STUDY ON CARBON NANOTUBES FOR FLEXIBLE ELECTRONICS

A Project report is submitted in partial fulfillment of the requirements for the award of Degree of Bachelor of Science in Electrical and Electronic Engineering.

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JUNE, 2023

DECLARATION

We hereby declare that this project “**Study on CNT for flexible electronics**” represents our own work which has been done in the laboratories of the Department of Electrical and Electronic Engineering under the Faculty of Engineering of Daffodil International University in partial fulfillment of the requirements for the degree of Bachelor of Science in Electrical and Electronic Engineering and has not been previously included in a thesis or dissertation submitted to this or any other institution for a degree, diploma or other qualifications. We have attempted to identify all the risks related to this research that may arise in conducting this research, obtained the relevant ethical and/or safety approval (where applicable), and acknowledged the participants’ obligations and rights.

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APPROVAL

The project entitled **"Study on Carbon Nanotubes for Flexible Electronics"** submitted by **Md. Esfar Alam (ID: 191-33-4985) & Md. Maidul Islam Sourov (ID: 191-33-5007)** has been done under my supervision and accepted as satisfactory in partial fulfillment of the requirements for the degree of **Bachelor of Science in Electrical and Electronic Engineering** in **June, 2023.**

Signed

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Dedicated

To

Our Beloved Parents

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LIST OF ABBREVIATIONS

CNT	Carbon Nano Tubes
2-D	Two Dimensions
SWCNT	Single-walled Carbon Nano Tubes
MWCNT	Multi-walled Carbon Nano Tubes
SWNT	Single-walled Nano Tubes
MWNT	Multi-walled Nano Tubes
PE	Printed electronics
EMG	Electroencephalography
EEG	Wearable Electromyography
LEDs	light-emitting diodes
TEM	Transmission Electron Microscope
HP-CO	Hydrogen Peroxide-Carbon Monoxide
IBM	International Business Machines Corporation
TEM	Transmission Electron Microscope
C60	Carbon 60, a molecule made up of 60 carbon atoms.
PECVD	Plasma-Enhanced Chemical Vapor Deposition
CVD	Chemical Vapor Deposition
CCVD	Catalytic Chemical Vapor Deposition
PECVD	Plasma Enhanced Chemical Vapor Deposition
PVDF	Polyvinylidene Fluoride
FETs	Field-Effect Transistors
PPy	Polypyrrole
REACH	Registration, Evaluation, Authorization, and Restriction of Chemicals.
ISO	International Organization for Standardization
CAGR	Compound Annual Growth Rate
IoT	Internet of Things

LIST OF SYMBOLS

Symbol	*Name of the symbol*
E	Angular velocity, rad/sec
S	Damping ratio
L	The Length of the CNT
r	The Radius of the CNT
pH	Potential of Hydrogen
TPa	Tissue Plasminogen activator
ρ	The resistivity of the CNT
S	The Tensile strength
F	The applied force
σ	The composite material's electrical conductivity
σ_m	The electrically conductive property of the matrix of polymers
σ_c	The carbon nanotubes' contribution to electrical conductivity is denoted

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ABSTRACT

Flexible electronics made from carbon nanotubes have become a viable technique for future-oriented electronic devices because of their remarkable electrical, mechanical, and thermal characteristics. With regard to flexible electronics based on CNTs, this study aims to investigate prospective applications, problems, and their preferable solutions. An overview of CNT's special qualities, including their high conductivity, electrical flexibility, and resilience, which make them the perfect material for flexible electronics, is presented at the beginning of the paper. In order to create outstanding CNT circuits on flexible substrates, proper analysis has been done on alternative manufacturing procedures, comprising CNT advancement and alignment. The article explores their applications in biomedical implants, wearable sensors, flexible screens, and energy storage systems. The presentation of significant accomplishments, such as efficient transistors, transparent sensors, and flexible batteries, illustrates the potential influence of CNT-based technology in various areas. It also outlines the remaining difficulties and possible solutions for the development of flexible electronics based on CNT. Along with the necessity of standardization and process optimization, the concerns of CNT purity, consistency, and device stability are examined. The most significant role of additional studies is to promote long-term stability, explore fresh applications, and improve device performance. For academics, engineers, and business professionals involved in the area of flexible electronics, this study offers an in-depth overview of the state of the sector today. The information gathered from this paper will help CNT-based technologies to continue to improve and be adopted, enabling the development of revolutionary applications across multiple fields of study.

KEYWORDS: Carbon Nanotube, Flexible Electronics, Nanotechnology, 2D materials, High-Performance Device

CHAPTER 1
INTRODUCTION

1.1 INTRODUCTION

In contrast to traditional nano-electronics, which emphasize shrinking for maximum performance and integration density, nano-electronics concentrates on a wide area and lower costly applications, as well as new application aspects such as flexible and elastic devices. Electronic components made of plastic or elastic materials, such as flexible flat panel displays, electronic paper, thin nanosensors, wearable technologies, injectable diagnostic interventions, and many others, have the potential to drastically alter people's perceptions of electronics. The creation of these new types of electronics is heavily reliant on material science. Unformed silicon, polysilicon, and sustainably grown electronics have continued their efforts as actual materials for relatively thin transistors, one of the most important components in nano-electronics. In the past few years, nanomaterials such as; One-dimensional CNTs, quantum dots, and 2-D materials with nanotubes have piqued the curiosity of various researchers in this area since they offer dramatically improved performance than elemental semiconductor materials and are less difficult to process Polysilicon or Silicon. Carbon nanotubes, in particular (CNTs) due to their extraordinarily high carrier mobility, mechanical flexibility, and superior performance, hold considerable potential for high-performance flexible electronics. They are extremely strong and lightweight and have unique electrical properties that make them useful in a wide range of applications, including electronics, materials science, and biotechnology. Carbon atoms make up the cylindrical structure of a CNT. Imagine a graphite sheet wrapped in a tube to represent a CNT. Graphite is created as a 2-D layer of carbon atoms stacked in a hexagonal array, as opposed to diamond, which forms a three-dimensional diamond square crystal structure with each atom of carbon having four closest neighbors grouped in a tetrahedron. Each carbon atom in this instance has three close neighbors. Carbon nanotubes are created by "rolling" graphite sheets into cylindrical shapes. The atomic configuration, tube diameter, length, and morphology, or nanostructure, all affect the qualities of nanotubes.[1] Single-walled and multi-walled nanotubes also exist, and MWCNTs are merely made up of concentrically arranged SWCNTs. In Fig.1.1 the shape of a planar graphene sheet is demonstrated, which also could lead to CNT upon rolling up.

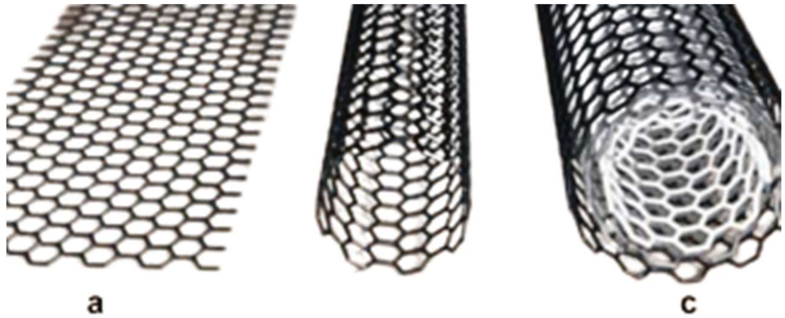

Fig.1.1: (a) The fundamental shapes of a planar graphene sheet, (b) SWCNT, and (c) MWCNT.

SWCNTs are single-walled carbon nanotubes with a single long twisted graphene sheet. waw. Because nanotubes have a length-to-diameter-to-diameter to diameter ratio of around 1000, they are considered nearly one-dimensional materials. SWCNTs typically have a diameter of about 1 nm and are thousands of times more significant in length. A uniform cylinder created by rolling up a sheet of graphene is commonly termed a single-wall carbon nanotube (SWCNT), I n in which a1 and a2 are sheets along a vector, $\boldsymbol{C_h} = \boldsymbol{na_1} + \boldsymbol{ma_2}$. The fundamental vectors of graphene's hexagonal crystal structure. The two structural parameters, diameter, and crystallinity, of the nanotube, are defined by the indices (n, m).[2] MWNTs (multi-walled carbon nanotubes) can be imagined as a sequence of single-walled tubes nestled within one another. There could be as few as six or as many as twenty-five such concentric barriers. As a result, MWNT diameters can be as large as 30nm, as compared to 0.7 - 2.0 nm for normal SWNTs.[3] Figure 1.2 illustrates a curved optical micrograph of a flexible IC.

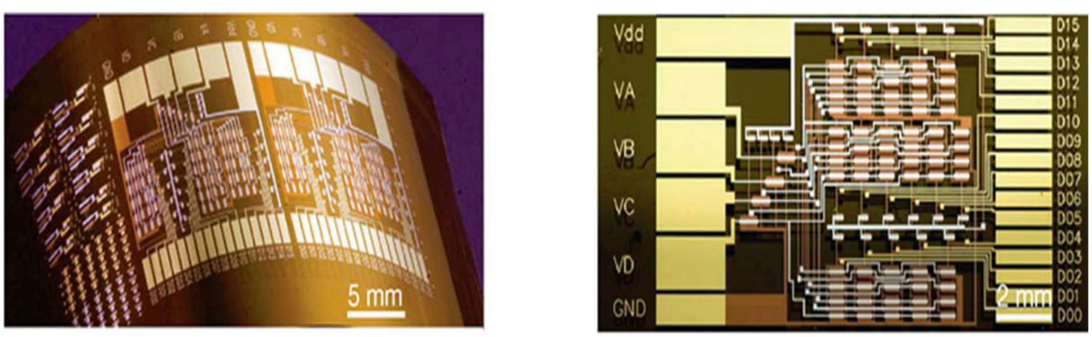

Fig.1.2: A curved optical micrograph illustrating a flexible integrated circuit.

Flexible electronics refers to electronic devices and circuit structures that are capable of conformably fitting to a curved or irregular surface or can be flexed or stretched. These devices are made using flexible materials such as plastics, metals, and ceramics, which enable them to be bent or folded without breaking or degrading their performance. The flexible electrode is made of an anisotropic CNT wrinkled film layer covered on a silicone-inflated surface (CNT@latex), whose resistivity is constant during 25000 stretching cycles of 0% to 50% tensile strain and can withstand a 500% tensile train. When employed as the electric current receiver of a flexible Zinc-ion battery, the highly conducting electrode can sustain a resultant potential of 1.3 V throughout the stretching process from 0 to 100%.[4] Applications of flexible electronics include flexible displays, sensors, solar cells, and batteries, as well as wearable and implantable medical devices. CNTs can be embedded in or printed on flexible substrates such as plastics, which allows them to be used to create lightweight and low-cost electronic devices that can conform to irregular or curved surfaces. Printed electronics (PE) refers to the printing of circuits on mediums such as paper and textiles, as well as a wide range of other possible media. The current fast development of PE technology is spurred by the prospect of reduced cost, high-volume, high-throughput manufacturing of electronic devices that are lightweight and compact, thin and flexible, affordable and disposable.

Frontier technologies are made possible by physically flexible electronics, which pave the way for cutting-edge applications including wearable technology, electronic skins (e-skins), folding displays, and electronic sheets. Interfacial conformity, bendability, stretchability, and low weight are benefits of flexible electronics. Biologically compatible semiconductors made from organic matter can be utilized safely for cutaneous and intramuscular applications without creating negative side effects, in contrast to inorganic materials (such as metals or oxides).[5] Epidermal electronics have the potential to revolutionize a variety of skin-inspired technologies, including synthetic sensors, soft neural sensors, prosthetic devices, injectable biomedical electronic devices, robotics, and an array of other skin-inspired devices.[6]

Here, Figure 1.3 demonstrates the reduction of film thickness reducing air gaps and improvement of the contact between the film and substrate.

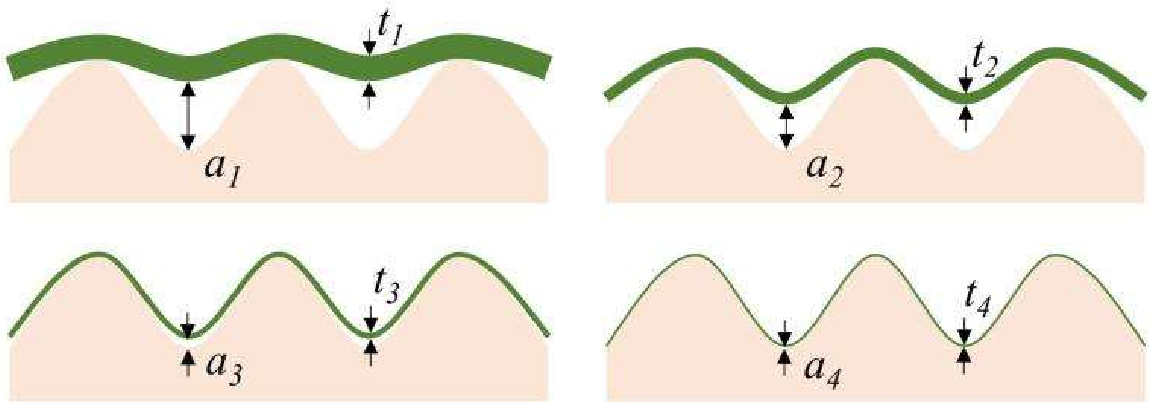

Fig.1.3: Reduction of the film thickness reducing air gaps and improving the conformal contact between the film and the substrate.[5]

Depending on the application, flexibility may take many different forms, from solar cell rolling to an electrode adapting to human skin. However, a thin film's bendability is determined by its bending rigidity, which is primarily determined by two variables: the thin film's overall thickness and its Young's modulus. In broad terms, a1 > a2 > a3 > a4 leads in t1 > t2 > t3 > t4. A thinner film (lower magnitude of ai) or lesser Young's modulus leads to a more conformal layer to the underlying base (smaller magnitude of ti).[7]

The Young's Modulus of a CNT can be determined using the following equations:

$$E = \frac{S \times L}{\pi \times r^2}$$

Where, E = Young's modulus, S = The Tensile strength, L = The Length of the CNT, r = The Radius of the CNT

CNTs can also be used to create transparent conductive films, which can be used in flexible displays and other transparent electronic devices. They are also highly flexible, and able to bend or stretch without breaking or degrading their performance. Carbon nanotube-based flexible printed electronic technologies originally emerged as promising low-cost substitutes for silicon-based electronics in a few key application areas. The promise of offering diverse electronic functionality at a price that will eventually be equivalent to the price of creating prints at a regular printing press manufacturing facility has therefore been the fundamental driving factor of CNT-based flexible printed electronics.

1.2 OBJECTIVES:

The major aims of research in CNT-based flexible electronics are to develop new materials, gadgets, and manufacturing procedures that can take advantage of the unique features of CNTs to construct flexible and stretchable electronic devices. Some specific targets of this research include:

➔ Developing novel ways to deposit CNTs on flexible substrates to make transparent conductive films or other electrical devices.

➔ Creating devices such as transistors, sensors, and solar cells that can take advantage of the high conductivity and mechanical strength of CNTs.

➔ Exploring the use of CNTs in flexible and stretchable batteries, which can be employed in wearable and implantable devices.

➔ Creating innovative strategies for regulating the structure and characteristics of CNTs to maximize their performance in electrical devices.

➔ Developing innovative means of manufacturing CNT-based devices on a big scale for commercial manufacture.

➔ Exploring novel applications for CNT-based flexible electronics, such as flexible screens, flexible robotics, and wearable devices

➔ Finding a cost-effective means of generating CNTs on a huge scale, since they are still rather pricey.

The goal of CNT-based flexible electronics is to create unique and sophisticated electronic devices that can bend, twist, and adapt to different shapes without sacrificing electrical function.

The use of carbon nanotubes in flexible electronics can enable a wide range of applications. Some of the possible benefits of employing CNTs in flexible electronics. Table 1.1 shows the benefits of CNT-based flexible electronics.

Table 1.1: Benefits of employing CNT in flexible electronics

Benefits	Description	Reference
Flexibility	Because carbon nanotubes are incredibly flexible and can be bent and twisted without breaking, they are suitable for applications in flexible electronics. CNTs may be embedded on flexible substrates like polymers, enabling the development of wearable and bendable electrical devices.	[2]
Lightweight	Because carbon nanotubes are exceedingly light, they can assist lower the weight of electrical equipment, making them simpler to carry and manage. This is especially true for wearable gadgets like smartwatches and fitness watches, which must be lightweight and easy to wear for long periods of time.	[8]
High conductivity	CNTs are extremely conductive, which means they can effectively transport electrical current, making them valuable for an extensive variety of electronic applications. CNTs may be utilized as an electrode in flexible screens, touchscreen devices, and solar cells, making electrical data transfer quicker and more efficient.	[9]
Mechanical strength	CNTs have an extremely high strength-to-weight ratio, making them excellent for use in applications requiring strength and longevity. CNTs can be utilized to improve the mechanical durability of substrates that are flexible by reinforcing their mechanical strength.	[10]
Small size	CNTs are extremely tiny, with dimensions on a nanometer level, making them ideal for usage in applications requiring small sizes, such as wearable electronics. CNTs have the potential to be utilized to make flexible electronic parts that are more compact and effective than their conventional equivalents.	[9]
Enhanced thermal conductivity	CNTs have a high level of thermal conductivity, that can aid in the dissipation of heat created by electrical equipment, reducing overheating and enhancing performance. CNTs can be utilized to improve the efficiency and longevity of flexible electronic devices by acting as heat sinks.	[11]
Better battery performance	CNTs have the potential to be utilized to make batteries with enhanced performance that are able to store greater amounts of energy, charge quicker, and remain functional longer than standard batteries. The CNT-based battery has the ability to transform the energy storage sector, allowing for the development of more effective and environmentally friendly energy solutions.	[12], [13]

Lower power consumption	CNTs can assist reduce electrical device power consumption, making them more efficient with energy and ecologically benign. CNTs can be employed as components for low-power applications like sensors, increasing energy efficiency and lowering environmental impact.	[13]
Improved sensor performance	CNTs may be utilized to make highly sensitive sensors capable of detecting minute changes in pressure, temperature, and other factors. CNT-based sensors have the potential to transform environmental monitoring, healthcare diagnosis, and industrial quality assurance by allowing for the development of more accurate and dependable sensors.	[8], [14]
Reduced cost	CNTs can be manufactured reasonably cheaply utilizing several processes, lowering the cost of electrical gadgets and making them more affordable to a larger range of individuals. CNTs may be utilized to make low-cost, adaptable electronic components, hence increasing the availability of technology and stimulating innovation.	[15]

Overall, CNT-based flexible electronics research intends to build a new generation of electronic devices that can conform to uneven or curved surfaces and can be flexed or stretched without breaking or impairing their performance.

1.3 BRIEF METHODOLOGY

The primary source for this thesis paper is based on acceptable keywords and search phrases in academic databases including Web of Science, Scopus, or Google Scholar. The information and data from these articles are presented to offer a thorough and coherent picture of the current and future status of the research in the area of CNT-based flexible electronic devices.

Here, Figure 1.4 shows the chart of brief methodology of this study.

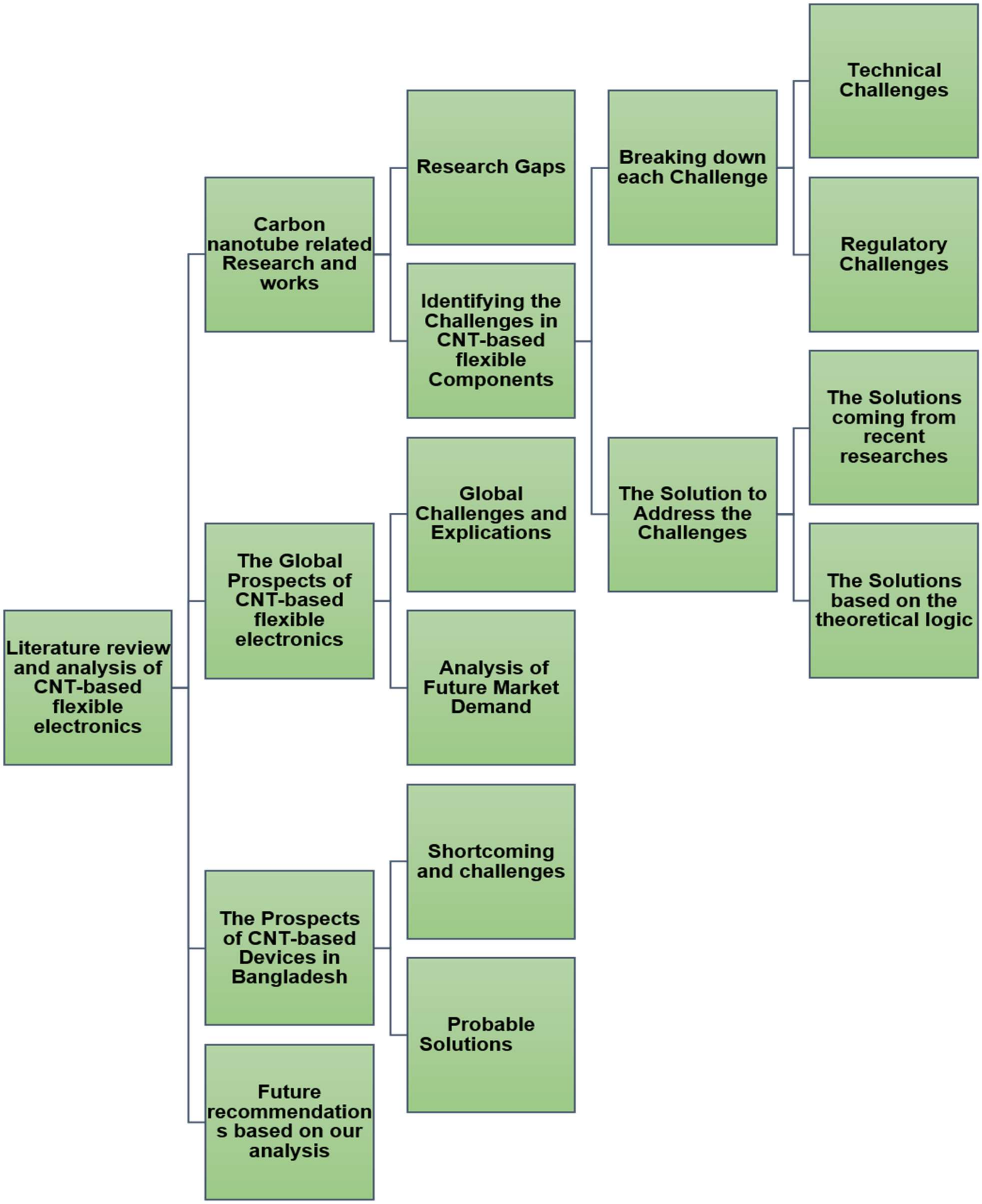

Figure 1.4: The chart of Brief Methodology

Here figure 1.5 represents a crystalline structure model of Graphene generated from Xcrysden through Quantum Espresso.

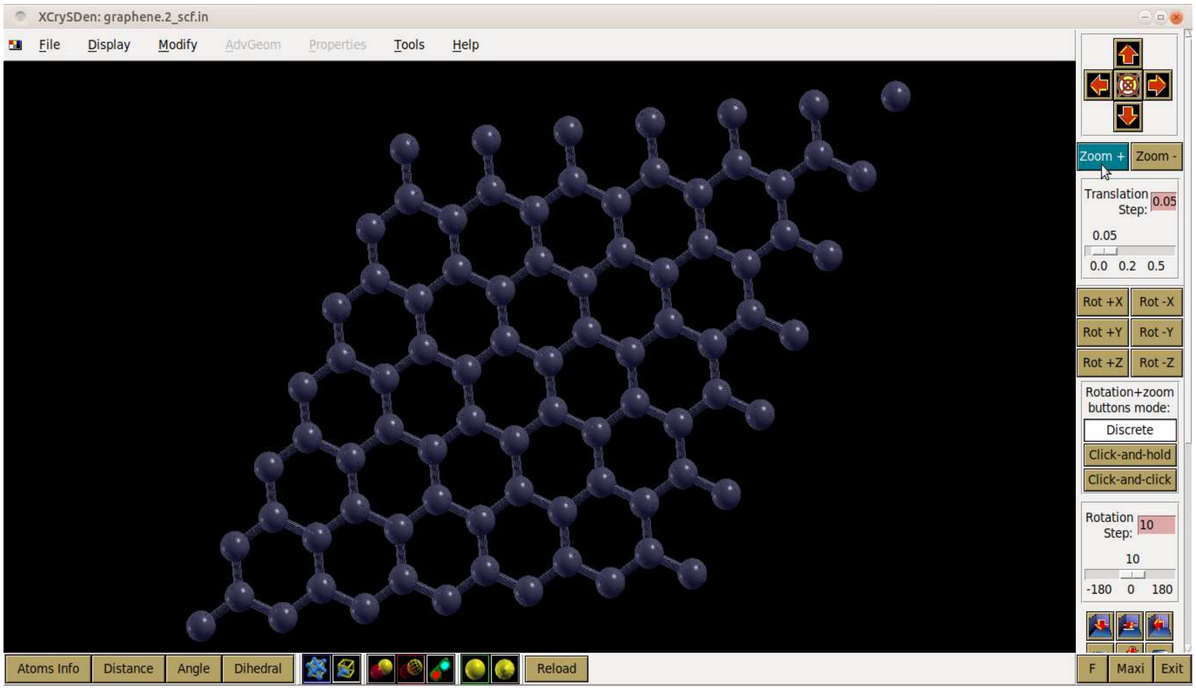

Figure 1.5: Crystalline Structure Model of Graphene from Xcrysden.

We coded and ran the input SCF file into Quantum Espresso to model the crystal structure of Graphene from Xcrysden. The input file is divided into parts, each with its own variety of keywords and parameters. The CONTROL section gives basic information about the computation, such as the calculation type (SCF for self-consistent field), the output directory, and the output file prefix. The crystal structure and other parameters, including the lattice constant and plane-wave energy cutoffs, are defined in the SYSTEM section. The ELECTRONS section defines the self-consistent calculation's convergence conditions. The ATOMIC_SPECIES section lists the system components and the appropriate pseudopotential file. Then we simulated the PWSCF input file through XCrysden and got our desired crystalline structure of Graphene.

1.4 STRUCTURE OF THE REPORT

The dissertation is structured in the following manner:

Chapter I encloses the introduction of the thesis topics and materials, a brief methodology, and the thesis's aims/ objectives.

Chapter II discusses the literature review part which includes thesis topic-related research works and current research gaps in this relevant field of technology.

Chapter III emphasizes the current challenges in Carbon nanotubes based flexible electronics systems. This chapter includes current technical and regulatory challenges in CNT-based flexible electronics systems.

Chapter IV contributes to figuring out the possible solutions to mitigate the challenges in Carbon nanotube-based flexible electronics systems.

Chapter V discusses the prospects of CNT-based flexible electronics systems from around the world. This chapter also briefly explains the prospect of such electronic systems in Bangladesh.

Chapter VI wraps up the whole thesis work, enlists the outcomes of the thesis, and paves possibilities and impact of the thesis with future research directions and recommendations.

CHAPTER 2
LITERATURE REVIEW

2.1 INTRODUCTION

High-performance flexible electronics are in quick demand for developing applications such as flexible sensors and the Internet of Things in which information may be acquired in real-time and processed in settings with minimal power and high speed. Because of their superior electrical and mechanical characteristics, carbon nanotubes have primarily been viewed as a superior choice for flexible electronics. Massive progress has been made in this area over the previous few decades, but there are still numerous key problems to solve before CNT-based flexible electronics may be deployed in real-world applications. We present a full description of research developments in CNT-based flexible electronics throughout this chapter.

There are many active research activities in the area of carbon nanotube (CNT) based flexible electronics. Some of the most promising applications include:

Transparent and flexible electronic devices:

CNTs can be utilized to produce transparent and flexible electronic devices like transparent transistors, touch panels, and flexible solar PV cells.[16] OLED and e-paper displays, among other flexible displays, utilize CNTs as transparent conductive sheets. Flexible printed circuits made on CNT-polymer composites are employed in a variety of electronic devices. Significant research has been conducted on the topic of transparent and flexible electronic devices, with an emphasis on creating materials and processes that allow for the manufacturing of such devices.

Wearable electronics:

CNTs can be utilized to construct flexible and stretchable electronics, such as wearable sensors and flexible displays, that can fit the shape of the body. CNT-based flexible electrodes are utilized in wearable electroencephalography (EEG) and electromyography (EMG) devices for monitoring brain and muscle function.[8] In order to power wearable electronics, CNTs are utilized in flexible wearable batteries—CNT-based wearable sensors to track hydration and skin temperature.

Energy storage:

CNTs can be utilized to produce flexible and high-performance batteries and supercapacitors, which can be integrated into a wide range of portable and wearable devices. Energy storage technologies like batteries and supercapacitors can be improved mechanically with CNTs to make them more resilient and flexible. Energy storage systems can function electrochemically better thanks to CNTs by having higher energy density, power density, and cyclability, for example. In sodium-ion batteries, CNT-based composites are employed as electrodes.[12]

Biomedical devices:

CNTs can be utilized to construct flexible and biocompatible electronic devices for monitoring and treating medical diseases, such as flexible sensors for monitoring vital signs and flexible electronics for managing the release of medications. Wearable chemical sensors based on CNT are efficient in identifying allergies and toxicants. Wearable biosensors that continuously measure biological variables including pH, lactate, and glucose using CNTs.[17]

Flexible and transparent conductors:

CNTs can be utilized to build flexible and transparent conductors that can be employed in a wide range of electronic devices, including touch screens, solar cells, and flexible displays. Electronic devices use CNT-polymer composites as flexible interconnects. Metal-polymer composites' conductivity and flexibility are enhanced by CNTs. In a variety of optical devices, including light-emitting diodes (LEDs) and photodetectors, CNTs are employed as transparent conductors. For data transport and communication in wearable technology, CNTs are used as flexible conductors.[9]

Environmental Monitoring:

CNTs are applied in numerous sensors which are effective in environmental monitoring. CNT-based gas sensors are utilized for detecting pollutants such as CO_2, NO_x, and SO_2 in the air. Humidity sensors which are built of CNT are used to monitor variations in atmospheric moisture levels and their effects on the environment.[18] The temperature sensors have a role in monitoring temperature changes in diverse habitats, including ocean waters and land. CNTs are also employed as pH sensors for detecting changes in acidity levels in water bodies, soil, and other environments. Radiation sensors based on CNT are used to detect ionizing radiations, such as gamma and beta rays, in nuclear power plants and other hazardous situations.[19] CNT-based toxicity sensors are used to detect the presence of harmful compounds, such as heavy metals, in the environment. CNTs are also employed in acoustic sensors for sensing underwater sounds and vibrations in oceanic conditions.

2.2 RELATED LITERATURES

Nanotubes are long, thin fullerenes with hexagonal carbon walls and are frequently capped at each end. It has been demonstrated that these cage-like structures of carbon display excellent material qualities as a result of their symmetrical structure. Carbon nanotubes are said to have mechanical qualities that are superior to any previously known materials, according to several studies. Although there are disagreements in the literature regarding the precise characteristics of carbon nanotubes, both theory, and experiment have revealed extremely high elastic moduli, greater than 1 TPa (a diamond's elastic modulus is 1.2 TPa), and reported strengths 10-100 times greater than the most durable metal at a fraction of the mass.[19] In fact, assuming the mechanical qualities stated are genuine, carbon nanotubes might result in a new type of material. Carbon nanotubes might provide a completely new class of sophisticated materials, assuming the observed mechanical characteristics are correct.[20] Since their discovery in 1991, carbon nanotubes (CNTs), one-dimensional materials with exceptional mechanical, electrical, and thermal characteristics, have been the subject of significant investigation. A rapidly expanding area of study, CNT-based flexible electronics have a variety of applications in sectors such as medical devices, consumer electronics, and aerospace. The performance and stability of flexible electronics based on CNTs are now being improved, and new uses for these unusual materials are being developed. A chronology of the development and history of carbon nanotubes is shown in Table 2.1.

Table 2.1: Advancements and history of Carbon Nanotubes.[21],[22]

Findings / Advancements	Researcher / Institution	Year
Discovery of MWCNTs using a transmission electron microscope (TEM).	Sumio Iijima	1991
Discovery of SWCNTs using a laser vaporization technique.	IBM	1993

Development of a method for synthesizing SWCNTs using a process called HP-CO disproportionation	Rice University	1995
Discovery of the implementation of CNTs as transistors	IBM	1999
Developed the first flexible transistor based on CNTs	University of California, Lawrence Berkeley Laboratory	2001
CNTs might be utilized as susceptible gas detectors.	University of Cambridge	2001
CNTs have the potential to be extremely effective solar cells.	Harvard University	2002
The separation of graphite into graphene, a single sheet of carbon	University of Manchester	2004
By putting CNTs onto the flexible substrate, the first CNT-based flexible display was created.	University of Illinois	2005
CNTs have the potential to be extremely sensitive biosensors for finding proteins and DNA.	University of Illinois	2006
By applying CNTs on to flexible substrate, the first CNT-based flexible display was created	University of Tokyo	2008
Created a transparent, bendable pressure sensor based on CNTs that could track pressure changes in real-time.	University of California, Lawrence Berkeley National Laboratory	2013
CNTs may be utilized as very effective water filters.	Rice University	2014
CNTs have the potential to be extremely effective batteries that stores lot of energy in a little area	Massachusetts Institute of Technology	2016

In 1991, Sumio Iijima, a researcher at NEC Corporation in Japan, examined carbon soot particles produced in a carbon arc discharge using a transmission electron microscope (TEM). Iijima discovered a novel class of cylindrical carbon structures that he called "multi-walled carbon nanotubes" (MWNTs).[23] Then in 1992, Scientists learned how to make carbon nanotubes in bulk by using a carbon arc discharge technique. Using a laser to ablate a graphite target while a catalyst was present, IBM researchers were able to produce carbon nanotubes with clearly defined ends in 1993. This procedure made it possible for carbon nanotubes to develop in a regulated manner, creating new opportunities for their application in electrical devices.[24]

In 1995 by using a process known as "high-pressure carbon monoxide disproportionation," researchers at Rice University in Houston, Texas, created a novel approach for creating single-walled carbon nanotubes (SWNTs) (HiPco). This technique is still one of the most popular ways to make SWNTs today since it made it possible to create high-quality SWNTs with a restricted size variation.[2]

Fullerene research has led to the formation of an ever-increasing number of novel compounds, now numbering over a thousand. The initial discovery of fullerenes sparked interest in carbon nanotubes, buckyballs' cylindrical counterparts, and the creation of new sectors of sophisticated materials. The unusual structure and bonding features of carbon nanotubes, which allow inner tubes of a multi-walled nanotube to glide within the outer tube, indicate applications in small motors, ball bearings, and lubricants. Fullerenes, discovered 25 years ago, continues to present several research possibilities in the pure field of chemistry, materials science, medicinal chemistry, and nanotechnology. The chemistry of fullerene (C60) was discovered by Smalley and colleagues at Rice University in the mid-1980s. Fullerenes are geometric enclosed structures made up of carbon atoms with hexagonal and pentagonal sides. The C60 molecule was the first to create a closed, convex shape. Buckminsterfullerene, named after the architect, was famed for building arches. R. Buckminster Fuller is an enclosed cage of 60 carbon atoms in which each angle of a pentagon is the opposite side of a hexagon, comparable to a soccer ball. Smalley, Kroto, and Curl were awarded the Nobel Prize in Chemistry in 1996.[25] The structure of Buckminsterfullerene (C60) is shown in Figure 2.1.

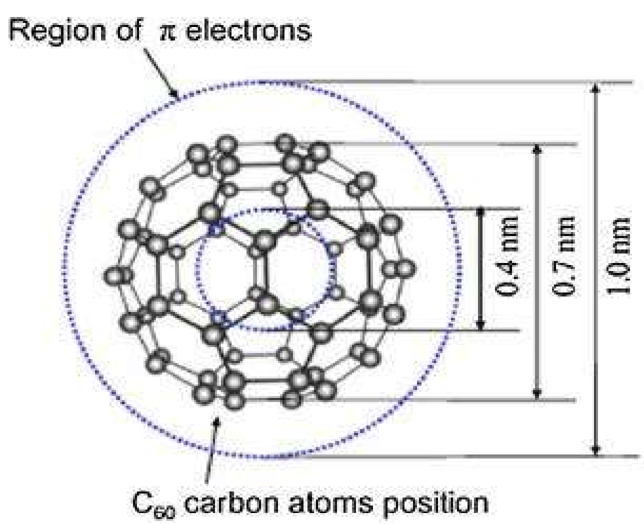

Figure 2.1: The structure and size of buckminsterfullerene, C60.

Dr. Iijima revealed his discovery of spiral microtubules in carbon-containing soot from an arc discharge in 1991. Carbon nanotubes (CNTs), a novel allotrope of carbon, took the stage after that. Their unusual structure endows them with extraordinary chemical, physical, and mechanical capabilities, which have piqued the curiosity of researchers and raised anticipation for potential uses.

A flexible display built with CNTs was developed by the University of Illinois at Urbana-Champaign researchers in 2005. CNTs were deposited onto a flexible substrate and utilized as the cathode in a field-emission panel to create this display. A flexible battery built with CNTs was developed by University of Tokyo researchers in 2008.[26] The battery was created by first covering a flexible material with a coating of CNTs, followed by layers of electrolyte and lithium cobalt oxide. The end product was a thin, flexible battery that could be bent and twisted while being charged and discharged. Figure 2.2 demonstrates the growth of paper and patents references in terms of Carbon nanotube.

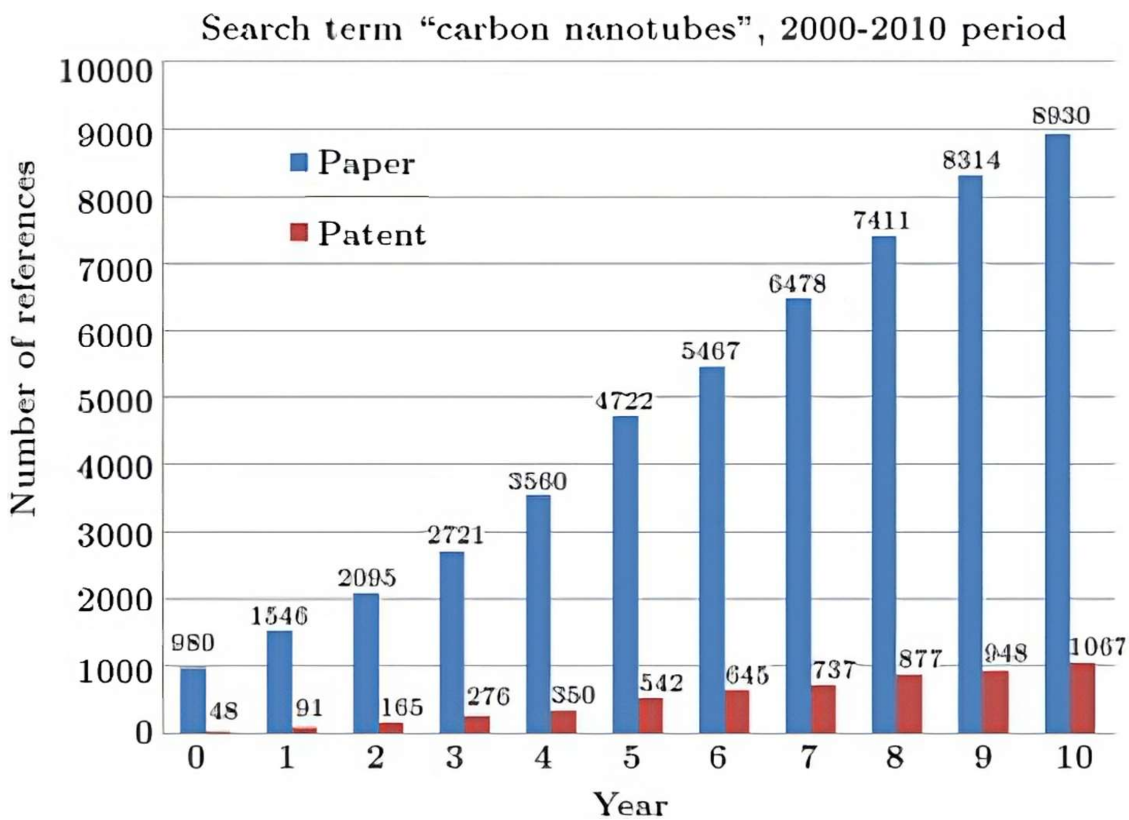

Figure. 2.2: Carbon nanotube references growth during the period of 2000–2010.[27]

Following Iijima's study, carbon nanotubes drew rapid interest, as evidenced by a sharp increase in the yearly number of publications during the first decades of the twenty-first century. After 2010, the figure remained stable at around 8000 each year.

The usage of CNTs in a variety of flexible electronic devices, like sensors, memory devices, and photovoltaics, was further investigated in the years that followed. A flexible, clear pressure

sensor based on CNTs was created in 2013 by researchers from the University of California, Berkeley, and Lawrence Berkeley National Laboratory. This sensor could be included in wearable technology for health monitoring and was able to detect pressure changes in real time. Nikolaev et al. describe the gas-phase growth of single-walled carbon nanotubes with carbon monoxide as the carbon source. The synthesis of well-aligned, straight carbon nanotubes on a variety of substrates has been accomplished by the use of plasma-enhanced chemical vapor deposition (PECVD) where the plasma is excited by a DC source or a microwave source. In CVD growth of straight carbon nanotube arrays, described by Ren a substrate is first coated with a layer of a nickel catalyst. High-purity ammonia is then used as the catalytic gas and acetylene is the carbon source.[20] Treacy first investigated the elastic modulus of isolated multi-walled nanotubes by measuring transmission electron microscope, the amplitude of their intrinsic thermal vibration.[7] Micrographs of MWCNTs are generated by PECVD demonstrating their straightness. The average of 11 samples obtained was 1.8 TPa. SWNTs typically form 'ropes' of nanotubes. The AFM (Atomic Force Microscopy) was used by Salvetat and colleagues to measure the characteristics of these nanotube bundles.[28]
An illustration of Hi-Pco carbon nanotube is shown in Figure 2.3.

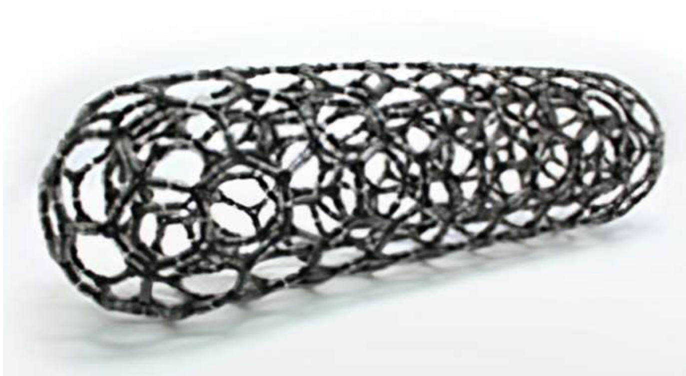

Figure 2.3: Hi-Pco nanotube.

Carbon Nanotechnologies Inc (Houston, TX) has commercialized the method for large-scale manufacturing of high-purity single-walled carbon nanotubes, called Hi-Pco nanotubes (high-pressure conversion of carbon monoxide).[20] Here, Figure 2.4 demonstrates the flexible carbon nanotube synaptic transistor for neurological electronic skin.

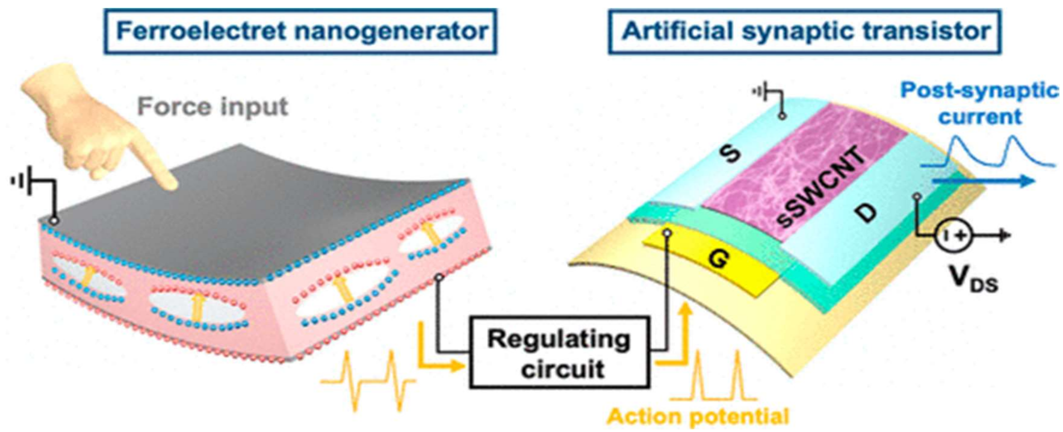

Figure 2.4: Flexible CNT synaptic transistor schematic for neurological electronic skin.[29]

One of the most anticipated uses of CNTs is as actual materials in FETs (field-effect transistors) and integrated circuits, due to their exceptionally high and well-balanced accessibility for both holes and electrons as well as good scaling characteristics. CNTs have also been claimed to be used in smart wearables as well as neurological electronic skins by researchers.[30] Furthermore, Carbon nanotubes have been investigated as possible bio-imaging probes. CNTs have sparked a lot of interest in biomedical applications. CNTs have been utilized to create biosensors that detect compounds including nucleic acids, proteins, and bacteria. It has been used in tissue engineering scaffolds to promote cell adhesion, growth, and differentiation. CNTs can also give electric conductivity to tissue-engineered scaffolds, which is critical for heart and brain tissues.[31]

At present time, universities and businesses are engaging in research and development to develop new applications for carbon nanotube materials. CNT fiber, microwave antennas, self-assembling fibers, aeronautical (radar-absorbing skin), surgical devices, medication delivery, fuel tank caps, IC trays, carrier tapes, vehicle body panels, sporting goods, coatings, and elastomers are additional growing applications of CNTs.

2.3 CURRENT RESEARCH GAP

Due to its distinctive electrical, mechanical, and thermal characteristics, carbon nanotube-based flexible electronics have grown into a viable technology for a variety of applications. Until this technology is able to be used extensively, there are still a number of research gaps that require to be filled. The following represent a few of the current research gaps:

Large-scale and cost-effective synthesis and purification of CNTs:

Research is needed to better understand and control the electronic, mechanical, and chemical properties of CNTs. This will allow for more predictable and reliable performance of CNT-based devices. Table 2.2 discusses the major research gaps in large scale and cost-effective synthesis and purification of CNTs.

Table 2.2: Research gaps in Control and predictability of CNT properties

Major Gaps	Description	Numerical Data	Reference
Lack of control over chirality	The flexibility of CNTs plays a significant role in determining their characteristics, and it can be difficult to manage chirality during synthesis. The likelihood of synthesizing a certain chirality is minimal, and as the CNT's diameter rises, the likelihood of doing so declines.	Researchers found that the likelihood of creating a (6,5) single-walled CNT using chemical vapor deposition (CVD) was extremely low—just 0.01%.	[32]
Influence of growth conditions	The growth circumstances, such as temperature, gas circulation rate, and catalyst concentration, have a significant impact on the characteristics of CNTs. As slight differences in growing conditions can have significant effects on CNT characteristics, it is challenging to precisely manage these factors to attain consistent qualities.	According to a research, the growth temperature and pressure had an impact on the diameter distribution of single-walled CNTs generated by CVD by up to 0.4 nm.	[32]

Challenges in characterizing CNTs	Understanding the properties of CNTs requires accurate characterization of their characteristics, including diameter, length, and chirality, but this can be difficult. Conditions for sample preparation and imaging, for instance, can have an impact on the diameter placement of CNTs..	According to a research, the diameter spacing of single-walled CNTs determined using transmission electron microscopy can change depending on the imaging circumstances by up to 0.2 nm.	[33]
Difficulty in achieving uniform properties	The random development of CNTs makes it difficult to get uniform features, including diameter and chirality. The standard deviation of the diameter pattern of CNTs can be rather high. The chirality distribution might differ from one CNT to another and is also influenced by the growing circumstances.	According to a research, the standard deviation of the diameter pattern of single-walled CNTs produced using CVD was 0.22 nm.	[34]

The issues with the control and predictability of CNT characteristics are illustrated by these numerical statistics, which are but a few of the issues.

High-performance device fabrication:

Several research gaps still need to be filled despite substantial advancements in the production of carbon nanotube (CNT) devices. The need for a greater comprehension of the fundamental characteristics and behavior of CNTs, which may guide the development and optimization of CNT-based devices, is one such knowledge gap.

Resistance of a CNT:

$$R = \frac{\rho L}{A}$$

Where, R = The resistance, ρ = The resistivity of the CNT, L = Cross sectional area of the CNT

There is also a need for methods that are more effective and scalable for making high-quality, equally aligned CNTs, as well as for combining CNTs with additional substances to make useful devices. The creation of CNT-based devices with enhanced performance traits, such as better on-off ratios and reduced contact resistance, is also necessary. Advances in device fabrication methods are needed to create CNT-based flexible electronics systems with high-performance, reproducible, and reliable devices. Addressing these research gaps will be critical in realizing the full potential of CNTs for high-performance device fabrication.[35] In table 2.3, the research gaps in high performance device fabrication is discussed.

Table 2.3: Research gaps in High-performance device fabrication

Major Gaps	**Description**	**Numerical data**	**Reference**
Contact resistance	The contact resistance between CNTs and metallic conductors can be quite significant since the two materials cannot come into direct contact. This might lead to performance restrictions for CNT-based devices, especially in high-frequency applications.	Some CNT-metal junctions have contact resistances as high as 1 kΩ·µm.	[36]
Alignment and integration with other materials	It can be difficult to align and include CNTs with other materials, especially metals, and polymers. Due to CNTs' flexibility, alignment can be challenging yet necessary for obtaining optimal device performance. Due to variations in thermal expansion parameters, integration with different materials is additionally difficult and leads to fractures and delamination.	CNTs can be strongly aligned or randomly orientated, with alignment factors varying between 10% to 80%.	[37], [38]
Device stability and reliability	CNT-based devices' stability and dependability might be a problem, especially in challenging working environments like high temperatures and humidity. CNTs may be vulnerable to oxidation and deterioration, which may have an effect on the functionality of the device and shorten its lifetime.	After being exposed to air for a month, CNTs can lose up to 30% of their electrical conductivity as well as 40% of their mechanical strength, two substantial alterations that can occur over time.	[10], [24]

Cost and scalability	The cost and scalability of manufacturing CNT-based devices are ongoing issues. Although development has been made in creating efficient CNT synthesis and processing techniques, mass-producing high-performance devices is still difficult.	CNTs can cost anywhere from $100 and $10,000 per gram, based on their characteristics and manner of manufacturing.	[15]

Energy storage and harvesting:

Carbon nanotube (CNT)-based energy storage and harvesting device manufacture involves a number of difficulties. The complexity and high expense of producing high-quality CNTs, the requirement for lengthy purification and dispersion procedures, the possibility of unintended reactions at the interface between the electrode and the electrolyte, and the difficulty of scaling up manufacturing for commercial usage are some of these difficulties. There is a need for developing high-performance, flexible, and stable energy storage and harvesting systems using CNTs for powering flexible electronic devices. Table 2.4 given below describes the major research obstacles related to CNT-based energy storage and harvesting.

Table 2.4: Current research gaps on energy storage and harvesting.

Research Gaps	Description	Related Data	Reference
CNT purification	When CNTs are manufactured using different methods, contaminants like amorphous carbon or metal catalyst particles are frequently present.	Up to 50% of the CNT material may be removed during the purifying process, lowering total yield.	[39], [10]
CNT dispersion	It is challenging to obtain a uniform dispersion of CNTs because they have a propensity to collect in solutions.	The CNTs may be harmed or have their characteristics changed if surfactants or sonication are used to distribute them.	[40]

Electrode/electrolyte interface	Performance in energy storage and harvesting can be impacted by the contact between the CNT electrodes and the electrolyte.	When using specific electrolytes, the CNT surface or electrode may experience unfavorable reactions.	[41], [13]
Scalability	It is frequently challenging to scale up the present processes for creating CNT-based energy storage and harvesting devices for commercial application.	It is necessary to create manufacturing techniques that can mass-produce CNT-based devices.	[12], [13]

Addressing these problems is crucial for the research of efficient and cost-effective CNT-based energy storage and harvesting technologies.

CNT-polymer interactions:

Due to the potential uses of CNT-polymer composites in a number of different disciplines, the interactions between carbon nanotubes (CNTs) and polymers remain a crucial area of research. There are still a number of research holes in this field, though. Table 2.5 discusses the research gaps related to CNT-polymer interactions;

Table 2.5 : Research gaps on CNT-polymer interactions

Research Gap	**Related Information**	**Reference**
CNT-polymer interactions governed by molecular mechanisms	The particular binding sites and energy of the interaction between CNTs and polymers are not well understood.	[42]
Methods that are effective and scalable for creating CNT-polymer composites with regulated shape and characteristics	Lack of scalable processes for mass manufacture of CNT-polymer composites and difficulty in producing uniform CNT dispersion in polymer matrix structures	[43], [44]
Stability and endurance throughout time of CNT-polymer composites	Lack of thorough research on how aging, exposure to the environment, and mechanical stress affect the characteristics of CNT-polymer composites	[11]

More research is needed to better understand and control the interactions between CNTs and polymers, optimize the properties of CNT-polymer composites, and achieve desired performance in flexible devices. Inadequate distribution and dispersion of CNTs in polymer matrices are characterized.

Environmental and lifetime stability:

CNTs are sensitive to environmental factors such as temperature, humidity, and mechanical stress, which can affect the performance and lifetime of CNT-based devices. Further research is needed to improve the environmental and lifetime stability of CNT-based flexible devices.

The main reasons behind such lack of research are demonstrated in Table 2.6.

Table 2.6: Research shortcoming due to environmental and stability issues

Research Gap	**Numerical Data**	**Reasons**	**Reference**
Effect of Environmental Factors on CNTs	Only a few research have looked at how the stability of CNTs is impacted by environmental variables such temperature, humidity, and UV exposure. For instance, one research discovered that CNTs' electrical conductivity decreased by up to 50% when exposed to high humidity.	Environmental exposure techniques are not standardized, and long-term research are required to determine how environmental conditions affect CNTs.	[45], [46]
Degradation of CNTs in Biological Environments	There hasn't been much study on how CNTs break down in biological contexts including soil, water, and living things. For instance, one study discovered that CNTs may build up in tissues of fish and influence fish behavior.	Monitoring the destiny of CNTs in varied biological contexts is challenging, and research on the decomposition of CNTs has to follow established standards.	[47]
Toxicity of CNTs in the Environment	Few studies have measured the possible ecological effect of CNTs, and their environmental toxicity is yet unknown. For instance, one study discovered that human lung cells might experience oxidative stress as well as inflammation as a result of exposure to CNTs.	There is a lack of standard toxicity testing techniques for carbon nanotubes, as well as a need for long-term research on the impact of carbon nanotubes on ecosystems.	[48], [18]

Effect of Manufacturing and Processing Methods on CNT Stability	The effect of manufacturing and processing methods on the stability of CNTs is not well understood, and few studies have quantified the impact of different processing methods on the lifetime of CNTs. For example, one study found that CNTs produced using a high-temperature method had better stability in water than those produced using a low-temperature method.	Lack of standardized processing and manufacturing protocols for CNTs, and the need for more research to understand the impact of different processing methods on CNT stability.	[49], [50]

There are a few reasons responsible for these shortcomings. They are,

i. Lack of knowledge of CNT behavior in harsh environments (e.g., high temperature, humidity, pressure).
ii. CNT-polymer composites have a limited lifespan and stability.
iii. Inadequate examination of the interaction between CNTs and polymers and the possibility of chemical deterioration.
iv. Only a few lifetime prediction models and evidence on long-term dependability.
v. Inadequate knowledge of the reaction to mechanical stress of CNT-based devices.

Fundamental physics of CNTs in flexible devices:

There's a need to better understand the fundamental physics of CNTs in flexible devices, such as the effect of mechanical deformation on the electronic properties of CNTs.

Besides all these research obstacles, there are a few other obstacles in the field of CNT-based flexible electronics research field and they are;

- ➔ Flexibility and high production cost.
- ➔ Quality control and uniformity in CNT synthesis.[24]
- ➔ Inefficient purifying processes.
- ➔ Environmental and health problems connected with CNT synthesis.[51]
- ➔ Limitations of consistency in CNT fabrication and purification processes.[52]

However, CNT-based flexible electronics is an active area of research and there will likely continue to be research gaps that need to be filled in the future.

2.4 SUMMARY

CNT-based studies have made significant advances during the last 30 years. CNTs' essential features have been widely explored, and several applications have been suggested and implemented. Carbon nanotubes are already present in our daily lives, for instance, as conductive additions inside the lithium battery cells that power our smartphones. However, the most interesting theoretical applications, such as quantum research and information technology, are still a long way off. Carbon nanotube-based flexible and stretchy electronics have made tremendous development. Yet scarcity of fundamentally pure, high-quality Carbon Nanotube materials hampers the development and research of these high-end applications. CNT-based flexible electronics development approaches have a promising future. Nonetheless, absolutely no CNT-based flexible electronic device is now commercially accessible. Several obstacles must yet be addressed before flexible electronic products and systems based on Carbon nanotubes may be used in global markets.

CHAPTER 3

CURRENT CHALLENGES IN CNT-BASED FLEXIBLE ELECTRONICS SYSTEM

3.1 INTRODUCTION

Technological advancement of wearable and flexible electronics is attempting to push Silicon-based semiconductors to their operational limits, flexible screens will render conductive oxide materials outdated, and weight reduction requirements in the aerospace industry require researchers to seek reliable low-density conductors. Carbon nanotubes (CNTs) are appealing prospects for future electronics because of their superior electrical and mechanical characteristics, as well as their low density.

However, converting these extraordinary qualities into practical macroscale applications has proven to be a challenge. To completely exploit their enormous potential, carbon nanotubes must be smoothly merged into metal structures or function constructively alongside them, which is currently difficult.

3.2 TECHNICAL CHALLENGE

A complete lack of micromechanical characterization methods for measuring properties directly, grave size limitations, uncertainty in data from indirect measurements, unsatisfactory test specimen preparation methods, and lack of control over nanotube alignment and distribution are a few of the challenges in categorizing nanotubes and their composites.

There are several technical challenges that need to be addressed in order to fully realize the potential of CNT-based flexible electronics systems:

CNT synthesis and purification:

One of the major challenges in CNT-based flexible electronics is the synthesis and purification of high-quality CNTs. CNTs are typically synthesized using chemical vapor deposition (CVD) or catalytic chemical vapor deposition (CCVD) methods, which can result in impurities and structural defects.[32] The following Table 3.1 shows a few challenges regarding synthesis and purification;

Table 3.1: Challenges in CNT synthesis and purification

Challenge	Example	Reference
Control of synthesis	Obtaining homogeneity in CNT size, length, chirality, and alignment.	[37], [53]
High-temperature growth	High-temperature processes, such as CVD (chemical vapor deposition) or laser ablation, need expensive machinery and may result in impurities.	[54], [55]
Low yield	Low yield in carbon nanotube synthesis leads to high manufacturing costs and restricted scalability.	[56]
Purification	CNT separation from other materials like catalysts made of metal or amorphous carbon.	[57]
Purity control	Purification of carbon nanotubes for use in fragile applications such as devices for biomedical use.	[57], [31]

It has been also discovered that the proportion of these contaminants rises as the size of CNTs rises.

CNT alignment and patterning:

Another challenge is aligning and patterning CNTs to form the desired electronic and mechanical structures. This requires advanced techniques such as using electric fields and surface chemistry methods to control the alignment of CNTs, as well as lithography techniques to pattern the CNTs. Here are a few challenges from this field of research detailed in Table 3.2.

Table 3.2: Challenges in CNT alignment and patterning

Challenge	Example	Reference
Achieving uniform alignment of CNTs	CNTs have a tendency to accumulate into clumps which may result in inconsistent alignments and poor electrical efficiency.	[58], [37]
Controlling the density of CNTs	CNT overcrowding or sparsity might result in a film with poor structural and electrical characteristics.	[59]

Achieving high-resolution patterning of CNTs	Because of their non-uniformity and limited adherence to the surfaces, traditional lithographic processes can be difficult to apply to CNTs.	[50], [60]
Avoiding contamination during processing	Because of their non-uniformity and limited adherence to the surfaces, traditional lithographic processes can be difficult to apply to CNTs.	[61], [62]
Achieving scalable, cost-effective processing	Current CNT processing methods are time-consuming and costly, restricting their capacity for large-scale manufacturing.	[56]

Synthesizing a sample of metal or pure semiconductor material CNTs remains a huge task. Effective strategies for isolating these various sorts of CNTs from the mixes are also lacking. In the laboratory, as-synthesized CNT arrays are frequently unspinnable. It is necessary to create a thorough knowledge base on the ideal conditions for manufacturing high-quality spinnable CNT arrays, as well as the underlying processes for pulling CNT sheets or fibers from CNT arrays.

CNT-polymer composites:

CNT composites made of polymers are a type of material that has received a lot of interest in recent years because of their outstanding electrical, mechanical, and thermal capabilities. Carbon nanotubes are integrated into a polymer matrix to generate these composites, which produce a composite material with qualities superior to either component alone. However, the fabrication of carbon nanotube-polymer composites is filled with difficulties. In order to create flexible electronic devices, CNTs need to be combined with polymers to form CNT-polymer composites. Figure 3.1 represents a graph based on different properties of CNT polymer composites.

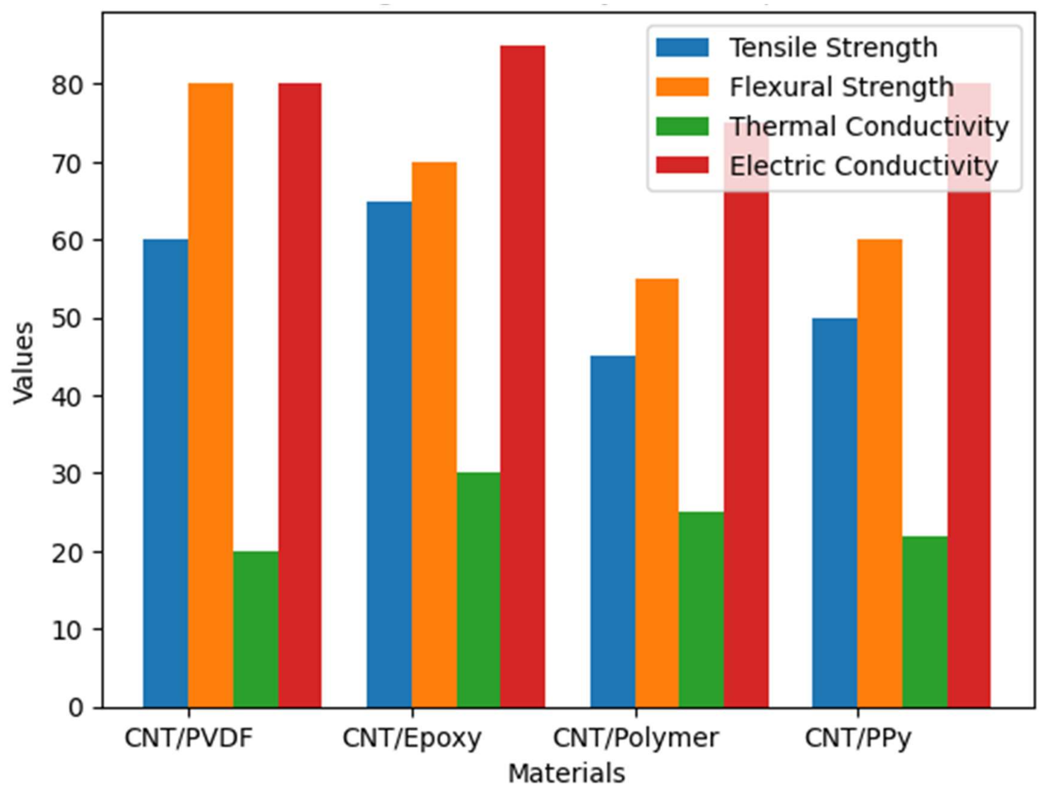

Figure 3.1: Properties of different CNT polymer composites.[63]

CNT/PVDF, CNT/Epoxy, CNT/Polymer, and CNT/PPy are among the most widely investigated forms of CNT polymer composites. Regardless of their potential, the properties of these composites pose several challenges.

The Table 3.3 below summarizes some of the challenges associated with the properties of these composites:

Table 3.3: Challenges of CNT composites regarding their properties

Composite	Challenge	Property	Reference
CNT/PVDF	Conductivity is low	Polymer that insulates	[64]
	Less dispersion	Polymer that repels water	
CNT/Epoxy	Interfacial bonding is poor	The matrix is brittle.	[65]
	Viscosity is high.	Molecular weight is high	

CNT/Polymer	Lower strength	Molecular weight is low	[42]
	Inadequate thermal stability	Melting point is low	
CNT/PPy	Processability is limited.	Polymer that conducts electricity	[66]
	Lower dispersion	Polymer that repels water	

However, these composites can be challenging to create and process, and the properties of the resulting composite materials can be difficult to predict and control.

Device fabrication and integration:

The manufacture and integration of CNT-based flexible electronic components are crucial steps in their development. Several challenges must be overcome in order to attain the highest possible efficiency, reliability, and scalability. The following Table 3.4 shows the challenges in device fabrication;

Table 3.4: Challenges in device fabrication and integration.

Challenges	Brief information	Reference
Compatibility with different elements and substrates	Damage and defects may develop when CNT-based nanomaterials are mixed with diverse components and substrates. Poor adhesion and weak interfaces may compromise the composite material's capacity to conduct electricity as well as its mechanical properties.	[43], [67]
Techniques for scalable fabrication	It is critical for commercialization to develop scalable processes that can be employed for large-scale manufacturing.	[61]
Alignment and patterning	For the production and implementation of CNT-based devices, precise patterning and orientation of the CNTs are required. Because the quality and precision of lithographic printing techniques are limited, new patterning techniques with greater resolution and proficiency are required.	[37]

Finally, addressing device manufacturing and integration challenges is crucial in ensuring the effective commercialization and development of CNT-based flexible devices for electronics. To achieve optimal performance and dependability, scalable and reliable manufacturing procedures, accurate pattern and alignment, and good integration with different substances and substrates are required.

Reliability and durability:

Another challenge of CNT-based flexible electronics is the reliability and durability of the devices over extended periods of use. This is due to the fact that CNTs are sensitive to environmental factors such as temperature, humidity, and mechanical stress.[68]

$$S = \frac{F}{\pi \times r^2}$$

Where, S = The Tensile strength, F = The applied force, r = The Radius of the CNT

Multiwalled carbon nanotubes can carry high current densities up to 109 – 1010 A/cm2 and remain stable for extended periods of time at higher temperature in air.[69] A few challenges regarding durability and reliability are discussed in the Table 3.5 given below;

Table 3.5: Challenges regarding reliability and durability.

Challenge	Brief Explanation	Reference
Mechanical stress	CNT-based flexible electronics are subjected to mechanical stress during bending or stretching, which can cause breakage or detachment of CNTs from the substrate.	[43], [67]
Environmental degradation	Exposure to harsh environmental conditions, such as humidity and temperature changes, can lead to oxidation and degradation of CNTs, affecting the performance and reliability of the device.	[18], [70]
Electrical stability	CNTs can exhibit changes in electrical properties over time due to factors such as aging, oxidation, and environmental factors, leading to variations in device performance and reliability.	[62]
Interface compatibility	Achieving good compatibility between CNTs and the substrate or other materials used in the device is crucial for reliable and durable performance. Poor adhesion can lead to delamination or detachment of CNTs from the substrate, while chemical incompatibility can lead to degradation of the device.	[69], [71]
Process variability	Variations in CNT synthesis and device fabrication processes can lead to differences in device performance and reliability, making it challenging to achieve consistent and repeatable results.	[57], [61]

Therefore, the devices will need to be designed and fabricated to be robust and withstand various environmental conditions. One of the most difficult applications is flexible energy because of the instability and high reaction from the strong oxidizing elements found in these devices.

Dispersion:

CNTs tend to clump together, which makes it difficult to create homogeneous CNT-based materials and devices. Researchers are working on ways to disperse CNTs in different matrices, such as polymers, to overcome this issue. The following Table 3.6 contains the challenges regarding dispersion.

Table 3.6: Challenges due to dispersion.

Challenge	Description	Reference
Agglomeration	Because of high van der Waals interactions, CNTs are likely to form agglomerates, limiting their dispersion through a polymer matrix.	[40], [72]
Inadequate interfacial adhesion	The poor interfacial adhesion between CNTs, as well as the polymer matrix, might result in an unstable composite material.	[71]
Non-uniform dispersion	Even when surfactants are used, CNTs may not be equally shared inside the polymer matrix, resulting in a non-homogeneous material.	[40]
Impurities that remain after purification	Impure substances from the CNT production process can disrupt CNT dispersion inside the polymer matrix.	[57]

Poor dispersion can lead to reduced mechanical and electrical properties, as well as uneven distribution of CNTs, resulting in non-uniform performance. This dispersion issue arises from the strong Van der Waals interactions between CNTs, which leads to their tendency to agglomerate.

In conclusion, CNT-based flexible electronics systems have the potential to provide many benefits, but realizing this potential requires addressing several technical challenges such as CNT synthesis and purification, CNT alignment and patterning, CNT-polymer composites, device fabrication, integration, and reliability and durability.

3.3 REGULATORY CHALLENGE

Both the micromechanical analysis of nanotubes and the simulation of flexible and fracture phenomena at the nanoscale provide significant problems. The challenges in the characterization of carbon nanotubes and their nanocomposite include,

- An utter absence of micromechanical analysis methods for measurement.
- Enormous specimen size limitations.
- A lack of certainty in data collected from different sensors.
- Deficiency in specimen processing methods and a lack of balance in nanotube orientation and distribution.

Here are a few regulatory challenges with brief explanations and relevant standards given in Table 3.7 below.

Table 3.7: Regulatory challenges in CNT-based flexible electronics

Regulatory Challenge	Brief Explanation	Relevant Regulations/Standards	Reference
Risks to Health and the Environment	CNTs may pose health and environmental hazards, prompting legislative limits on their manufacturing and usage.	REACH, TSCA, and the European Union's Classification, Labeling, and Packaging Regulation	[73], [74], [75]
Classification of Nanomaterials	CNTs are classified as nanomaterials and are regulated differently than non-nanomaterials	EU Nano-Register, EU Regulation 2018/1881	[76]
Intellectual Property	Due to the intricacy of the technology and the possibility of several patent holders, preserving the intellectual property in CNT-based flexible electronic devices may be difficult.	Agreements on intellectual property and patent law	[77]
Export-Import Regulations	These rules may influence the capacity to get CNTs from overseas vendors carbon nanotube-based goods	Relevant nations' import/export laws, such as the EU dual-use regulations	[78]

Product Safety	For consumer usage, CNT-based electronic devices that are flexible must fulfill product safety criteria.	Regulations of the European Union on Product Safety and the Consumer Product Safety Commission in the United States.	[79]

These regulatory challenges emphasize the importance of carefully considering the safety and ecological effects of CNT-based flexible electronic components, as well as collaborating among industry and regulatory organizations to make sure that these obstacles are addressed responsibly and effectively. A percentage wheel of the regulatory challenges for CNT-based flexible electronics is shown in Figure 3.2.

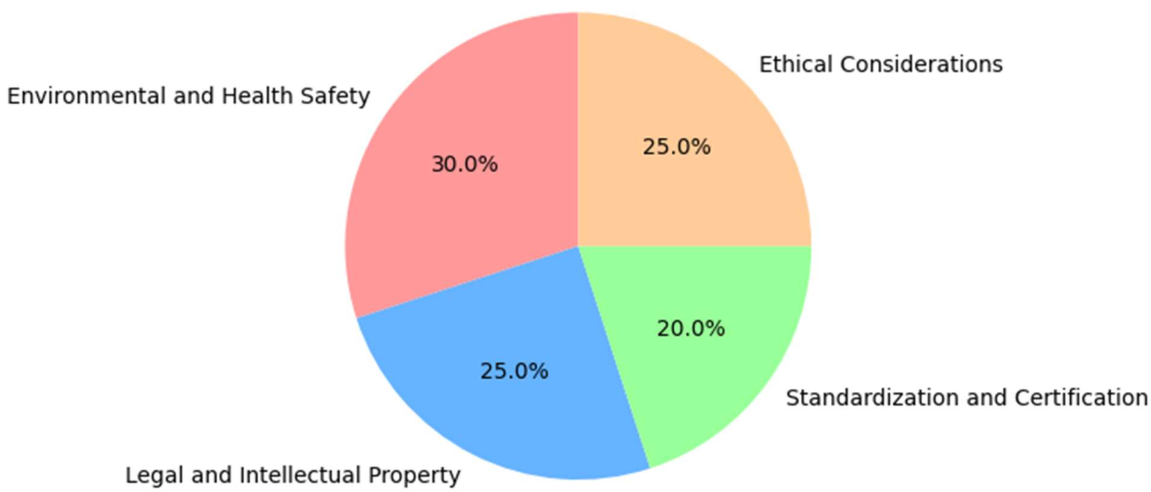

Figure 3.2: Percentage wheel of the regulatory challenges.[80]

Concerns have been raised about the health and safety of carbon nanotubes (CNTs) if they are breathed or get into contact with human skin.[73] This has resulted in legislation governing the implementation of carbon nanotubes in consumer items in several places, including the European Union. Concerns about the ability of CNTs to accumulate become accumulated in environments and harm animals are at the forefront of environmental concerns. This has resulted in legislation governing the disposal of carbon nanotubes and items containing them.

However, several regulatory issues must be addressed before they can be used and commercialized safely. The necessity for uniform testing and characterization methodologies, assuring biocompatibility and safety in the environment, and addressing possible health hazards related to CNT exposure are among the issues. Furthermore, issues concerning CNT dispersion in polymer matrices, as well as the durability and dependability of CNT-based flexible electronics, must be addressed. To overcome these obstacles, scientists, regulatory bodies, and industry stakeholders will need to work together to produce secure and dependable CNT-based flexible electronic gadgets for general usage.

3.4 SUMMARY

The synthesis, purification, functionalization, and integration of CNTs with additional substances on flexible substrates are among the main difficulties faced by CNT-based flexible electronics devices. Because CNTs are hydrophobic, it can be difficult to incorporate them into systems that use water. A scalable, uniform method for manufacturing exquisite CNTs for application in flexible electronics is also lacking. Another difficulty that impacts CNTs' mechanical and electrical properties is the removal of contaminants like crystalline carbon and metal catalysts. Additionally, it is extremely difficult to integrate CNTs with different substances on substrates that are flexible without disrupting their electrical properties. Integrated research and development, including improvements in material synthesis, characterization, and processing methods, are required to meet these challenges.

CHAPTER 4

POSSIBLE SOLUTIONS TO MITIGATE THE CHALLENGES IN CNT-BASED FLEXIBLE ELECTRONICS SYSTEM

4.1 INTRODUCTION

Because of their exceptional mechanical, electrical, and thermal characteristics, carbon nanotubes are now recognized as a viable material for flexible electronics. Nevertheless, the incorporation of CNTs into composites of polymers to create electronic devices that are flexible faces a number of obstacles, which include dispersion, device manufacturing and insertion, dependability and longevity, and regulatory issues. These issues must be solved in order to achieve the maximum efficiency of CNT-based flexible electronic gadgets. Several potential solutions have been proposed in this context to ease these difficulties while enhancing the effectiveness of CNT-based flexible electronics. This article will go through some of the potential methods for overcoming these obstacles and enabling the creation of high-performance and dependable CNT-based flexible electronic devices.

4.2 SOLUTION TO TECHNICAL CHALLENGES

CNT-based flexible electronics have a number of technological problems, including poor CNT dispersion, limited electrical conductivity, poor mechanical characteristics, and poor CNT-polymer matrix adhesion. A number of remedies have been proposed to address these issues. Functionalization of carbon nanotubes, for example, can improve the way they dissolve, dispersion, and interact with the matrix of polymers. In addition, hybridization with additional conductors like graphene and nanowires of silver might improve the electrical insulation of CNT-based composites. Furthermore, optimizing processing conditions such as ultrasound time and temperature can improve CNT dispersion in the matrix of polymers. Furthermore, by modifying the polymer matrix, like mixing with additional polymer compounds or using cross-linking agents, CNT-based composites' mechanical characteristics and adhesion can be improved.

The Solution to CNT Synthesis and Purification Challenges:

One of the primary hurdles in CNT-based flexible electronics is the synthesis and purification of CNTs. Impurities and flaws in carbon nanotubes can have a substantial impact on their mechanical and electrical characteristics, thereby affecting how they function in electronic devices. Several approaches to the synthesis and purification of CNTs have been developed to address this challenge which are noted in the following Table 4.1;

Table 4.1: Solution to CNT synthesis and purification challenges

Challenge	Solution	Reference
High-quality CNT synthesis	Using high-purity carbon sources, optimizing synthesis conditions, and employing catalysts with increased selectivity and activity.	[57]
Optimizing the variation in chirality and diameter of carbon nanotubes	The employment of chiral-specific catalysts, the regulation of growth factors such as temperature and the flow of gases percentage, and the use of post-synthesis sorting procedures are all examples of chiral-specific catalysts.	[34]
Removal of impurities, as well as metallic catalysts	Techniques for purification include treatment with acids, thermal annealing, and the use of specific adsorbents.	[57], [11]
CNT integration into flexible substrates	Spray coating, inkjet printing, and roll-to-roll coating are examples of deposition processes, as is the usage of adhesion boosters or transfer mechanisms.	[81]

It should be noted that these solutions are not exhaustive, and research efforts to enhance CNT synthesis and purification for flexible electronic devices are underway.

The Solution to CNT Alignment and Patterning Challenges:

Because of their distinctive properties, carbon nanotubes have demonstrated considerable promise in flexible electronics. However, attaining regulated alignment as well as patterning carbon nanotubes on flexible substrates is one of the main obstacles to using CNTs for flexible electronics. To solve these issues, numerous approaches have been addressed which are shown in the following Table 4.2;

Table 4.2: Solution to CNT alignment and purification challenges

Challenge	Solution	Reference
Obtaining precise CNT alignments	Mechanical alignment methods like Langmuir-Blodgett assembly or expansion, utilizing electric or magnetic field for aligning CNTs during development, or use of templates to regulate CNT growth are all examples of CNT alignment techniques.	[37]
Patterning CNTs into precise shapes or patterns	By using lithography methods like photolithography or laser lithography, or printing techniques like inkjet or printing on screen.	[82]
CNT transfer onto flexible substrates	Use of the stamping process, layers-by-layers assembly, or CVD transmission processes.	[83]
Maintaining CNT orientation and conductivity on flexible substrates	Coating materials can be used to shield CNTs from environmental variables like humidity or mechanical stress, or post-processing processes like annealing can be used to increase conductivity.	[10]

It should be noted that these solutions are not thorough, and that CNT alignment and patterning continue to be an active research topic in the fabrication of CNT-based flexible electronics.

The Solution to Challenges Regarding CNT Polymer Composites:

Because of their unique mechanical, electrical, and thermal capabilities, CNT polymer composites have shown significant promise in flexible electronics. However, several challenges must be overcome before the potential advantages of CNT polymer composites can be fully realized. However, the difficulties of attaining uniform dispersion of CNT within the matrix of polymers and strong interfacial bonds between CNTs and the polymer have hampered their widespread use. To address these challenges, various solutions have been proposed, including the application of surfactants to enhance reliability, high shear mixing or ultrasound for breaking up agglomerates, appropriate processing techniques like solvent casting or melt mixing, and the application of coupling substances or cross-linking agents. An equation related to the solution regarding CNT composite based issues,

$$\boldsymbol{\sigma = \sigma_m + \sigma_c}$$

When solving for:

- σ denotes the composite material's electrical conductivity.
- The electrically conductive property of the matrix of polymers is represented by σ_m.
- The carbon nanotubes' contribution to electrical conductivity is denoted by the symbol σ_c.

According to the equation, the total electrical conductivity of a CNT composite made of polymers is equal to the sum of the electrical conductivity contributions from the carbon nanotubes and the polymer matrix.

These solutions have been used for CNT/PVDF, CNT/epoxy, CNT/polymer, and CNT/PPy composites, with a particular solution or mix of solutions based on the CNT-polymer combination and desired application. Ongoing research aims to improve the characteristics and manufacturing process of CNT composites of polymers for usage in flexible electronics.

The Solution to Challenges Regarding Reliability and Durability:

CNT durability and dependability are important elements influencing the performance and longevity of cnt-based flexible electronics. The difficulties in this field originate mostly from CNTs' proclivity to deteriorate and disintegrate over time as a result of environmental conditions such as moisture, temperature, and mechanical strain. to overcome these issues, scholars have devised many solutions, which are added in the following table 4.3:

Table 4.3: Solutions to the challenges regarding reliability and durability

Challenge	**Solution**	**Reference**
Environmental degradation	Coating CNTs with protective coatings to shield them from deterioration caused by temperature, moisture, and other environmental variables.	[75]
Mechanical strain	Adding additional materials or additives to CNT composites to improve mechanical durability and toughness.	[43]
Fabrication defects	Optimizing manufacturing procedures to reduce flaws and damage to carbon nanotubes through synthesis and processing.	[50]
Nanoscale characterization	Using sophisticated characterization techniques, including as high-resolution imaging and spectroscopy, to examine the characteristics of CNTs at the nanoscale.	[19]

Interface engineering	Creating interfaces between CNTs and other materials in composites to improve cohesiveness, adhesion, and compatibility.	[71], [63]

Overall, the creation of long-lasting and dependable CNT-based flexible electronics necessitates an integrated strategy that brings together the fields of materials science, the field of engineering, and physics to optimize the characteristics of CNTs and their composites for prolonged usage in real-world applications.

The Solution to Challenges Regarding Device Fabrication:

Because of CNT's unique qualities, carbon nanotube (CNT)-based flexible electronics have been the topic of significant research in recent years. On the other hand, the fabrication of these electronics unveils several challenges that must be overcome in order for their full potential to be realized. Here are a few solutions to overcome these obstacles. The following Table 4.4 contains the solutions to the challenges regarding device fabrication;

Table 4.4: Solutions to the device fabrication challenges.

Challenge	Solution	Advantages	Limitations	Reference
CNT deposition on flexible substrates	Spray coating	Simple and scalable approach for uniformly covering huge regions	CNT alignment and density are subject to limited control.	[84]
	Inkjet printing	Control over the design and thickness of the CNT film is precise.	The density and volume of the ink limit the possibilities.	
	Transfer printing	CNTs can be transferred from the growing to the flexible substrate.	It is difficult to obtain high-quality alignment.	
Controlling alignment and thickness of CNTs	Chemical vapor deposition	CNT orientation and density can be precisely controlled.	Device size and complexity limitations	[37]
	Growth governed by templates	The template is used to direct the development of CNTs in a selected pattern	Template complexity and repeatability limit	

	Electrospinning	Deposition of coordinated CNT fibers on a flexible substrate	Management over fiber diameter and dispersion is limited.	
Integration of CNT-based devices with other components and systems	Design optimization	Device architecture that has been carefully designed allows for integration with several electronic parts.	Device design skill is required.	[85], [86]
	Materials and interfaces that are compatible	Development of materials and interfaces can aid in resolution of integration.	The availability of suitable materials is a constraint.	

It is crucial to note, however, that the specific benefits and limits of each solution may differ based on the exact device and application, and more study may be required to discover the best appropriate strategy.

The Solution to Challenges Regarding Dispersion:

One of the most difficult issues in the production of CNT-based flexible electronic devices is achieving uniform CNT dispersion in a solution. CNT aggregation can result in inconsistent film thickness, poor adherence to the substrate, and decreased electrical conductivity. To address this issue, numerous techniques for CNT dispersion have been devised, involving surfactant-assisted dispersion, ultrasonic treatment, and CNT functionalization. The following Table 4.5 summarizes the answers to the issues associated with the dispersion of CNT-based flexible electronic products:

Table 4.5: Solution to challenges regarding the dispersion.

Method	Description	Pros	Cons	Reference
Dispersion with the help of a surfactant	To stabilize CNTs in solution and avoid agglomeration, surface-active agents are used.	Low cost, effective in creating uniform dispersion	Contamination is possible, as is diminished electrical conductivity owing to the insulating qualities of the surfactant.	[40]

Ultrasonic treatment	To promote more equal dispersion and high-frequency sound waves are used to break apart CNT agglomerates.	Low cost, can be used in conjunction with surfactant-assist dispersion.	CNTs may be damaged, and electrical conductivity may be diminished.	[56], [87]
Functionalization	Chemical alteration of the CNT surface to increase solution solubility and dispersibility	It improves solubility and dispersibility and can be employed in specialized applications.	CNT electronic characteristics as well as efficiency in electronic devices may be affected.	[68], [70]

Overall, consistent CNT dispersion is crucial for fabricating exceptionally well CNT-based flexible electronics. The method used to achieve dispersion will be determined by the device's unique needs as well as the desired attributes of the CNTs. Additional research is required to improve and standardize these techniques for different purposes in the field.

4.3 SOLUTION TO REGULATORY CHALLENGES

Several regulatory challenges have hampered the development and commercialization of CNT-based flexible electronic devices, which must be dealt with to ensure their reliability and sustainability. As a result, numerous solutions have been developed, including risk assessments, standard creation, life cycle evaluations, regulatory compliance, and effective communication and education. Various regulatory bodies and organizations, including the European Union's REACH supervision, the International Organization for Standardization, the European Commission's Joint Research Centre, and the National Institute for Occupational Safety and Health, have proposed these solutions.[75] In this context, the purpose of this paper is to present an overview of the methods proposed to overcome the regulatory problems of CNT-based flexible electronics devices, based on relevant and trustworthy data. Table 4.6 directs us the solutions to the regulatory challenges.

Table 4.6: Solutions to the regulatory challenges

Challenge	Solution	Description	Example	Reference
Safety concerns	Risk assessment	To identify possible dangers and risks connected with CNT-based flexible electronics devices, conduct a thorough risk assessment.	A full risk assessment must be performed by the European Union's REACH legislation for every material produced or imported in amounts of one ton or more per year.	[75], [79]
Lack of standards	Development of Standards	Create guidelines for the evaluation, testing, and secure use of CNT-based flexible electronics.	The International Organization for Standardization (ISO) has released a number of nanotechnology standards, including ISO/TS 80004-6:2013, which gives guidelines on carbon nanotube characterization.	[88]
Environmental impact	Life cycle assessment	Conduct a life cycle evaluation to determine and mitigate the possible adverse effects associated with the manufacture, use, and disposal of carbon nanotube-based flexible electronics..	The Joint Research Centre of the European Commission has produced recommendations for the life cycle evaluation of nanomaterials, including special concerns for carbon nanotubes.	[30], [79]
Regulatory compliance	Observance of existing regulations	Ensure that current norms and standards are followed in the manufacturing, testing, and commercialization of CNT-based flexible electronics devices.	CNT-based goods are regulated in the United States by several government agencies, including the Environmental Protection Agency, the Food and Drug Administration, and the Occupational	[89]

			Safety and Health Administration.	
Public perception	Communication and education	Communicate to the public and stakeholders the benefits and hazards of CNT-based flexible electronic devices, as well as provide information and instruction on safe handling and use.	The National Institute for Occupational Safety and Health has created guidelines for the safe handling of nanomaterials in the workplace, including carbon nanotubes. Furthermore, the European Union's NanoReg2 initiative seeks to provide instructions and resources for nanomaterial risk assessment and communication.	[90]

In conclusion, dealing with regulatory issues necessitates a multifaceted strategy that encompasses risk assessment, standard formulation, life cycle evaluation, compliance with regulations, and efficient interaction and education. With such solutions in place, the promise of CNT-based flexible electronics devices may be fulfilled while also assuring their safety and long-term viability.

4.4 SUMMARY

CNT-based flexible electronics devices have shown significant promise for a variety of applications, but they confront regulatory and technological obstacles that must be overcome before they can be developed and commercialized. Concerns about safety, a lack of standards, environmental effect, regulatory compliance, and public opinion are among the regulatory issues. Risk assessment, standard creation, life cycle evaluation, compliance with regulations, and effective interaction and instruction are among the solutions recommended to solve these difficulties. Technical problems include CNT dispersion, device manufacture, and integration with different substances. Surfactants, additives, and integration have been presented as solutions to these issues, as have the development of novel manufacturing processes and the introduction of hybrid materials. The successful application of these technologies will allow for the safe and long-term growth and commercialization of CNT-based flexible electronic devices.

CHAPTER 5

PROSPECTS OF CNT-BASED FLEXIBLE ELECTRONICS SYSTEM

5.1 INTRODUCTION

The rapid scaling of transistors produced on hard silicon wafers has continuously increased the performance of consumer gadgets and supercomputers during the last decades. High-performance logic circuits and sensors constructed on flexible materials are required for new applications such as real-time analytics and IoT to allow actual computing at the edge. Below in figure 5.1, various kinds of CNT-based flexible electronic devices are shown.

Figure 5.1: CNT-based flexible electronic devices

These are only a few of the emerging applications where flexible nanomaterials, such as carbon nanotubes (CNTs), might provide several benefits over rigid silicon, such as cheap cost, low power, large-area manufacturing, or even roll-to-roll fabrication. Wearable technology, including fitness trackers and smartwatches, is becoming more popular in first-world nations like the US, Europe, and Japan. These devices call for flexible and compact electronics. A developing market exists for flexible screens that can be folded and bent without harming the circuitry, such as those seen in smartphones and laptops. Figure 5.2 shows the market share of CNT-based flexible electronics by continent.

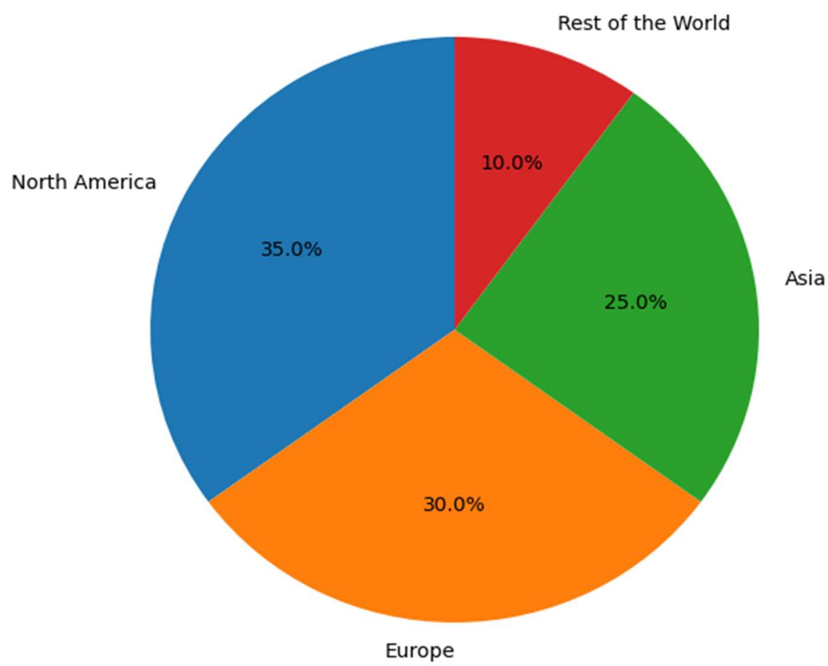

Figure 5.2: Market share of CNT-based flexible electronics by continents.[15]

Flexible electronics are becoming more and more in demand in developing nations like China and India, particularly within the consumer and automotive sectors.[91] The consumer demand for electronics, such as smartphones and wearable technology, will rise as these nations' economies continue to improve and their middle classes expand, which will fuel the expansion of the market for CNT-based flexible electronics. Because of their excellent mechanical strength, flexibility, and electrical conductivity, CNTs are projected to be used more frequently in various applications.

5.2 GLOBAL PROSPECTS OF CNT-BASED FLEXIBLE ELECTRONICS

Carbon nanotube-based flexible or wearable electronics, which are compatible with curved surfaces and movable elements, is an emerging technology with intriguing applications in large-area electronics. The gradual advancement of extremely thin electronics and optoelectronics devices, biocompatible encapsulated layers, sensors, and actuators has hastened the creation of flexible electronics interfaces for complicated geometries and curved structures. A market report scope is given below in table 5.1,

Table 5.1: Carbon nanotubes market report scope.[91]

Report Metric	**Details**
Market Size Value in 2021	USD 876 million
Revenue Forecast in 2026	USD 1,714 million
Growth Rate	CAGR of 14.4% from 2021 to 2026
Years considered for the study	2019-2026
the Base year	2020
Forecast period	2021–2026
Units considered	Value (USD) and Volume (Kiloton)
Regions covered	APAC, Europe, North America, South America, and the Middle East & Africa
Companies profiled	The major market players are LG Chemical Limited (South Korea), Cabot Corporation (US), Showa Denko K.K. (Japan), Jiangsu Cnano Technology Co., Ltd. (China), and Chengdu Organic Chemicals Co. Ltd. (China). (Total of 28 companies)

The global market for CNT-based flexible electronics is expected to grow in the coming years, driven by increasing demand for flexible electronic devices such as wearable technology, Internet of Things (IoT) devices, and flexible displays. According to a report by Marketsand Markets, the global CNT-based flexible electronics market was valued at $1.5 billion in 2019 and is projected to reach $5.8 billion by 2024, at a CAGR of 30.7% during the forecast period. The growth of the market is driven by factors such as the increasing use of CNTs in flexible displays, solar cells, and sensors. The Asia Pacific region is expected to dominate the CNT-based flexible electronics market during the forecast period, due to the presence of major companies such as Samsung, LG, and Sony in the region, as well as the increasing adoption of flexible electronic devices in countries such as China and South Korea.[91]

The increasing use of CNTs in flexible displays is a major driving factor for the market. CNTs are used as transparent conductive electrodes in flexible displays, which are used in smartphones, tablets, and laptops. In addition, the growing adoption of IoT devices, such as smart homes and smart cities, is expected to drive the demand for CNT-based flexible electronics. However, the high cost of production of CNTs and the lack of efficient methods for synthesizing and purifying CNTs are the major challenges faced by the market. The global prospects for CNT-based flexible electronics are positive, as CNTs have unique properties that make them an attractive option for a wide range of applications in the field of flexible electronics. The market for flexible electronics is expected to grow significantly in the coming years, driven by advances in technology and the increasing demand for flexible and wearable devices. In several fields, including environmental pollution surveillance, national security, industrial emission monitoring, and medical diagnostics, early detection of gasses and dangerous vapors are now more vital than ever.[15]

5.3 PROSPECTS OF CNT-BASED FLEXIBLE ELECTRONICS IN BANGLADESH

CNT-based flexible electronics have a wide range of potential applications in Bangladesh, including health care, electronics, energy, and others. The future prospects of CNT-based flexible electronics devices are particularly important in developing nations like Bangladesh, where there is a tremendous need for low-cost, sustainable, and creative technology. The development of such items, among other things, can lead to advances in medical care, the agricultural sector, and transportation, as well as chances for economic expansion and employment opportunity creation.

In figure 5.3, the prospects of CNT-based flexible electronics in developing countries is represente as a percentage wheel.

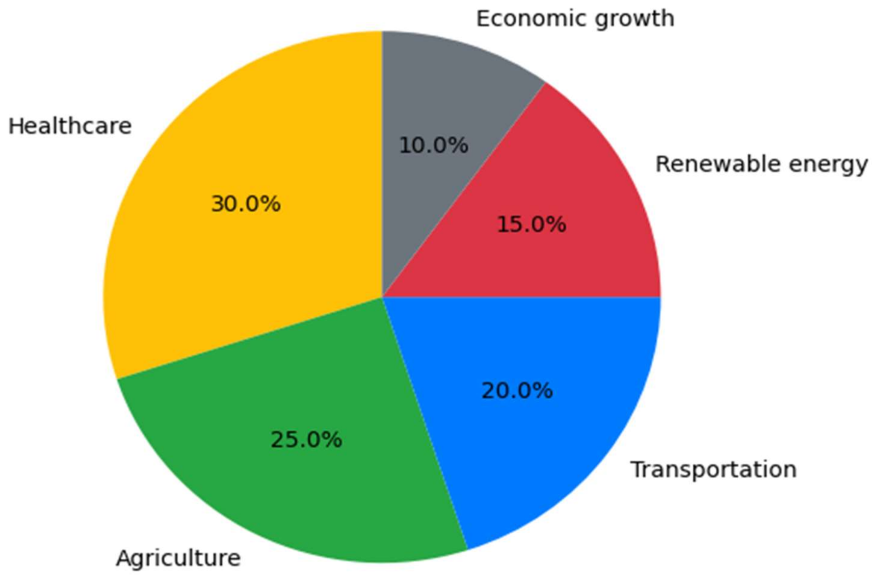

Figure 5.3: Prospects of CNT-based flexible electronics in developing countries.[91]

On January 24, 2022, the Planning Minister of Bangladesh added that "By providing solar-powered electricity in Bangladesh, nanotechnology directly benefits 18 million people."[92] The textile sector in Bangladesh, for example, might profit from CNT-based conductive fibers, that can be used to create smart fabrics that can detect the temperature of the body, heart rate, and other physiological characteristics. CNT-based sensors may also be utilized in agriculture for monitoring soil moisture, temperature, and levels of nutrients, enhancing agricultural output and efficiency. CNT-based materials may be employed in the energy industry to create lightweight, powerful batteries and supercapacitors, that can be used to power portable gadgets and electric vehicles. Furthermore, CNT-based photovoltaic cells have demonstrated encouraging efficiency and stability findings, making them a viable alternative to classic silicon-based solar cells.[93] CNT-based flexible electronics are projected to play an important role in the growth of the Internet of Things (IoT) and smart technologies in the future. As the need for smart devices and wearables grows, adaptable and lightweight electronic parts that may be incorporated into clothes and other accessories will be in high demand. Because of their flexibility and mechanical properties, CNT-based materials are ideal for such applications.

Figure 5.4 shows a graph based on the growth of wearable sensors value in global market.

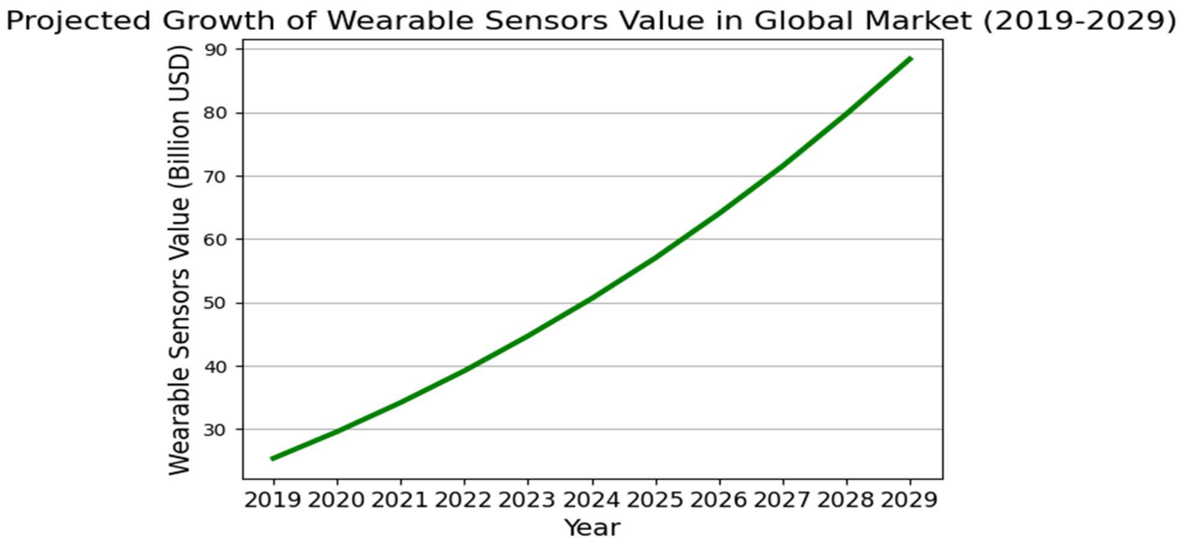

Figure 5.4: Growth of wearable sensors value in the global market.[94]

The global market for wearable sensors is anticipated to reach a value of nearly $60 billion by 2025, with a compound annual growth rate (CAGR) of 30.4% from 2020 to 2025, according to MarketsandMarkets. Another possible application for CNT-based materials is in electronics, where they may be utilized to produce flexible screens, touchscreens, and other gadgets.[94]

However, significant hurdles must be overcome before CNT-based flexible electronics may be extensively utilized in developing nations like Bangladesh. These include scalability, cost-effectiveness, and safety concerns. Furthermore, talented researchers and engineers who can design and deploy CNT-based technologies are in high demand.[93] Here are a few challenges with their probable solutions that Bangladesh needs to overcome in order to produce and develop efficient CNT-based flexible electronics products given in Table 5.2;

Table 5.2: Proposed Solutions and the Challenges of CNT-based flexible electronics development in Bangladesh.

Challenge	Solution	Reference
A scarcity of trained labor in CNT and device production	Creating specialized courses at universities and research institutes, as well as providing industry people with training programs	[84]
Higher cost for the production of CNT	Establishing low-cost and efficient synthesis methods, as well as investigating alternate CNT sources	[56]

Difficulties in attaining uniform CNT dispersion in polymer matrix	Surfactants and sonication are used to increase dispersion and processing parameters are optimized.	[40]
Accessibility to modern equipment and facilities is limited.	Collaboration with foreign research institutes, construction of joint research and development facilities	[27]
Governmental funding and assistance for CNT-based research are limited.	Advocating for additional funding and support, as well as demonstrating to stakeholders and policymakers the promise of CNT-based flexible electronic devices	[91], [15]
Regulatory impediments to the commercialization of carbon nanotube-based goods	Compliance with worldwide safeguarding and environmental standards, as well as collaboration with regulatory organizations to enable a smooth market introduction	[75]

According to our analysis, the future prospects of CNT-based flexible electronic items in Bangladesh and other developing nations are looking positive due to increased government initiatives to develop the electronics industry, increasing consumer appetite for smartwatches, and increased investments in R&D activities. Collaboration between government, educational institutions, and industry is required to build an environment that stimulates innovation and allows for the secure and environmentally friendly development of these CNT-based flexible products.

5.4 SUMMARY

The prospects for CNT (carbon nanotube) based flexible electronics systems are promising. CNTs have unique properties such as high electrical conductivity, mechanical strength, and thermal stability, which make them suitable for use in flexible electronic devices. They can be used as transparent conductive electrodes, interconnects, and transistors in flexible displays, solar cells, and sensors. Additionally, CNTs can be used to create thin and lightweight electronic devices, which are desirable for applications such as wearable technology. However, there are still some challenges that need to be addressed, such as the cost of production and the development of efficient methods for synthesizing and purifying CNTs. Because of global warming, there is a high need for renewable energy sources. Organic solar cell research and carbon nanotubes (CNTs), which play a significant role in thin film photovoltaic development, have seen enormous progress. Because of its potential applications in the realm of energy, such as smart electronics, biosensors, artificial skins, and fundamentally sensing items, there has been great growth in research in wearable and flexible technologies in recent years.

CHAPTER 6
CONCLUSIONS AND RECOMMENDATIONS

6.1 FUTURE RECOMMENDATIONS

Overall, CNTs have a lot of potential for flexible electronics, as they have excellent mechanical and electrical properties, are lightweight and can be easily integrated into various device architectures and can be fabricated using roll-to-roll processing, which is a cost-effective method of large-scale production. Furthermore, research on techniques to increase the mechanical and electrical characteristics of carbon nanotubes, as well as strategies for incorporating carbon nanotubes into diverse device topologies, would be advantageous.

Future research in flexible electronics should focus on several key areas:

- Materials: Creating novel materials and refining current ones' qualities like flexibility, conductivity, and stability in order to create more sophisticated and dependable gadgets.
- Fabrication: Creating novel fabrication processes that are suitable for large-scale manufacturing and can generate high precision and uniformity devices.{Citation}
- Integration: Creating methods for integrating flexible electronics into various applications such as wearable gadgets, medical devices, and smart packaging.
- Energy harvesting and storage: Creating novel ways to collect and store energy in flexible devices such as solar cells and batteries to allow self-powered and wireless gadgets.
- Advanced functions: Investigating new functionalities that can be accomplished with flexible electronics, including sensing, actuation, and communication, in order to generate new sorts of devices and applications.
- Interdisciplinary Collaboration: Collaboration with researchers from other disciplines, including materials science, device physics, and computer science, to create new technologies and applications.
- Cost: Making flexible electronics more cost-effective, so that they may be used in a wide range of industries and applications.

6.2 CONCLUSION

Every day, new research is pushed from composite materials with extraordinary form factors to new approaches for producing devices in unorthodox forms in quicker, cost-effective-effective, and more accessible ways. Rather than contending with traditional electronic goods in terms of efficiency and computational power, they provide novel methods to connect with surroundings that were not before feasible. The development of flexible electronics offers an infinite number of new uses. From extracting light energy across glass panels, cars, and clothing, as well as thermal gradients from our bodies and the surrounding environment to consumer devices like foldable phones and bendable displays, to implantable and wearable flexible electronics that observe our health and make diagnostics easier using machine learning. The CNT-based flexible electronics research field is still far from delivering quality goods because of limitations such as device functionality durability, stability, and reliability, as well as manufacturing barriers such as equipment adaptation to developed products and adhesives and trying to balance the low initial rates of emerging technologies with investment projects.

However, bioelectronics and customized treatment have enormous promise. Research that advances the features and suitability of Carbon Nanotube composites with the skin, sensors with enhanced validity and consistency, and the combination of several devices to independently collect, analyze data, and transfer the data without the necessity of heavy and costly external components will position the field at the leading edge of new applications and products.

REFERENCES

[1] C. M. Das, L. Kang, Q. Ouyang, and K. Yong, ‘Advanced low-dimensional carbon materials for flexible devices’, *InfoMat*, vol. 2, no. 4, pp. 698–714, Jul. 2020, doi: 10.1002/inf2.12073.

[2] L. Cai and C. Wang, ‘Carbon Nanotube Flexible and Stretchable Electronics’, *Nanoscale Res. Lett.*, vol. 10, no. 1, p. 320, Dec. 2015, doi: 10.1186/s11671-015-1013-1.

[3] C. Wang, K. Xia, H. Wang, X. Liang, Z. Yin, and Y. Zhang, ‘Advanced Carbon for Flexible and Wearable Electronics’, *Adv. Mater.*, vol. 31, no. 9, p. 1801072, Mar. 2019, doi: 10.1002/adma.201801072.

[4] X. Gong *et al.*, ‘Efficient Fabrication of Carbon Nanotube-Based Stretchable Electrodes for Flexible Electronic Devices’, *Macromol. Rapid Commun.*, vol. 44, no. 5, p. 2200795, Mar. 2023, doi: 10.1002/marc.202200795.

[5] M. Mirshojaeian Hosseini and R. Nawrocki, ‘A Review of the Progress of Thin-Film Transistors and Their Technologies for Flexible Electronics’, *Micromachines*, vol. 12, no. 6, p. 655, Jun. 2021, doi: 10.3390/mi12060655.

[6] A.-C. Bunea *et al.*, ‘E-Skin: The Dawn of a New Era of On-Body Monitoring Systems’, *Micromachines*, vol. 12, no. 9, p. 1091, Sep. 2021, doi: 10.3390/mi12091091.

[7] M. M. J. Treacy, T. W. Ebbesen, and J. M. Gibson, ‘Exceptionally high Young’s modulus observed for individual carbon nanotubes’, *Nature*, vol. 381, no. 6584, pp. 678–680, Jun. 1996, doi: 10.1038/381678a0.

[8] B.-C. Kang and T.-J. Ha, ‘Wearable carbon nanotube based dry-electrodes for electrophysiological sensors’, *Jpn. J. Appl. Phys.*, vol. 57, no. 5S, p. 05GD02, May 2018, doi: 10.7567/JJAP.57.05GD02.

[9] B.-J. Kim and J.-S. Park, ‘Applications of Carbon Nanotubes to Flexible Transparent Conductive Electrodes’, in *Carbon Nanotubes - Recent Progress*, M. M. Rahman and A. M. Asiri, Eds., InTech, 2018. doi: 10.5772/intechopen.72002.

[10] X. Zhang, W. Lu, G. Zhou, and Q. Li, ‘Understanding the Mechanical and Conductive Properties of Carbon Nanotube Fibers for Smart Electronics’, *Adv. Mater.*, vol. 32, no. 5, p. 1902028, Feb. 2020, doi: 10.1002/adma.201902028.

[11] Y. Wang, X. Qiu, and J. Zheng, ‘Study the mechanism that carbon nanotubes improve thermal stability of polymer composites: An ingenious design idea with coating silica on CNTs and valuable in engineering applications’, *Compos. Sci. Technol.*, vol. 167, pp. 529–538, Oct. 2018, doi: 10.1016/j.compscitech.2018.08.040.

[12] X. Wang, X. Lu, B. Liu, D. Chen, Y. Tong, and G. Shen, ‘Flexible Energy-Storage Devices: Design Consideration and Recent Progress’, *Adv. Mater.*, vol. 26, no. 28, pp. 4763–4782, Jul. 2014, doi: 10.1002/adma.201400910.

[13] H. Wu, Y. Huang, F. Xu, Y. Duan, and Z. Yin, 'Energy Harvesters for Wearable and Stretchable Electronics: From Flexibility to Stretchability', *Adv. Mater.*, vol. 28, no. 45, pp. 9881–9919, Dec. 2016, doi: 10.1002/adma.201602251.

[14] K. Chen *et al.*, 'Printed Carbon Nanotube Electronics and Sensor Systems', *Adv. Mater.*, vol. 28, no. 22, pp. 4397–4414, Jun. 2016, doi: 10.1002/adma.201504958.

[15] H. U. Modekwe *et al.*, 'The Current Market for Carbon Nanotube Materials and Products', in *Handbook of Carbon Nanotubes*, J. Abraham, S. Thomas, and N. Kalarikkal, Eds., Cham: Springer International Publishing, 2021, pp. 1–15. doi: 10.1007/978-3-319-70614-6_73-1.

[16] X. Fu, L. Xu, J. Li, X. Sun, and H. Peng, 'Flexible solar cells based on carbon nanomaterials', *Carbon*, vol. 139, pp. 1063–1073, Nov. 2018, doi: 10.1016/j.carbon.2018.08.017.

[17] J. Kim, A. S. Campbell, B. E.-F. De Ávila, and J. Wang, 'Wearable biosensors for healthcare monitoring', *Nat. Biotechnol.*, vol. 37, no. 4, pp. 389–406, Apr. 2019, doi: 10.1038/s41587-019-0045-y.

[18] M. S. Mousa, I. Tulbure, and S. Fawaeer, 'Environmental monitoring odds by carbon nanotubes', *MATEC Web Conf.*, vol. 342, p. 03022, 2021, doi: 10.1051/matecconf/202134203022.

[19] T. Belin and F. Epron, 'Characterization methods of carbon nanotubes: a review', *Mater. Sci. Eng. B*, vol. 119, no. 2, pp. 105–118, May 2005, doi: 10.1016/j.mseb.2005.02.046.

[20] E. T. Thostenson, Z. Ren, and T.-W. Chou, 'Advances in the science and technology of carbon nanotubes and their composites: a review', *Compos. Sci. Technol.*, vol. 61, no. 13, pp. 1899–1912, Oct. 2001, doi: 10.1016/S0266-3538(01)00094-X.

[21] AZO Nano, 'A History of Carbon Nanotubes', [Online]. Available: https://www.azonano.com/article.aspx?ArticleID=4843

[22] J. Chen, S. Wei, and H. Xie, 'A Brief Introduction of Carbon Nanotubes: History, Synthesis, and Properties', *J. Phys. Conf. Ser.*, vol. 1948, no. 1, p. 012184, Jun. 2021, doi: 10.1088/1742-6596/1948/1/012184.

[23] P. Harris, 'Transmission Electron Microscopy of Carbon: A Brief History', *C*, vol. 4, no. 1, p. 4, Jan. 2018, doi: 10.3390/c4010004.

[24] S. Rathinavel, K. Priyadharshini, and D. Panda, 'A review on carbon nanotube: An overview of synthesis, properties, functionalization, characterization, and the application', *Mater. Sci. Eng. B*, vol. 268, p. 115095, Jun. 2021, doi: 10.1016/j.mseb.2021.115095.

[25] '"The Discovery of Fullerenes" commemorative booklet produced by the National Historic Chemical Landmarks program of the American Chemical Society in 2010 (PDF).', [Online]. Available: http://www.acs.org/content/acs/en/education/whatischemistry/landmarks/fullerenes.html

[26] P. Sharma and P. Ahuja, 'Recent advances in carbon nanotube-based electronics', *Mater. Res. Bull.*, vol. 43, no. 10, pp. 2517–2526, Oct. 2008, doi: 10.1016/j.materresbull.2007.10.012.

[27] H. Golnabi, 'Carbon nanotube research developments in terms of published papers and patents, synthesis and production', *Sci. Iran.*, vol. 19, no. 6, pp. 2012–2022, Dec. 2012, doi: 10.1016/j.scient.2012.10.036.

[28] W. E. W. Sheehan P.E., 'Nanobeam Mechanics: Elasticity, Strength, and Toughness of Nanorods and Nanotubes.'.

[29] H. Wan, Y. Cao, L.-W. Lo, J. Zhao, N. Sepúlveda, and C. Wang, 'Flexible Carbon Nanotube Synaptic Transistor for Neurological Electronic Skin Applications', *ACS Nano*, vol. 14, no. 8, pp. 10402–10412, Aug. 2020, doi: 10.1021/acsnano.0c04259.

[30] T. Dinh *et al.*, 'Environment-friendly carbon nanotube based flexible electronics for noninvasive and wearable healthcare', *J. Mater. Chem. C*, vol. 4, no. 42, pp. 10061–10068, 2016, doi: 10.1039/C6TC02708C.

[31] D. C. Ferrier and K. C. Honeychurch, 'Carbon Nanotube (CNT)-Based Biosensors', *Biosensors*, vol. 11, no. 12, p. 486, Nov. 2021, doi: 10.3390/bios11120486.

[32] X.-D. Wang, K. Vinodgopal, and G.-P. Dai, 'Synthesis of Carbon Nanotubes by Catalytic Chemical Vapor Deposition', in *Perspective of Carbon Nanotubes*, H. El-Din Saleh and S. Moawad Mohamed El-Sheikh, Eds., IntechOpen, 2019. doi: 10.5772/intechopen.86995.

[33] Y. F. Chan, H. Y. Peng, Z. K. Tang, and N. Wang, 'Transmission electron microscopy study of single-walled 0.4 nm carbon nanotubes', *Chem. Phys. Lett.*, vol. 369, no. 5–6, pp. 541–548, Feb. 2003, doi: 10.1016/S0009-2614(02)02050-X.

[34] Q. Liu *et al.*, 'Diameter-Selective Growth of Single-Walled Carbon Nanotubes with High Quality by Floating Catalyst Method', *ACS Nano*, vol. 2, no. 8, pp. 1722–1728, Aug. 2008, doi: 10.1021/nn8003394.

[35] F. Xia *et al.*, 'High-Performance Carbon Nanotube-Based Transient Complementary Electronics', *ACS Appl. Mater. Interfaces*, vol. 14, no. 10, pp. 12515–12522, Mar. 2022, doi: 10.1021/acsami.1c23134.

[36] F. Wakaya, K. Katayama, and K. Gamo, 'Contact resistance of multiwall carbon nanotubes', *Microelectron. Eng.*, vol. 67–68, pp. 853–857, Jun. 2003, doi: 10.1016/S0167-9317(03)00147-3.

[37] S. U. Khan, J. R. Pothnis, and J.-K. Kim, 'Effects of carbon nanotube alignment on electrical and mechanical properties of epoxy nanocomposites', *Compos. Part Appl. Sci. Manuf.*, vol. 49, pp. 26–34, Jun. 2013, doi: 10.1016/j.compositesa.2013.01.015.

[38] Z. Liu and G. Chen, 'Advancing Flexible Thermoelectric Devices with Polymer Composites', *Adv. Mater. Technol.*, vol. 5, no. 7, p. 2000049, Jul. 2020, doi: 10.1002/admt.202000049.

[39] S. Kholghi Eshkalak, A. Chinnappan, W. A. D. M. Jayathilaka, M. Khatibzadeh, E. Kowsari, and S. Ramakrishna, 'A review on inkjet printing of CNT composites for smart applications', *Appl. Mater. Today*, vol. 9, pp. 372–386, Dec. 2017, doi: 10.1016/j.apmt.2017.09.003.

[40] P.-C. Ma, N. A. Siddiqui, G. Marom, and J.-K. Kim, ‘Dispersion and functionalization of carbon nanotubes for polymer-based nanocomposites: A review’, *Compos. Part Appl. Sci. Manuf.*, vol. 41, no. 10, pp. 1345–1367, Oct. 2010, doi: 10.1016/j.compositesa.2010.07.003.

[41] I. Felhősi, Z. Keresztes, T. Marek, and T. Pajkossy, ‘Properties of electrochemical double-layer capacitors with carbon-nanotubes-on-carbon-fiber-felt electrodes’, *Electrochimica Acta*, vol. 334, p. 135548, Feb. 2020, doi: 10.1016/j.electacta.2019.135548.

[42] M. Yang, V. Koutsos, and M. Zaiser, ‘Interactions between Polymers and Carbon Nanotubes: A Molecular Dynamics Study’, *J. Phys. Chem. B*, vol. 109, no. 20, pp. 10009–10014, May 2005, doi: 10.1021/jp0442403.

[43] L. Dai and J. Sun, ‘Mechanical Properties of Carbon Nanotubes-Polymer Composites’, in *Carbon Nanotubes - Current Progress of their Polymer Composites*, M. R. Berber and I. H. Hafez, Eds., InTech, 2016. doi: 10.5772/62635.

[44] I. Shown, A. Ganguly, L. Chen, and K. Chen, ‘Conducting polymer-based flexible supercapacitor’, *Energy Sci. Eng.*, vol. 3, no. 1, pp. 2–26, Jan. 2015, doi: 10.1002/ese3.50.

[45] R. Girardello, S. Tasselli, N. Baranzini, R. Valvassori, M. De Eguileor, and A. Grimaldi, ‘Effects of Carbon Nanotube Environmental Dispersion on an Aquatic Invertebrate, Hirudo medicinalis’, *PLOS ONE*, vol. 10, no. 12, p. e0144361, Dec. 2015, doi: 10.1371/journal.pone.0144361.

[46] T. Nguyen *et al.*, ‘Impact of UV irradiation on multiwall carbon nanotubes in nanocomposites: Formation of entangled surface layer and mechanisms of release resistance’, *Carbon*, vol. 116, pp. 191–200, May 2017, doi: 10.1016/j.carbon.2017.01.097.

[47] M. Yang and M. Zhang, ‘Biodegradation of Carbon Nanotubes by Macrophages’, *Front. Mater.*, vol. 6, p. 225, Sep. 2019, doi: 10.3389/fmats.2019.00225.

[48] Y. Liu, Y. Zhao, B. Sun, and C. Chen, ‘Understanding the Toxicity of Carbon Nanotubes’, *Acc. Chem. Res.*, vol. 46, no. 3, pp. 702–713, Mar. 2013, doi: 10.1021/ar300028m.

[49] Y. Zeng, Z. Ying, J. Du, and H.-M. Cheng, ‘Effects of Carbon Nanotubes on Processing Stability of Polyoxymethylene in Melt−Mixing Process’, *J. Phys. Chem. C*, vol. 111, no. 37, pp. 13945–13950, Sep. 2007, doi: 10.1021/jp0740191.

[50] J. Wiklund *et al.*, ‘A Review on Printed Electronics: Fabrication Methods, Inks, Substrates, Applications and Environmental Impacts’, *J. Manuf. Mater. Process.*, vol. 5, no. 3, p. 89, Aug. 2021, doi: 10.3390/jmmp5030089.

[51] X. Wang, Z. Liu, and T. Zhang, ‘Flexible Sensing Electronics for Wearable/Attachable Health Monitoring’, *Small*, vol. 13, no. 25, p. 1602790, Jul. 2017, doi: 10.1002/smll.201602790.

[52] W. Zeng, L. Shu, Q. Li, S. Chen, F. Wang, and X.-M. Tao, ‘Fiber-Based Wearable Electronics: A Review of Materials, Fabrication, Devices, and Applications’, *Adv. Mater.*, vol. 26, no. 31, pp. 5310–5336, Aug. 2014, doi: 10.1002/adma.201400633.

[53] R. Zhang, Y. Zhang, and F. Wei, ‘Controlled Synthesis of Ultralong Carbon Nanotubes with Perfect Structures and Extraordinary Properties’, *Acc. Chem. Res.*, vol. 50, no. 2, pp. 179–189, Feb. 2017, doi: 10.1021/acs.accounts.6b00430.

[54] J. Hansson *et al.*, ‘Effects of high temperature treatment of carbon nanotube arrays on graphite: increased crystallinity, anchoring and inter-tube bonding’, *Nanotechnology*, vol. 31, no. 45, p. 455708, Nov. 2020, doi: 10.1088/1361-6528/ab9677.

[55] M. Chitranshi *et al.*, ‘Carbon Nanotube Sheet-Synthesis and Applications’, *Nanomaterials*, vol. 10, no. 10, p. 2023, Oct. 2020, doi: 10.3390/nano10102023.

[56] S. F. Nitodas and T. K. Karachalios, ‘Low-cost production and applications of high purity carbon nanotubes’, *Int. J. Nanomanufacturing*, vol. 6, no. 1/2/3/4, p. 111, 2010, doi: 10.1504/IJNM.2010.034777.

[57] S. Awais Rouf, Z. Usman, H. Tariq Masood, A. Mannan Majeed, M. Sarwar, and W. Abbas, ‘Synthesis and Purification of Carbon Nanotubes’, in *Carbon Nanotubes - Redefining the World of Electronics*, P. Kumar Ghosh, K. Datta, and A. Dinkarrao Rushi, Eds., IntechOpen, 2021. doi: 10.5772/intechopen.98221.

[58] A. M. Amani, S. A. Hashemi, S. M. Mousavi, H. Pouya, and V. Arash, ‘Electric Field Induced Alignment of Carbon Nanotubes: Methodology and Outcomes’, in *Carbon Nanotubes - Recent Progress*, M. M. Rahman and A. M. Asiri, Eds., InTech, 2018. doi: 10.5772/intechopen.70481.

[59] NASA, ‘Control of Carbon Nanotube (CNT) Density’, [Online]. Available: http://technology.arc.nasa.gov.

[60] A. Corletto and J. G. Shapter, ‘Nanoscale Patterning of Carbon Nanotubes: Techniques, Applications, and Future’, *Adv. Sci.*, vol. 8, no. 1, p. 2001778, Jan. 2021, doi: 10.1002/advs.202001778.

[61] S. Park, M. Vosguerichian, and Z. Bao, ‘A review of fabrication and applications of carbon nanotube film-based flexible electronics’, *Nanoscale*, vol. 5, no. 5, p. 1727, 2013, doi: 10.1039/c3nr33560g.

[62] J.-W. Song, J. Kim, Y.-H. Yoon, B.-S. Choi, J.-H. Kim, and C.-S. Han, ‘Inkjet printing of single-walled carbon nanotubes and electrical characterization of the line pattern’, *Nanotechnology*, vol. 19, no. 9, p. 095702, Mar. 2008, doi: 10.1088/0957-4484/19/9/095702.

[63] Z. Spitalsky, D. Tasis, K. Papagelis, and C. Galiotis, ‘Carbon nanotube–polymer composites: Chemistry, processing, mechanical and electrical properties’, *Prog. Polym. Sci.*, vol. 35, no. 3, pp. 357–401, Mar. 2010, doi: 10.1016/j.progpolymsci.2009.09.003.

[64] S. Mishra, K. T. Kumaran, R. Sivakumaran, S. P. Pandian, and S. Kundu, ‘Synthesis of PVDF/CNT and their functionalized composites for studying their electrical properties to analyze their applicability in actuation & sensing’, *Colloids Surf. Physicochem. Eng. Asp.*, vol. 509, pp. 684–696, Nov. 2016, doi: 10.1016/j.colsurfa.2016.09.007.

[65] F. H. Gojny, M. H. G. Wichmann, U. Köpke, B. Fiedler, and K. Schulte, ‘Carbon nanotube-reinforced epoxy-composites: enhanced stiffness and fracture toughness at low nanotube content’,

Compos. Sci. Technol., vol. 64, no. 15, pp. 2363–2371, Nov. 2004, doi: 10.1016/j.compscitech.2004.04.002.

[66] H. Lee, H. Kim, M. S. Cho, J. Choi, and Y. Lee, 'Fabrication of polypyrrole (PPy)/carbon nanotube (CNT) composite electrode on ceramic fabric for supercapacitor applications', *Electrochimica Acta*, vol. 56, no. 22, pp. 7460–7466, Sep. 2011, doi: 10.1016/j.electacta.2011.06.113.

[67] N. M. Nurazzi *et al.*, 'Mechanical Performance and Applications of CNTs Reinforced Polymer Composites—A Review', *Nanomaterials*, vol. 11, no. 9, p. 2186, Aug. 2021, doi: 10.3390/nano11092186.

[68] A. Takakura *et al.*, 'Strength of carbon nanotubes depends on their chemical structures', *Nat. Commun.*, vol. 10, no. 1, p. 3040, Jul. 2019, doi: 10.1038/s41467-019-10959-7.

[69] B. Q. Wei, R. Vajtai, and P. M. Ajayan, 'Reliability and current carrying capacity of carbon nanotubes', *Appl. Phys. Lett.*, vol. 79, no. 8, pp. 1172–1174, Aug. 2001, doi: 10.1063/1.1396632.

[70] Z. Peng *et al.*, 'Advances in the application, toxicity and degradation of carbon nanomaterials in environment: A review', *Environ. Int.*, vol. 134, p. 105298, Jan. 2020, doi: 10.1016/j.envint.2019.105298.

[71] H.-C. Su *et al.*, 'Improving the adhesion of carbon nanotubes to a substrate using microwave treatment', *Carbon*, vol. 48, no. 3, pp. 805–812, Mar. 2010, doi: 10.1016/j.carbon.2009.10.032.

[72] R. Atif and F. Inam, 'Reasons and remedies for the agglomeration of multilayered graphene and carbon nanotubes in polymers', *Beilstein J. Nanotechnol.*, vol. 7, pp. 1174–1196, Aug. 2016, doi: 10.3762/bjnano.7.109.

[73] A. Helland, P. Wick, A. Koehler, K. Schmid, and C. Som, 'Reviewing the Environmental and Human Health Knowledge Base of Carbon Nanotubes', *Environ. Health Perspect.*, vol. 115, no. 8, pp. 1125–1131, Aug. 2007, doi: 10.1289/ehp.9652.

[74] S. R. Vinceti, A. O. Docea, C. Tsitsimpikou, and T. Filippini, 'Updating the European Union's regulation on classification, labelling and packaging of substances and mixtures (CLP): A key opportunity for consumers, workers and stakeholders with interests in the legislation and toxicology of hazardous chemicals', *Toxicol. Rep.*, vol. 8, pp. 1865–1868, 2021, doi: 10.1016/j.toxrep.2021.11.011.

[75] K. Schwirn, D. Voelker, W. Galert, J. Quik, and L. Tietjen, 'Environmental Risk Assessment of Nanomaterials in the Light of New Obligations Under the REACH Regulation: Which Challenges Remain and How to Approach Them?', *Integr. Environ. Assess. Manag.*, vol. 16, no. 5, pp. 706–717, Sep. 2020, doi: 10.1002/ieam.4267.

[76] M. Miernicki, T. Hofmann, I. Eisenberger, F. Von Der Kammer, and A. Praetorius, 'Legal and practical challenges in classifying nanomaterials according to regulatory definitions', *Nat. Nanotechnol.*, vol. 14, no. 3, pp. 208–216, Mar. 2019, doi: 10.1038/s41565-019-0396-z.

[77] European Commission. Joint Research Center. Institute for Prospective and Technological Studies, *The future of semiconductor intellectual property architectural blocks in Europe*. LU:

Publications Office, 2009. Accessed: Jun. 03, 2023. [Online]. Available: https://data.europa.eu/doi/10.2791/13315

[78] European Union, ‘Regulation (EU) 2021/821 setting up an EU regime for the control of exports, brokering, technical assistance, transit and transfer of dual-use items’, [Online]. Available: https://eur-lex.europa.eu/EN/legal-content/summary/dual-use-export-controls.html

[79] European Commission, ‘The General Product Safety Directive’, [Online]. Available: https://commission.europa.eu/business-economy-euro/product-safety-and-requirements/product-safety/consumer-product-safety_en

[80] D. Corzo, G. Tostado-Blázquez, and D. Baran, ‘Flexible Electronics: Status, Challenges and Opportunities’, *Front. Electron.*, vol. 1, p. 594003, Sep. 2020, doi: 10.3389/felec.2020.594003.

[81] L. Cai, S. Zhang, J. Miao, Z. Yu, and C. Wang, ‘Fully Printed Stretchable Thin-Film Transistors and Integrated Logic Circuits’, *ACS Nano*, vol. 10, no. 12, pp. 11459–11468, Dec. 2016, doi: 10.1021/acsnano.6b07190.

[82] L. Nayak, S. Mohanty, S. K. Nayak, and A. Ramadoss, ‘A review on inkjet printing of nanoparticle inks for flexible electronics’, *J. Mater. Chem. C*, vol. 7, no. 29, pp. 8771–8795, 2019, doi: 10.1039/C9TC01630A.

[83] C. E. Owens *et al.*, ‘Flexible Electronics: Substrate-Versatile Direct-Write Printing of Carbon Nanotube-Based Flexible Conductors, Circuits, and Sensors (Adv. Funct. Mater. 25/2021)’, *Adv. Funct. Mater.*, vol. 31, no. 25, p. 2170181, Jun. 2021, doi: 10.1002/adfm.202170181.

[84] W. Hou, Q. Liao, S. Xie, Y. Song, and L. Qin, ‘Prospects and Challenges of Flexible Stretchable Electrodes for Electronics’, *Coatings*, vol. 12, no. 5, p. 558, Apr. 2022, doi: 10.3390/coatings12050558.

[85] D. S. Saidina, N. Eawwiboonthanakit, M. Mariatti, S. Fontana, and C. Hérold, ‘Recent Development of Graphene-Based Ink and Other Conductive Material-Based Inks for Flexible Electronics’, *J. Electron. Mater.*, vol. 48, no. 6, pp. 3428–3450, Jun. 2019, doi: 10.1007/s11664-019-07183-w.

[86] Y.-Y. Chen *et al.*, ‘High-Throughput Fabrication of Flexible and Transparent All-Carbon Nanotube Electronics’, *Adv. Sci.*, vol. 5, no. 5, p. 1700965, May 2018, doi: 10.1002/advs.201700965.

[87] A. Kamyshny and S. Magdassi, ‘Conductive nanomaterials for 2D and 3D printed flexible electronics’, *Chem. Soc. Rev.*, vol. 48, no. 6, pp. 1712–1740, 2019, doi: 10.1039/C8CS00738A.

[88] *ISO/TS 80004-6:2021(en), Nanotechnologies*. [Online]. Available: https://www.iso.org/obp/ui/#iso:std:iso:ts:80004:-6:ed-2:v1:en

[89] Center for Diseases Control and Prevention, ‘Occupational Exposure to Carbon Nanotubes and Nanofibers’, [Online]. Available: http://www.particleandfibretoxicology.com/content/7/1/28

[90] National Institutes of Health, ‘Nanotechnology Safety and Health Program’, [Online]. Available: https://www.nih.gov/

[91] MarketsnandMarkets, ‘Carbon Nanotubes Market by Type (Single Walled & Multi Walled), End-use Industry (Electronics & Semiconductors, Chemical Materials & Polymers, Structural Composites, Energy & Storage, Medical), Method, and Region - Global Forecast to 2026’, [Online]. Available: https://www.marketsandmarkets.com/Market-Reports/nanotechnology-market-6889262.html

[92] ‘“Bangladesh has started to see impact of nanotechnology”’, *Dhaka Tribune*. [Online]. Available: https://www.dhakatribune.com/bangladesh/2022/01/24/bangladesh-has-started-to-see-impact-of-nanotechnology

[93] M. L. P. Md. Zahirul Hoque Mojumder, ‘Nanotechnology and Governance in Bangladesh’, HEINONLINE. [Online].
Available:
https://heinonline.org/HOL/LandingPage?handle=hein.journals/nantechlb10&div=16&id=&page=

94] ‘Global Wearable Sensors Market by Product Type (Temperature Sensor, Motion Sensor, Medical Sensor, Image Sensor, Position Sensor, and Pressure Sensor) and Application (Eye Wear, Wrist Wear, Body Wear, Footwear, and Other Wearable Devices): Global Opportunities Analysis and Industry Forecast, 2014 - 2022’, *Allied Mark. Res.*, [Online]. Available: https://www.alliedmarketresearch.com/wearable-sensor-market

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