammonium compounds (QAC) [23] sensors. For instance, CNT-based pH [8, 35] sensors, which exploit the optical and electrical [24] properties of single-walled carbon nanotubes (SWCNTs), offer rapid and precise measurement capabilities that are pivotal in various industrial and biomedical applications. Moreover, gas sensors made from CNTs have exhibited remarkable sensitivity towards gases like CO, NO2, and CH4, owing to their high surface area and electrical conductivity [25]. Considerable emphasis is placed on the prospective impact of carbon nanotube (CNT)-based sensors on the advancement of analytical methodologies, as they hold the potential to significantly enhance sensitivity, specificity, and enable the prospect of miniaturization [26]. This review seeks to offer insights into the opportunities and challenges associated with carbon nanotube (CNT)-based sensing technologies by conducting a thorough analysis of existing literature. Additionally, it aims to provide a forward-looking perspective on the future potential of these technologies. If these nanostructures are successfully developed, they have the potential to initiate a novel phase of technological progress, thereby transforming our quality of life in unprecedented manners.

C: Energy Storage

Carbon nanotubes (CNTs) exhibit significant promise in augmenting energy storage capabilities within various devices, such as supercapacitors. Kumar (2018) elucidates the distinctive characteristics of carbon nanotubes (CNTs), including their notable surface area and electrical conductivity, which confer them with inherent advantages for applications in energy conversion and storage [27]. The study conducted by Kaempgen in 2007 provides evidence that carbon nanotube (CNT) networks, which possess high conductivity and porosity, can function as the exclusive material for electron conduction in supercapacitors [27]. This discovery has significant implications as it enables the development of lightweight devices for storing electrical charge 27. The study conducted by Cao in 2013 [28] examines the utilization of carbon nanotube (CNT) macro-films in various energy storage devices, including stretchable supercapacitors and lithium-ion batteries. The papers presented collectively provide evidence in support of the notion that carbon nanotubes (CNTs) possess a substantial surface area and exceptional electrical conductivity [28]. These properties contribute to an increased capacity for charge storage in energy storage devices [30] such as supercapacitors.

V. CONCLUSION

In summary, the domain of carbon nanotube technology has experienced notable progress, resulting in a broadened range of applications spanning from fundamental scientific inquiry to practical implementation in diverse industries such as electronics, aerospace, and sensing. As elucidated in the review, various synthesis methods, including electric-arc discharge, laser-based techniques, and chemical vapor deposition, have undergone advancements throughout time, each possessing distinct merits, constraints, and domains of utilization. The remarkable potential of these sensors, specifically in the domain of pH and QAC sensing, is highly noteworthy. Through the utilization of advanced synthesis and functionalization methodologies, significant enhancements have been achieved in the quality of nanotubes, resulting in the development of highly durable and dependable sensors that exhibit considerable potential for practical applications in various domains.

The field of advanced composite materials, which involves the incorporation of nanotubes into polymer matrices, has experienced significant growth, presenting remarkable mechanical, thermal, and electrical characteristics. This statement suggests a shift in paradigm towards multifunctional materials that possess both structural significance and embedded smart functionalities, facilitated by advancements in nanotechnology. These technological advancements create opportunities for groundbreaking applications, spanning from the development of sustainable energy sources to the design of precise drug delivery systems. Despite significant advancements, there are still obstacles pertaining to the cost-effectiveness, scalability, and environmental sustainability that persist, thus requiring additional investigation and ingenuity.

In anticipation of the future, it is evident that carbon nanotube-based technologies possess the potential to surmount the constraints imposed by present materials and processes. The potential impact of carbon nanotube technologies is significant due to the increasing demand for miniaturization in electronics, fuel-efficient transportation, precision sensing, and other necessities of a rapidly progressing society. Hence, it is crucial to engage in continuous research and development, as well as foster interdisciplinary collaboration, to fully harness the profound capabilities of this revolutionary technology.

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