



Carbon Nanotubes: Structure, Synthesis, Functionalization, Characteristics, and Textile Applications (A Review)

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Abstract

Carbon nanotubes (CNTs) are one of the most distinctive innovations in the world of nanotechnology. CNTs have been intensively examined by numerous experts across the world over the last two decades due to their enormous potential in a variety of technical fields such as nanoelectronics, biotechnology, material science, polymer, composite, and textile industries because of their excellent polycrystalline, electrical, mechanical, and thermal characteristics. CNT synthesis may be accomplished using a variety of approaches, for example, the arc-discharge process, chemical vaporization deposition (CVD), and laser ablation. There are three types of CNT walls: single, double, and multi-walled. The current study focuses on the synthesis, functionalization, characteristics, and applications of carbon nanotubes (CNTs).

Keywords: Carbon nanotubes, functionalization, textile applications

Introduction

Nanotechnology provides a highly fascinating and bright future for the textile industry. [1, 2] The word nanotechnology refers to any technology that operates on the nanoscale and has real-world applications, that is, the use of single atoms and molecules to construct functional structures. Nanotechnology is associated with systems and materials, the components and structures of which reflect innovative, greatly enhanced chemical, physical, and biological qualities, processes, and phenomena due to their nanoscale dimension.[3] Nanotechnology overcomes the limitations of traditional processes or technology by improving certain properties.[1, 4-9]

The rapid progress of nanoscience and nanotechnology has created several prospects for biological research in a variety of fields to build revolutionary nano-based smart and environmentally adaptive fabrics. So carbon nanomaterials, or nano-carbons, have captured the interest of researchers in a wide range of sectors.[10, 11]

Carbon is a unique element in that it can connect with itself to create long chains with a center core made entirely of carbon atoms. This adaptability gives birth to a wide range of solid carbon structural shapes.[12-15] The majority of the materials studied in carbon science and industry are thought to be constituted mostly of significant polycyclic

aromatic molecules. The changes in the form of such macromolecules, as well as the way the molecules assemble (how they stack and link to one another), result in an enormous diversity of possibilities.[16]

In the sp^2 hybridization, elements of carbon can create a variety of forms. Typical sp^2 -carbon nanomaterials with well-defined structures include zero-dimensional (0D) fullerene, one-dimensional (1D) carbon nanotubes (CNTs), and two-dimensional (2D) graphene. Carbon nanoparticles, commonly known as carbon dots (CDots), are nano-clusters of amorphous carbon (or tiny crystalline structures) with diameters less than 10 nm. They are also a form of 0D sp^2 -carbon nanomaterial. On the other hand, Sp^3 -carbon nanomaterials, are often nano-diamonds (NDs) with nano-scale crystal sizes, in which four bounds are pointed towards the corners of a conventional tetrahedron, the resultant three-dimensional network (diamond) is highly stiff, which contributes to its hardness[17], and **Fig 1** illustrated these forms of nano-carbon.[3, 11]

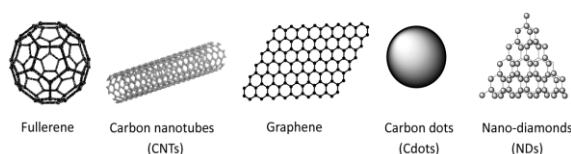


Figure 1 Various forms of nano-carbons

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One of the major components of nanotechnology is a Carbon nanotube (CNT).[18] CNTs are the members of the fullerene family which are molecules having 60 carbon atoms, usually abbreviated as C₆₀, and are soccer-ball-shaped molecules composed of pure carbon atoms linked by single and double bonds in spherical, hexagon, and pentagon shapes as shown in Fig 1.[19-22] Because CNTs are formed from fullerenes, they are also known as tubular fullerenes.[23] The term CNT comes from the size of a nanotube, which has a diameter of a few nanometres ranging from one to tens of nanometres.[24, 25]

CNTs, also known as buckytubes, are cylindrical carbon molecules that possess unique features. CNTs exhibit excellent thermal conductivity, Young's modulus, enormous surface area, and high current density that make them potentially beneficial in a wide range of applications such as nanoelectronics, optics, and textile applications.[26]

Nanotubes' chemical bonding is entirely made up of sp² bonds, which are identical to those found in graphite.[18, 25, 27] Carbon nanotubes have a greater tensile strength than steel and Kevlar because they have sp² bonds between the individual carbon atoms. These bonds are even stronger than diamond's sp³ bonds. Elasticity is another incredible characteristic of carbon nanotubes. Under high force and pressure, and when exposed to great axial compressive forces, it can bend, twist, kink, and finally buckle without damaging the nanotube, and the nanotube will return to its original structure, but the elasticity of nanotubes does have a limit, and it is possible to temporarily deform the shape of a nanotube under very physically powerful forces. Some faults in the structure of the nanotube, such as atomic vacancies or a rearrangement of the carbon bonds, might reduce the strength of the nanotube.[28]

On the other hand, CNTs, are cylindrical, with at least one end usually capped with a hemisphere (dome-shaped half-fullerene molecules) with the buckyball structure.[24, 26] The half-fullerene molecules (pentagonal ring defect) contribute to the closing of the tube at both ends.[28]

When fullerenes are compared to nanotubes, it is clear that the first ones are curved in all three directions in space, but nanotubes have no curvature at all in the axial direction. CNTs are hollow cylinders created by rolling graphite sheets a few nanometres (about 50,000 times the diameter of a human hair).[26] Because of their unique graphite structure, carbon nanotubes are mechanically durable and impermeable to deterioration and have been employed in advanced composites, textiles, and fibers, as well as the manufacture of cables for the space elevator.[29] Furthermore, CNT exhibits

metallic, semiconducting, and superconducting electron transport.[30]

Classification of CNTs

Carbon nanotubes (CNTs) are classified into two categories based on their wall structure. These are Single-walled carbon nanotubes (SWNTs) and Multi-walled carbon nanotubes (MWNTs).[27] CNT classifications are explained in Fig 2.[31]

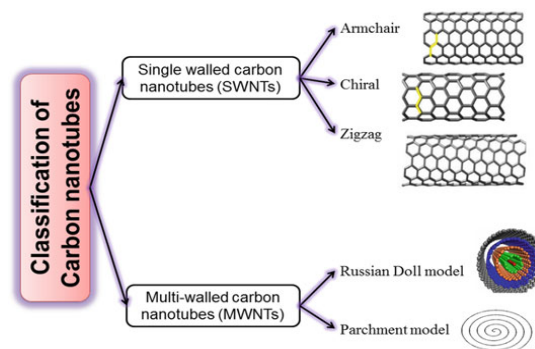


Figure 2 Classifications of CNTs

Single-walled carbon nanotubes

Single-walled carbon nanotubes (SWCNTs) are created by rolling a single layer of graphite (referred to as a graphene layer) into a seamless cylinder (long twisted graphene sheets) as shown in Fig 3.[32] its diameter ranges from 0.4 to 2 nm depending on the temperature at which they were manufactured. It was discovered that the higher the growing temperature, the wider the diameter of CNTs.[33] No more than one sheet of graphene will be needed to provide a one-atom-thick cylindrical framework. During synthesis, SWNTs are closed with cap-like structures at both ends and the ring shape is completed with C-C bonds. The length might vary based on the preparation procedures.[24, 31] Theoretically, SWCNTs might have tensile strengths hundreds of times greater than steel.

The structure of SWCNTs may be armchair, zigzag, chiral, or helical arrangements. SWCNTs offer an ultrahigh surface area of up to 1300 m²/g, providing sufficient space for drug loading and biological conjugation. SWCNTs are known to be more efficient than MWCNTs in drug delivery. This is owing to SWCNTs' ultrahigh area of coverage and excellent drug-loading capacity.[33] They also have essential electric features that MWCNT versions do not have. The electric wire is the most fundamental component of these systems, and SWCNTs can be great conductors.[32]

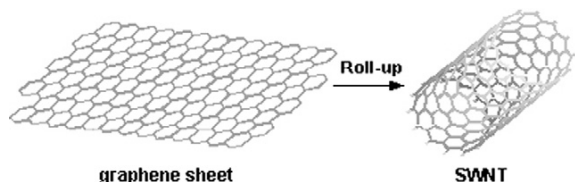


Figure 3 Rolling of a single layer of graphite sheet into SWNTs

Double-walled carbon nanotubes

Aside from this, there is another type of SWNT-like nanotube known as double-walled nanotubes (DWNTs), which have a similar structure to SWNTs and have significant importance in the pharmaceutical industry.[31] Double-walled carbon nanotubes (DWNTs) are constructed from two concentric carbon nanotubes, the outer tube enclosing the inner tube. As shown in Fig 4. It improved thermal and chemical stability as compared to SWNTs.[24]

Multi-walled carbon nanotubes

Multi-walled carbon nanotubes (MWNTs) are made up of several concentric graphene layers folded in on themselves to produce a tube shape.[32] These are made by rolling 3-5 sheets of single-walled nanotubes over one another surrounding a hollow core.[31, 33, 34] The outer diameter of these tubes ranges from 2 to 100 nm, while the inner diameter is in the range of 1-3 nm, and their length is one to several micrometers depending on the number of graphene tubes. MWCNT structures are classified into two types based on how the graphite layers are arranged: one has a parchment-like structure with a graphene sheet rolled up around it, and the other is known as the Russian doll model, which has layers of graphene sheets arranged within a concentric structure.[24, 28, 33] Fig 4 illustrates the types of carbon nanotubes.[21]

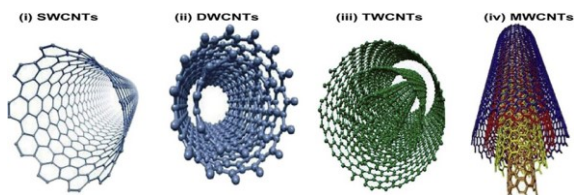


Figure 4 Carbon nanotubes

SWCNTs differ structurally from MWNTs because SWNTs have a different basic arrangement of carbon atoms, resulting in three dissimilar structural configurations such as a zig-zag arrangement, where the tube is characterized by a V-shape structure, is at right angles to the axis of the tube; arm-chair arrangement, which characterized by chair structure, where the chiral

vector is characterized, by perpendicular to the axis of the tube.[31] The differences between single-walled and multi-walled carbon nanotubes result in substantially different properties and corresponding impacts on materials after their introduction and they are shown in Fig 5.

MWCNTs and SWCNTs have similar characteristics. Because of the multilayer structure of MWCNTs, the outside walls may not only shelter the inner carbon nanotubes from chemical reactions with outside substances, but they also have high tensile strength capabilities that SWCNTs do not (or just partially) have.[28]

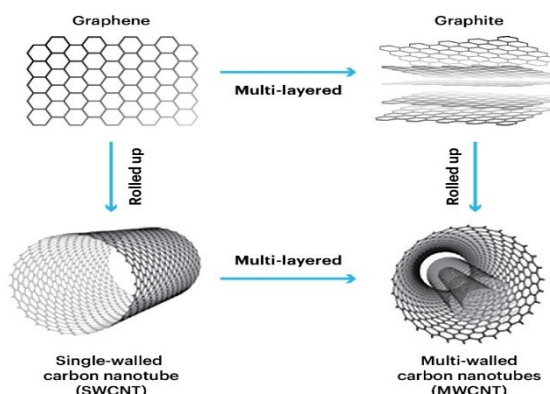


Figure 5 The differences between single-walled and multi-walled carbon nanotubes

Structure of CNTs

CNTs are separate from carbon fibers, which are strands of stacked graphite sheets rather than single molecules.[17] The variation between these sorts of carbon nanotubes is caused by how the graphite is "rolled up" during the manufacturing process. The radius of the closing cylinder and the rolling axis relative to the hexagonal network of the graphene sheet allow for different sorts of SWCNTs.[35]

To describe such an important characteristic of the nanotube, The chiral vector (C_h) which is a vector connecting the centers of the two hexagons and determines the structure of a single-walled carbon nanotube connecting two equivalent carbon atoms, $C_h = n\hat{a}_1 + m\hat{a}_2$, where \hat{a}_1 and \hat{a}_2 are the two basis vectors of graphite, n and m are integers. n and m are also called indexes and determine the chiral angle θ , these two integers correspond to the number of unit vectors along the two directions in the honeycomb crystal lattice of grapheme. When $m = 0$ the nanotube is called a "zigzag", when $n = m$ the nanotube is called an "armchair", and all other configurations are designated as chiral or helical nanotubes, with hexagonal rows spiraling along the nanotube axis.[17, 19, 28, 35-37] As illustrated in Fig 6.[17, 35]

When $n-m$ is a multiple of 3, the nanotube is termed as 'metallic' or highly conducting, and when it is not, the nanotube is classified as semi-metallic or semiconductor. The armchair shape is always metallic, whereas other configurations can make the nanotube a semiconductor.[28] The chiral angle determines the degree of twisting in a carbon nanotube. This angle is the angle formed by the vectors a_1 and C_h . This angle can fall anywhere in the range of $0^\circ \leq |\theta| \leq 30^\circ$. Based on the geometry of these carbon bonds around the outer edges of the carbon nanotube, which corresponds to the achiral tubes, there can be two limiting cases:

zig-zag, in which $\theta = 0^\circ$ and Armchair, in which $\theta = 30^\circ$. Apart from these two, the carbon nanotube is referred to as chiral if $0^\circ < |\theta| < 30^\circ$.

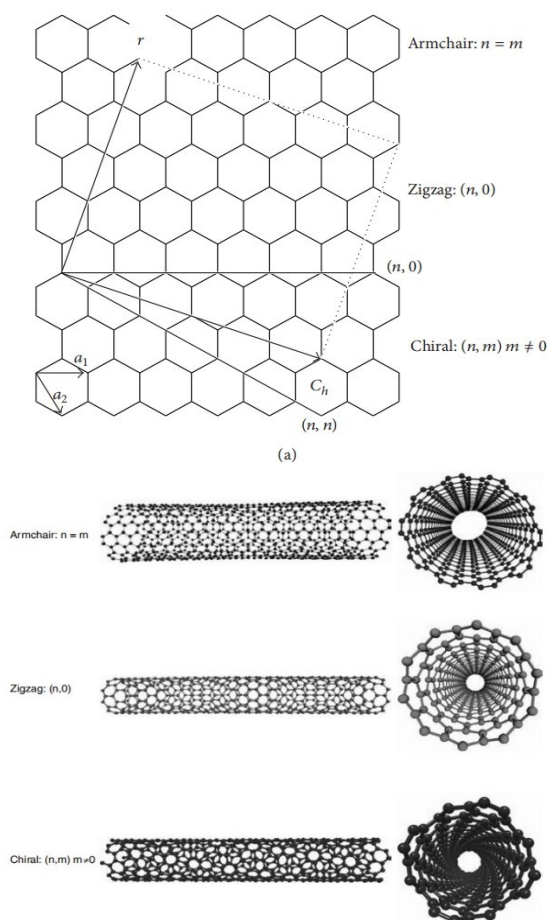


Figure 6 The graphene sheet labeled with the integers (n, m) to identify the types of SWNTs

Synthesis of carbon nanotubes

Rapid progress is being made in modifying the characteristics of carbon nanotubes and minimizing contaminants and imperfections during manufacture. Nonetheless, significant challenges exist in the following areas:

- Low-cost, large-scale manufacture of high-quality nanotubes, particularly SWCNTs with desirable shapes and electrical characteristics.
- A deeper knowledge of the carbon nanotube development mechanism.
- Large-scale procedures for the construction and integration of carbon nanotubes into devices and systems with controlled orientation and position.[36]

There are different methods for producing MWNTs or SWNTs. Electric arc discharge, laser vaporization, and chemical vapor deposition (CVD) However, with the CVD process, it is difficult to get high-quality CNTs.[38, 39] These processes are well-known methods for producing a wide range of CNTs. The choice of synthesis method depends on the specific requirements of the intended application.[40, 41]

Electric arc discharge

The tubes were created using an arc-discharge evaporation approach similar to the one used to create fullerenes.[22] This ancient technique of producing arcs with electric current was first employed to create CNTs.

The arc discharge method is known for producing high yields of carbon nanotubes and is particularly suitable for multi-walled carbon nanotube synthesis. However, the process can also generate other carbon structures, and additional steps are often necessary to separate and purify the desired carbon nanotubes.[42]

In this technique, the chamber is made up of two electrodes that can be positioned horizontally or vertically; one (anode) is filled with powdered carbon source and the catalyst, while the other (cathode) is normally a pure graphite rod, which is the source of carbon atoms for the nanotube. The chamber is either filled with gas such as helium or argon (The role of the gas is to create an environment free of oxygen and other reactive gases that could interfere with the process and also to stabilize the electric arc and thermalize the sublimation carbon atoms, allowing the CNT to form during the deposition phase).[43] After turning on the power supply (AC or DC), the electrodes are brought into contact to create an arc and are maintained at an intermittent spacing of 1-2 mm to achieve a constant discharge. A high electrical current is passed between the graphite electrodes. The arc current produces plasma at extremely high temperatures (4000-6000 K) this is not enough for the carbon precursor contained within the anode to sublime during the sublimation the pressure runs very high as carbon atoms are grouped in the gas phase and migrate towards the cathode, where they cool down and condense to form carbon nanoparticles because of

the temperature differential. After a few minutes of arc application, the discharge stops, and the cathodic deposit, which includes a mixture of CNTs, ash, amorphous carbon, and other carbonaceous structures, is collected from the chamber walls.[41, 42, 44] Additional purification steps, such as acid treatment or filtration, may be employed to isolate and enrich the carbon nanotubes. The synthesized carbon nanotubes are then characterized using various techniques, such as electron microscopy, spectroscopy, and other analytical methods, to assess their quality, structure, and properties.[45] Fig 7 displays a schematic of an arc discharge chamber.[45-47]

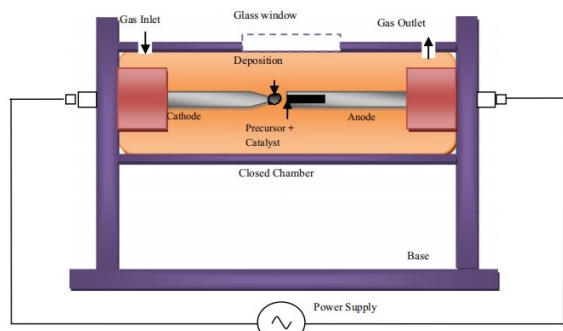


Figure 7 Schematic of an arc discharge setup.

Laser ablation method

Laser ablation is one of the methods used to synthesize carbon nanotubes (CNTs). The laser ablation method works by vaporizing a sample of graphite with laser irradiation in an inert environment. A graphite target is put in the center of a long quartz tube positioned in a temperature-controlled furnace. After the closed tube has been evacuated, the furnace is heated to 1200°C. A flowing inert gas such as nitrogen ammonia helium or argon gas fills the tube to keep the pressure at 500 torr.[48] The gas also plays a crucial role in controlling the synthesis and preventing unwanted reactions. The laser beam spreads across the target surface to provide a smooth and consistent vaporization surface. The high-energy laser ablation creates a plasma plume, which is a mixture of highly energetic electrons, ions, and neutral species. The carbon species in the plasma are produced by laser vaporization and are carried by the moving gas from the high-temperature zone and deposited on a spherical water-cooled copper collector.[36, 49, 50] Dust containing nanotubes is collected from the apparatus's water-cooled copper collector, the walls of the quartz tube, and the downstream face of the graphite target.[36] The laser ablation device, like the arc-discharge approach, may generate either MWCNTs or SWCNTs. SWCNTs are created by adding a small quantity of catalyst to the graphite target.[51, 52] A schematic diagram of this method is given in Fig 8.[36]

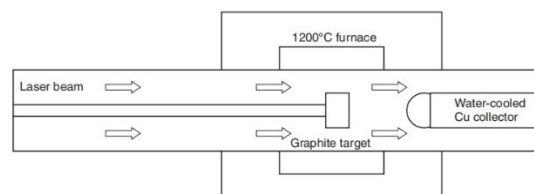


Figure 8 Schematic of particle generation procedure in the laser ablation process

The primary benefit of employing Pulsed laser ablation in liquid (PLAL) is that it does not need vacuum equipment to produce NPs, making it a low-cost and easy process. Furthermore, the particles produced by this process are easily collected and of high purity. The diameter distribution of SWNTs produced using this approach ranges between 1.0 and 1.6 nm. Scientists are attempting to increase laser ablation because of the high quality of nanotubes produced by this process.[50]

However, the PLAL approach has many disadvantages, including a low yield of ablated nanoparticles, large particle aggregations, and agglomeration as well as its difficulty in controlling size distribution.[52, 53] The length of MWNT generated by laser ablation is significantly shorter than that produced by the arc discharge approach. As a result, this method does not appear to be suitable for the synthesis of MWNT.[50]

The characteristics of nanomaterials created by laser ablation of solids in liquids are determined by two factors: first, the laser parameters such as wavelength, pulse energy, exposure period, and laser repetition rate. Second, the material parameters, which include the bulk target, solvent, substances, as well as the system temperature and pressure.[54]

Chemical vapor deposition (CVD)

Chemical Vapor Deposition (CVD) is considered the most acceptable and promising approach for producing carbon nanotubes because it offers lower processing equipment costs, better total manufacturing yield, and considerably simpler scale-up. It operates at lower temperatures (300-1200°C) and pressures, which can be very advantageous for large-scale CNT manufacture.[55]

Catalytic chemical vapor deposition (CCVD)—either thermal or plasma-enhanced (PE) oxygen-helped CVD, water-assisted CVD, microwave plasma (MPECVD), radiofrequency CVD (RF-CVD), or hot-filament (HFCVD) are all examples of CVD. However, catalytic chemical vapor deposition (CCVD) is the current standard approach for producing carbon nanotubes.[28]

The technique requires passing a hydrocarbon vapor (usually 15-60 minutes) through a tubular

reactor containing a catalyst material (typically transition metal nanoparticles such as iron, nickel, or cobalt) at a sufficiently high temperature (600-1200 °C) or the presence of plasma to degrade the hydrocarbon like methane (CH_4), ethylene (C_2H_4), or acetylene (C_2H_2). CNTs form on the catalyst in the reactor and are collected after the system is cooled to room temperature. In the case of a liquid hydrocarbon (benzene, alcohol, etc.), the liquid is heated in a flask, and an inert gas flows through it, carrying the hydrocarbon vapor into the reaction zone. If a solid hydrocarbon is to be utilized as the CNT precursor, it can be immediately stored in the reaction tube's low-temperature zone. Volatile materials (camphor, naphthalene, ferrocene, etc.) directly convert from solid to vapor and perform CVD while passing over the high-temperature zone catalyst.[56, 57] Catalyst precursors in CVD, like CNT precursors, can be employed in any form: solid, liquid, or gas, and can be put inside the reactor or supplied from outside. At an appropriate temperature, hydrolysis of the catalyst vapor releases metal nanoparticles directly (this is known as the floating catalyst technique). Alternatively, catalyst-coated substrates can be put in the furnace's hot zone to encourage CNT growth.[58, 59] **Figure 9** shows a schematic diagram of the experimental set-up used for CNT growth by the CVD method in its simplest form.[58, 60]

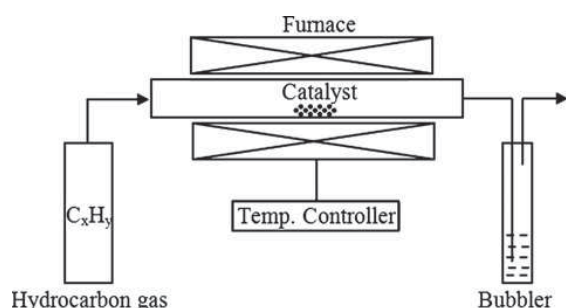


Figure 9 Schematic diagram of a CVD setup in its simplest form.

The general mechanism can be summarized as follows. When a hydrocarbon vapor comes into touch with the heated catalyst, (typically transition metal nanoparticles such as iron, nickel, or cobalt), it decomposes first into carbon and hydrogen. Carbon dissolves in the metal catalyst as hydrogen leaves with another carrier gas or reducing gas. When the temperature rises over the metal's carbon solubility limit, the dissolved carbon particles precipitate and crystallize to form CNTs. The breakdown of hydrocarbons is an exothermic process, while carbon crystallization is an endothermic reaction that is continued by the temperature gradient. The growth conditions, such as temperature, pressure, and precursor gas flow

rate, are carefully controlled to achieve specific CNT properties. The growth time and cooling rate also influence the final characteristics of the CNTs.[61, 62] After the synthesis process, the resulting CNTs can be characterized using techniques like scanning electron microscopy (SEM) or transmission electron microscopy (TEM) to examine their structure, diameter, and length.

There are now two general cases as shown in **Fig 10 (a)**,[61] When the catalyst-substrate interaction is weak (the metal has an acute contact angle with the substrate), hydrocarbon decomposes on the metal's top surface, carbon diffuses down through the metal, and CNT precipitates out across the metal bottom, pushing the entire metal particle off the substrate (as shown in step **(i)**). CNT continues to grow longer and longer as long as the metal's top is open for new hydrocarbon breakdown (concentration gradient occurs in the metal enabling carbon diffusion) **(ii)**. Once the metal is completely coated in extra carbon, its catalytic activity and CNT creation stop **(iii)**. This is referred to as the "tip-growth model." [57, 58, 63]

When the catalyst-substrate interaction is strong (metal has an obtuse contact angle with the substrate) as shown in **Fig 10 (b)**, initial hydrocarbon decomposition and carbon diffusion occur similarly to tip-growth, but the CNT precipitation fails to push the metal particle up, forcing the precipitation to emerge from the metal's apex (farthest from the substrate, having the weakest interaction with the substrate). Carbon first crystallizes as a hemispherical structure (the most advantageous closed-carbon network on a spherical nanoparticle), then rises as a continuous graphitic cylinder. Later hydrocarbon deposition occurs on the metal's lower outer surface, and dissolved carbon diffuses upward. As a result, CNT grows up with the catalyst particle rooted on its base; this is known as the "base-growth model." [57, 58, 63]

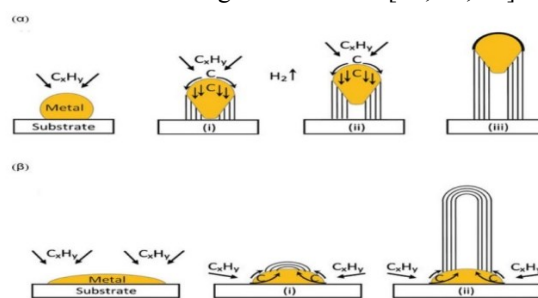


Figure 10 Two growth model diagrams for CNTs: (a) tip-growth mechanism and (b) root-growth mechanism

Carbon nanotube properties

Carbon nanotubes (CNTs) exhibit a range of remarkable properties due to their unique structure, which consists of rolled-up graphene sheets. CNTs are considered to have extraordinarily large surface

areas, enormous aspect ratios, and remarkable mechanical strength. CNTs are also effective combining agents because of their distinct electrical, mechanical, and thermal capabilities. Here are some key properties of carbon nanotubes: electrical, thermal, chemical, mechanical, and optic properties.[24]

Electrical Properties of Carbon Nanotube

CNTs have been shown to have unique conducting properties. These findings were the first to demonstrate that geometric variables like as defects, chirality, various diameters, and the degree of crystallinity of the tubular structure had a significant impact on the electronic characteristics of CNTs.[24]

Carbon nanotubes have amazing electrical characteristics. It has a high electrical conductivity (equivalent to that of copper) due to the sp² connections between carbon atoms. Because of the strength of the bonds, they can also endure high electric currents.

It's worth noting that nanotubes can be metallic or semiconducting. Semiconducting nanotube bandgaps scale inversely with diameter, ranging from around 1.8 eV for extremely tiny diameter tubes to 0.18 eV for the most stable SWCNT. When utilized as interconnects on semi-conducting devices, single-walled nanotubes may transport electrical impulses at rates of up to 10 GHz.[18, 64, 65]

As a result, some nanotubes have conductivities greater than copper, while others act more like silicon. There is a lot of interest in the idea of making nanoscale electrical devices-based carbon nanotubes. Carbon nanotubes are already being employed in a variety of technological applications. Flat panel displays, electron microscopes, sensor devices, and fuel cells are examples of these. [17]

Thermal Properties of carbon nanotube

Carbon nanotubes can resist high temperatures, making them excellent thermal conductors that enable efficient heat transmission. They are thought to be temperature stable up to 28000°C and around 750°C in air. Carbon nanotubes have been demonstrated to transfer more than 15 times the amount of watts per minute than copper lines.[65, 66]

Optical Properties of carbon nanotube

Fluorescence happens when a material absorbs one wavelength of light and responds by releasing a different wavelength. According to certain research, nanotubes absorb and emit light in the near-infrared

range, which might be valuable in biomedical and nanoelectronics applications.[66]

Single-walled nanotubes can be transparent and exhibit unique optical properties, making them promising for applications in transparent conductive films and optoelectronics.[67]

Chemical Properties of carbon nanotube

The chemical reactivity of a CNT is increased when compared to a graphene sheet due to the curved shape of the CNT surface. This curvature causes the π and σ orbitals to mix, resulting in hybridization between the orbitals. The degree of hybridization increases as the diameter of a SWNT decreases. As a result, the π -orbital incompatibility generated by increased curvature is directly connected to carbon nanotube reactivity. As a result, a difference must be made between a nanotube's sidewall and end caps. Similarly, a reduced nanotube diameter resulted in higher reactivity. As a result, nanotubes are often chemically inert.[68]

Mechanical Properties of carbon nanotube

CNTs have a tensile strength of 100 times stronger than steel and an estimated elongation at a break of 20-30%. CNTs possess extraordinary mechanical characteristics. So, they considered it one of the strongest known materials. They are also able to sustain high mechanical stress without distortion. CNTs have a high Young's modulus, suggesting that they are extremely stiff and bending-resistant.[18, 69] They are the fastest oscillators known and are ideal as building pieces for molecular electronics.[20]

Advantages and disadvantages of Carbon Nanotubes (CNTs)

Advantages of Carbon Nanotubes (CNTs)

- a) Extremely lightweight and tiny and have low density, they are a good substitute for metallic wires.
- b) High surface area with strong chemical stability.[70]
- c) The resources needed to make them are numerous, and many may be manufactured with just a small amount of material.
- d) Are resistant to temperature variations, which means they work almost as effectively in extreme cold as they do in excessive heat.
- e) They might be employed as nanocarriers to carry anticancer medicines, genes, and proteins if properly functionalized.
- f) Improve composites' conductive mechanical characteristics.[68]

Disadvantages of Carbon Nanotubes (CNTs)

1. Despite much investigation, experts still do not understand how carbon nanotubes function.
2. They are quite small and tough to work with.
3. Insolubility in solvents especially in a water
4. Now, the method for producing nanotubes is very complex.
5. It would be expensive to apply this new technology and replace the old technology in all possible areas.[68]
6. CNT toxicity must be observed and experimentally tested, and appropriate safeguards must be put in place against potential interactions between CNTs and biological systems.[70]

Application of carbon nanotubes in the textile industry

CNT can be applied to fabric by spray-coating, exhaustion, or just dipping the material in a CNT solution. CNTs have also been built into macroscopic yarns or fibers using various manufacturing methods such as wet spinning, carpet spinning, and aerogel-spun technologies. CNT might be used for a variety of textile purposes, which are discussed in this review.[18, 20] **Fig 11** explains the different applications of CNT in the textile field.[71]



Figure 11 Potential applications for the use of carbon nanotubes in textiles.

Carbon nanotubes in textile finishing

Conductive textiles

Materials made entirely of carbon atoms, such as graphene, carbon black, and carbon nanotubes, can have a broad variety of conductivities, ranging from the insulator diamond to conductors. The purity of carbon compounds is an essential factor for conductivity levels.[18, 72]

Several ways can be employed to create electrically conductive fibers, yarns, or textiles. Other electrically conductive materials that can be employed include metal powders, graphite, carbon black, carbon nanotubes, and naturally conductive polymers such as polyaniline, thiophene, and polypyrrole.[73] Integration of electrical

components with traditional textiles is vital for the fabrication of intelligent clothing for military, work wear, sportswear, transportable power, folding screens, and healthcare applications.

Many researchers used carbon nanotubes to study the electrical conductivity of fibers and textiles. Conductive wool textiles were created by combining various concentrations of MWCNT and carboxylate multi-wall carbon nanotubes (CMWCNT) with citric acid as a cross-linking agent and sodium hypophosphite as a catalyst. Various pretreatment procedures, including potassium permanganate oxidation, protease enzyme treatment, and nanoTiO₂ finishing, have been investigated. To create the optimal conditions for dispersion of the nanotubes, anionic and cationic surfactants such as sodium dodecyl sulfate (SDS) and cetyltrimethylammonium ammonium bromide (CTAB) were also utilized. They concluded that CTAB was more successful in dispersing MWCNT in water. Because of interactions between the carboxyl groups of CMWCNT and the functional groups of wool, CMWCNT-treated samples had ten times the conductivity of MWCNT. Wool processed with protease and treated with 5 g/L CMWCNT was considered the best sample with the maximum electrical conductivity.[74]

PET textiles were changed by treating them with MWCNT. The nanotubes were formed on the surface of water-suspended fibers using the padding technique. Treated materials were flexible and easy to shape, and the network's conductivity was long-lasting.[75]

The electrical characteristics of a Polyester/Cotton woven fabric with an arrangement of carbon nanotubes produced on its surface were investigated. The researchers employed multi-wall carbon nanotubes with a diameter of 9.5 nm, a length of 1.5 m, a purity of 90%, and a specific surface area of 250-300 m² /g. The amount of carbon nanotubes put on the fiber surface determines the conductivity of the PET/CO woven fabric. They concluded that the generated electro-conductive and hydrophobic composite textiles can be employed in a variety of industrial applications.[76]

According to the findings, MWCNT was employed in many studies on the electrical conductivity of textiles. These processes produced conductive yarns and textiles with enough electrical conductivity for usage in the electric and electronic equipment industries.[77]

Electrically conductive textile coatings with varying quantities of carbon nanotubes (CNTs) are demonstrated. Based on the solid weight of the binder, textile coating formulations containing up to 15% CNT were created. The binders are water-based polyacrylate dispersions. The CNTs were blended into the binder dispersion using a

commercially available aqueous CNT dispersion that is compatible with the binder dispersion. Coating formulations with varying CNT concentrations were applied to polyester and cotton woven and knitted textiles using various textile coating processes, including direct coating, transfer coating, and screen printing. The coatings' electrical conductivity increased as CNT content increased. Starting at 3 wt% CNT, the coatings are electrically conductive. In the coatings, the CNT particles form honeycomb-structured networks, demonstrating a high degree of dispersion. The honeycomb structure of CNT particles in the coating forms a conductive network, resulting in low resistance values.[78]

EMI shielding textiles

The widespread use of electrical devices has resulted in major electromagnetic wave radiation (EMR) and electromagnetic interference (EMI) issues. On the one hand, EM contamination from EMR has caused significant harm to human health. EMI, on the other hand, has the potential to disrupt the regular operation of communication systems, and broadcast signals, and even cause information leaks.[79, 80]

Electromagnetic interference (EMI) shielding of radiofrequency radiation is still a major issue in society. In this case, EMI shielding materials (ESMs) have gained popularity due to their capacity to reduce unwanted EM waves via intrinsic shielding processes.[79]

Traditional EMI shielding materials include common metals and their composites such as Al foil, and Cu foil, (The foil is pliable, and can be readily bent or wrapped around objects). which have a high shielding efficacy due to their high conductivity and dielectric constant. While metals offer high EMI shielding qualities, they have limitations such as large weight, quick corrosion, and poor shielding material manufacturing.[79, 80] Because of the need for lightweight EMI shielding systems, conducting polymers and polymer-based conducting composites are gaining popularity as a way to avoid the limitations of ordinary metals for EMI shielding.[68] Lightweight EMI shielding is required to protect the workstation and environment from radiation emitted by computers and telecommunications equipment, as well as to safeguard sensitive electronics.[81] Many variables influence this, including the related conductivity, dielectric constant, and aspect ratio of the filler.

The fundamental method of EMI shielding is reflection. The material must have mobile charge carriers, such as electrons or holes, that interact with the electromagnetic radiation to reflect it. The radiation reflected may be harmful to the environment, particularly to the organisms that are present, making the absorption method better for SE

materials in terms of safety.[82] The reflection mechanism will provide shielding against EM (electromagnetic) radiation if the material is very conductive. However, conductivity is not a need for EMI shielding, although it helps improve an EMI shielding material's reflection mechanism.[83] As shown in **Fig 12a**.[79]

Absorption is a secondary process for EMI shielding that needs the presence of electric or magnetic dipoles to interact with the electromagnetic radiation. It varies according to the thickness of the material. Electric dipoles are provided by materials with a high dielectric constant, while magnetic dipoles are provided by materials with a high magnetic permeability for EMI shielding using absorption.[83] EM wave absorption can transform EM energy into thermal or other sources of energy via dielectric/magnetic loss. In comparison to the dominating process of reflection loss, which may produce secondary pollution, EM wave absorption is a more efficient technique to protect undesired EM waves and minimize undesirable emissions.[84] As seen in **Fig 12b**.[79]

Multiple reflections, or reflections at distinct surfaces or the material's interface, are the third mechanism. Materials having large specific internal surfaces, as well as composites including fillers, exhibit a multiple reflection mechanism. Multiple reflection reduces the overall shielding value if the material is thinner than the skin depth, and it may be ignored if the material is thicker than the skin depth (skin depth is that distance below the surface of a conductor). At greater energies, electromagnetic radiation only reaches the electrical conductor's near surface area. This is referred to as the skin effect. The strength of an electromagnetic wave's penetration reduces exponentially with increasing conductor depth.[83] As seen in **Fig 12c**.[66]

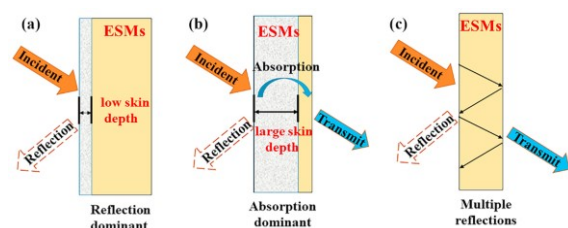


Figure 12 Schematic illustration of EMI shielding mechanisms: (a) reflection-dominant mechanism, (b) absorption-dominant mechanism, and (c) multiple reflections mechanism

Carbon nanotubes are the most often used EMI shielding material, and the accessible free electrons in metals interact with electromagnetic radiation. Carbon nanotubes (CNTs), particularly SWNTs and MWNTs, are a great choice for generating

conductive composites for high-performance EMI shielding materials due to their tiny diameter, high aspect ratio, high conductivity, and mechanical strength.[81] Carbon materials, such as carbon black, carbon filaments, and carbon fibers, are particularly effective as EMI shielding fillers in polymer composites. Carbon nanostructures as fillers in polymer composites are appealing for EMI shielding materials.[68] As shown in Fig 13.[85]

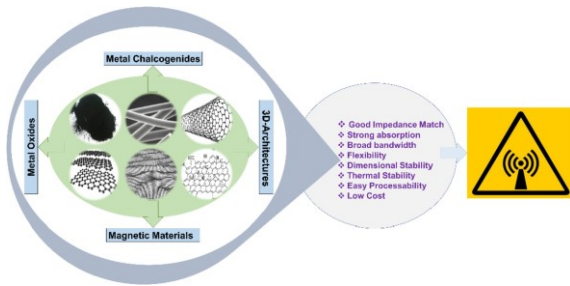


Figure 13 Demonstration of efficacy of carbon-based nanostructures for EMI shielding applications.

Pyrolytic carbon (PyC) and carbon nanotubes were in situ generated on the surface of SiC fibers (Silicon carbide fibers) using chemical vapor deposition to develop flexible electromagnetic shielding materials with thin thickness and low electromagnetic wave reflection. Flexible CNT/SiC textiles with thin thickness could improve EM wave absorption while keeping reflected EM waves. The EMISE of SiC textiles increased as CNTs formed, as did reflection loss. The prepared CNT/ SiCf has a remarkable EMI shielding effect and a strong absorption capability.[86]

CNT, metal nanoparticles, and conductive polymer were used to create electromagnetic shielding (EM) textiles. As conductive materials, silver nanoparticles, nickel-coated carbon fiber filler, MWCNT, and polypyrrole nanoparticles (Ppy) were employed. Fabrics with EM shielding of 95-99.99% have been manufactured using this technology.[87]

Using carbon nanofibers and a tiny amount of CNT inside the polystyrene matrix, a nanocomposite with better microstructure was created and enhanced EMI shielding characteristics. Because of its low cost, high shielding performance, ease of processing, and lightweight, the aforementioned nanocomposite is employed as an excellent EMI shielding material.[88] Fig 14 explains the general mechanism for EMI shields using CNT.[89]

Fire retardant textiles

Fire retardant textiles have become an essential class of materials since they are widely employed in

a variety of areas, from conventional apparel to specialized textiles such as military, automotive, and aerospace applications, as well as safety and protective garments.[90]

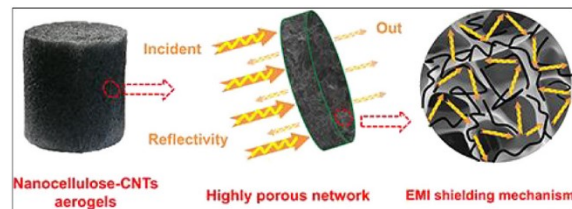


Figure 14 General mechanism for EMI shield using CNT

CNTs have an ultra-high tensile strength along their main longitudinal axis. CNTs' interesting physical features make them an excellent candidate material for developing multi-functional polymer nanocomposites.[91]

Carbon-based nano-additives are an interesting family of nanoparticles that are being studied for flame retardancy. Similarly, polymer/CNT nanocomposite is useful for the development of a structured continuous network. It features a protective layer with crack development that helps flame retardant efficacy. This protective layer appears to act as a heat shield for the original polymer below it. The dispersion of CNTs in nanocomposites is an important step in determining CNT contribution to nanocomposites.[92, 93]

Carbon nanotubes are resistant to flame and thermally anisotropic. Heat may be conducted down the axis of a CNT tube. They are reasonably insulating across the diameter of the tube. The anisotropic characteristic of carbon nanotubes allows heat to be transferred via a layer of aligned carbon nanotubes in textiles and partially diverted to a cool storage tank, protecting the wearer and firefighters from weariness and heat stress.[18]

Carbon nanotube integration into polymer matrix substances, a tiny quantity (typically 5 wt%) of carbon nanotubes has been claimed to lessen fire hazards for a wide range of materials such as polypropylene, polyamides, polyimides, polystyrene, polyaniline, epoxy, and polyurethane, which has resulted in a range of flame-retardant nanocomposites. As a consequence, CNT is an effective filler for increasing the potential of generated polymer nanocomposites.[91, 92]

CNTs were modified with poly-butyl acrylate using a surface grafting method and then the PBA-grafted CNTs were applied to cotton fabrics using a common dipping-drying-curing finishing procedure. CNTs-treated cotton samples were hung on a metal supporter, and then the samples were ignited with a lighter simultaneously. As shown in Fig 15. The untreated cotton sample quickly catches

fire, and as it burns, the untreated cotton sample burns to ashes. The CNTs coated cotton, on the other hand, did not burn and was just charred at the edge, generating a stiff sinter.[93]

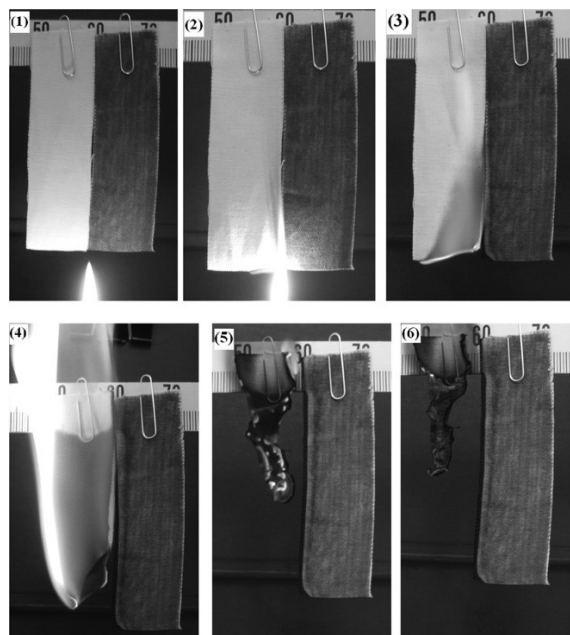


Figure 15 Flammability comparison of pristine cotton fabrics (left) and CNTs coated cotton fabrics over time (right, treated with 5% CNTs-PBA composites).

Melt blending was used to create MWNT/polypropylene composites with no organic treatment or other additives. The inclusion of MWNT increased the fire retardant effectiveness of polypropylene: the peak heat release rate of composites containing 1 vol% MWNT is lowered by about 73% when compared to polypropylene alone.[91]

Cotton fabric with carbon nanotubes inserted in it is more flame-resistant and thermally stable than raw fabrics. MWCNTs were stabilized on a cotton surface using vinyl phosphonic acid monomer as a cross-linking agent and benzophenone as a catalyst to create a flame-retardant coating on the cotton by UV irradiation. They observed that direct usage and stabilization of CNT resulted in high-efficiency flame retardant finishing of cotton textiles and enhancement of their thermal qualities.[94]

MWCNT was electro-spun into polyurethane fibers as a flame retardant. Surfaces of the MWCNT were oxy-fluorinated to increase dispersity in polyurethane fibers. MWCNT encouraged the production of a burned layer as a protective coating to prevent polyurethane breakdown by oxygen radicals. Carbon nanotubes can be utilized to improve the flame retardancy of textiles and composites.[95]

Crease-resistant fabrics

Crease-resistant finishing of fabric is an essential treatment. Cotton textiles' crease resistance and strength are increased by incorporating carbon nanotubes and carboxylate CNTs into the cellulosic chains.[96, 97]

Like other nanomaterials, it is predicted that greater WRA can be obtained by cross-linking CNTs with cellulosic chains using a cross-linking reagent such as Poly carboxylic acids. One of the studies includes using succinic acid and SHP as a catalyst in conjunction with CNTs to improve cross-linking efficiency. Crosslinking lowers the flexibility of cellulose chains and inhibits their ability to move, raising the WRA. Research was carried out to examine the WRA of CNT-embedded textiles with cross-linked fabrics at different CNT concentrations. At a CNT concentration of 1500 ppm, the WRA of cross-linked textiles was found to be greater than that of CNT-embedded raw fabrics. However, when the CNT concentration was increased over 250 ppm, the WRA of CNT-embedded textiles increased significantly. More study is needed to get a better understanding of CNTs' capacity to provide anti-wrinkling qualities.[98]

Water repellence textiles

The "lotus effect" produces ultrahydrophobic surfaces with water contact angles greater than 150 °C, resulting in highly water-resistant fabrics.[99]

The aligned carbon nanotubes exhibit superhydrophobic characteristics due to the CNT nanostructures. CNT treatment on the surface of cotton textiles creates an artificial lotus leaf structure that roughens the surface of the treated cotton and makes the fabric superhydrophobic with water contact angles of more than 150°.[93]

We present an unusual superhydrophobic surface that can withstand physically and chemically severe circumstances. While some of the CNTs have been attached to the poly-dimethyl siloxane (PDMS) and an adhesive multilayer adhered to a substrate, the remaining sections are exposed on the surface. The exposed CNTs and PDMS on the surface are both hydrophobic, and the surface is superhydrophobic due to the rough morphology of the CNTs. The contact angles of the created CNT-implanted PDMS/adhesive (CIPA) surfaces exceeded 160 as shown in Fig 16.[100]

Superhydrophobic finishing with Nafion-MWCNTs coating resulted in long-lasting electromagnetic interference shielding cotton textiles. For MWCNTs, Nafion, a perfluoro sulfonated polymer, has a low surface energy and strong dispersion capability. The uniform

distribution of MWCNTs benefits not only the formation of a connective conductive network, which improves the electrical conductivity and shielding performance of the cotton fabric but also the construction of a nano-micrometer multiple-scale structure, which is required for a superhydrophobic surface. **Fig 17** explains the formation of Nafion-MWCNTs. The final fabric has a good shielding efficacy of 9.0 dB and a water contact angle of 154.6° after 6 cycles of Nafion-MWCNTs deposition.[101]

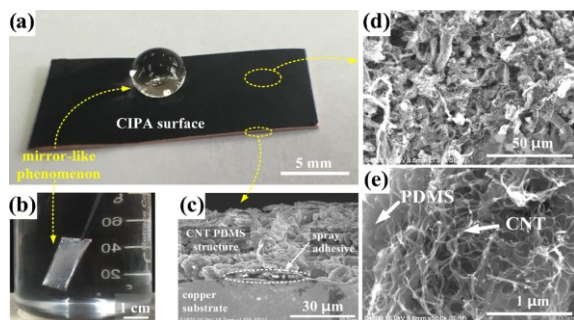


Figure 16 (a) Photo of a fabricated CIPA layer formed on a copper substrate. (b) Photo of the specimen dipped into water. (c) SEM image of a cross-section of the CIPA layer. (d,e) SEM images at the surface of the CIPA layer

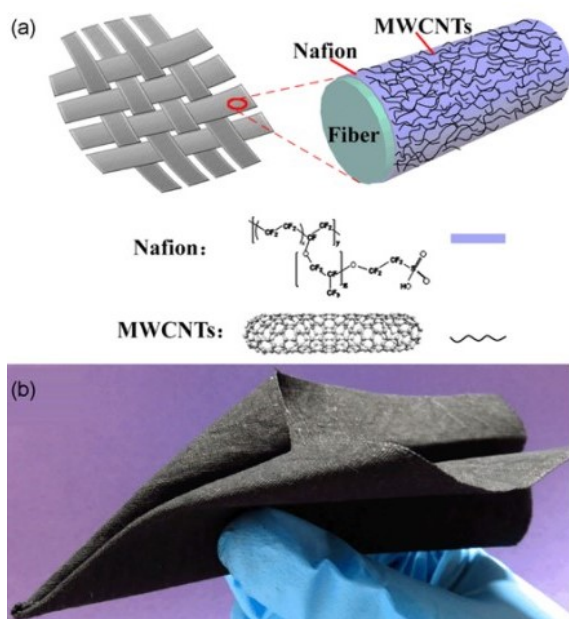


Figure 17 Structural schematic (a) and (b) photograph of cotton fabric coated with Nafion-MWCNTs.

UV protection textiles

UV light is electromagnetic radiation with a wavelength shorter than visible light but longer than X-rays. The sun emits UV radiation. UV radiation is a form of electromagnetic energy. UVR is

classified into three wavelength ranges: 320-400 nm, 290-320 nm, and 200-290 nm, which correspond to UVA, UVB, and UVC and UVA are present in 95% of sunlight and 5% UVB, which may come into contact with human skin.[102]

The chemical structure of inorganic UV blockers, as well as their size, shape, crystallinity degree, and crystal form, all have an impact on the protective mechanism. However, because UV blockers are primarily intended to protect the skin from UV radiation, their major function when utilized in clothing is to prevent UV rays from passing through the textile material in both direct and indirect ways.[103] To be effective, UV protective apparel should be performed by UV light absorption and reflection/scattering by the garment surface.[104]

CNT network defense has been created on the surface of cotton fibers, and cotton textiles with 0.25% CNT demonstrate extremely high UV protection. CNTs could increase the UV-blocking capabilities of polymer materials. The coloring effect is a disadvantage of employing CNT in textiles. Cotton materials will become black after treatment. It is recommended to mix the CNT with additional UV-blocking chemicals to reduce the coloring impact of the CNT on fabrics.[93]

MWCNTs show excellent UV blocking properties and could be integrated into the textile matrix by coating with polymer solution. The UPF of coated cotton fabric with just polyurethane (PU) solution was 46 (good, >40), compared to untreated cloth. UV transmission of MWCNT-coated textiles was nearly small, indicating that MWCNT-containing polymer-coated fabrics might protect the wearer from both UVA and UVB radiation. The UV protection factor of treated cloth has risen as MWCNT concentration in PU solution has increased. The UPF rating of coated fabric containing 1.00 wt% MWCNT-containing polymer was 174, whereas the UPF rating of coated fabric containing 2.5 wt% MWCNT-containing polymer was 421. The outstanding UV-blocking properties of MWCNT resulted in a very high UPF rating for carbon nanotubes with PU coating.[104] The coating protects cotton garments from UV radiation by producing a strong, wide absorption band in the 280-400 nm range.[93, 105]

Anti-microbial textile

Many fabrics used in hospitals or hotels are at risk of cross-infection or sickness transmission caused by microorganisms. In the textile business, fabrics for safe or beneficial usage are critical. Antimicrobial qualities can be given to textile materials in general by chemical techniques or by physically integrating functional agents into

textiles, in addition to the use of nanoparticles in textile finishing.[102]

SWNT (highly pure single-walled carbon nanotubes) has significant antibacterial action and is considerably more hazardous to bacteria than MWNT.[106] Longer SWCNT aggregated more successfully with bacterial cells, but short SWCNT tended to assemble without engaging many bacterial cells. Cell death is caused by bacterial cell aggregation and CNT.[107]

It has been reported that a microwave-assisted synthesis technique is used to cover carboxylate SWCNTs with Ag-NPs for increased antibacterial activity. The microwave-assisted technique decreases the silver preparation in 40 seconds, resulting in the formation of AgNPs with a size of roughly 60 nm on SWCNTs as demonstrated in **Fig 18**. The preparation of this previous composite and coating of cotton fabric is shown in **Fig 19**. [108]

Anti-bacterial activity measurements show that Ag-SWCNTs nanocomposite coated cotton fabric has better and longer-lasting anti-bacterial activity against *E. coli* as a gram-negative pathogenic bacteria and *S. aureus* as a gram-positive pathogenic bacteria than cotton fabric coated with pure SWCNTs or Ag-NPs individually.[108]

Crosslinking multi-walled carbon nanotubes (MWCNTs) with cotton fabric was accomplished. The polymer 3-Glycidoxypropyltrimethoxy silane (GPTMS) was utilized to stabilize and modify the surfaces of MWCNTs. The tannic acid in the finishing mix gives long-term functionality to the treated surface. The MWCNTs-GPTMS nanocomposite fabric post-treated with tannic acid demonstrated remarkable antibacterial properties, with the maximum inhibition zones for *Staphylococcus aureus* and *Escherichia coli* (26 mm, 24 mm).[109]

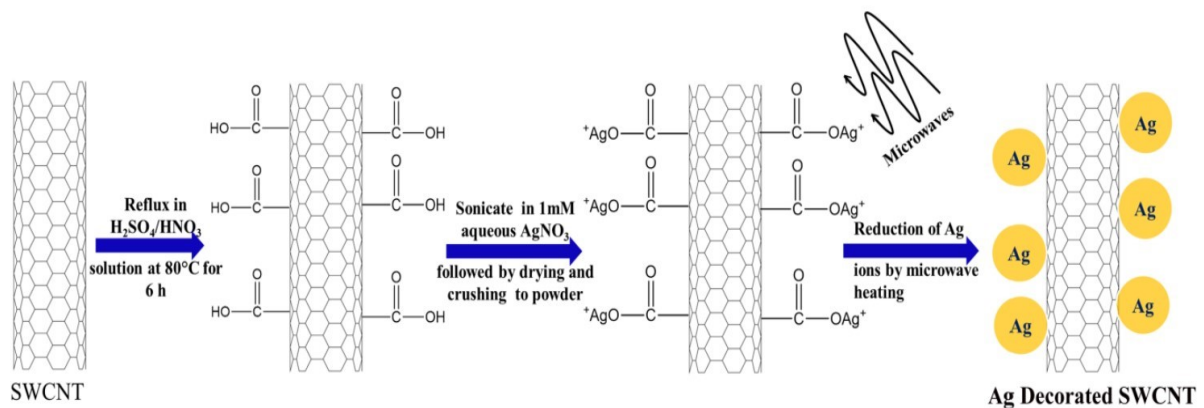


Figure 18 Diagram of functionalization of SWCNTs and decoration of Ag-NPs on SWCNTs by microwave irradiation.

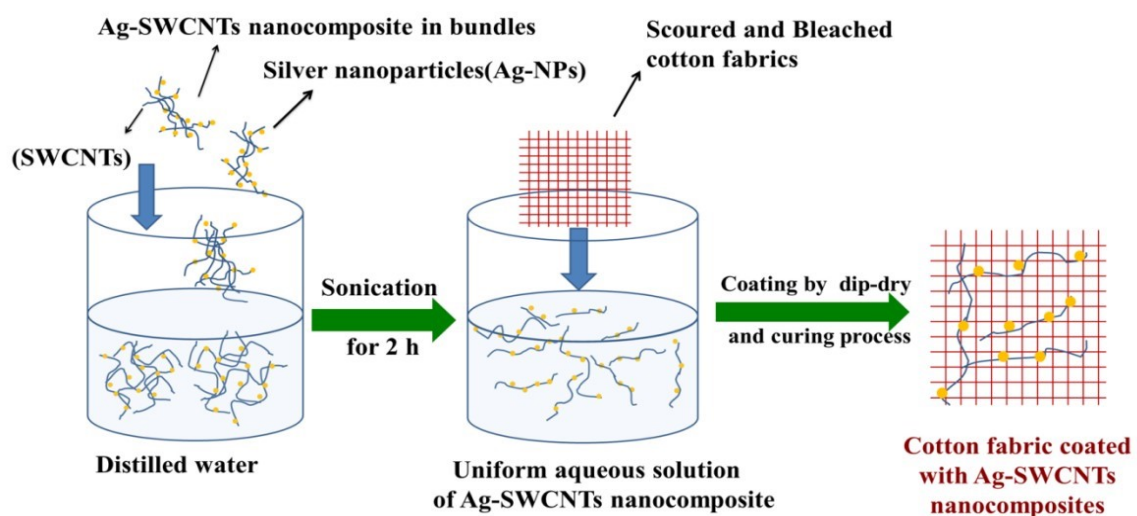


Figure 19 Diagram of preparation aqueous dispersion of Ag-SWCNTs nanocomposites and deposition on cotton fabric.

The microwave synthesis green approach was used to create a smart multifunctional lightweight bismuth oxide (Bi₂O₃) impregnated MWCNT-based bandage. The new material's specific shape has prevented the development of these harmful microorganisms. When bacteria came into touch with the created substance, it may have penetrated through its cell membrane and successfully inhibited the growth of the bacterium. The nanocomposite's high surface area to volume ratio may have encouraged the combined material's significant interaction with biological systems.[110]

The effect of plasma pretreatment on the absorption of carboxylate carbon nanotubes on the surface of cotton textiles was also explored. CNT was applied by exhaustion technique on plasma-pretreated cotton fabric. It was discovered that the plasma treatment improves CNT absorption by cotton fabric. Cotton fabric's antibacterial activity was also enhanced when it was treated using low-temperature plasma and stabilized with CNT.[111]

ZnO-1, 2, 3, 4-butane tetracarboxylic acid (BTCA) and ZnO-BTCA-carbon nanotube (CNT) composites were created. Separately, the synthesized materials were pad-dry-cure coated on cotton fabric. The materials were tested for gram-positive and gram-negative *Staphylococcus aureus* and *Escherichia coli*. They concluded that the ZnO-BTCA-CNT-coated cloth had much higher antibacterial activity than the ZnO-BTCA-coated fabric.[112]

Carbon Nanotubes in Textile Printing

CNTs were employed in printing procedures to impart special functionality to fabrics.[113] The purpose of this research was to develop CNT-based multifunctional inks capable of imparting functional antistatic and antibacterial capabilities to printed fabrics.

AquaCyl, a commercial dispersion of CNTs, was modified and utilized for printing to give antistatic and antibacterial qualities to the printed fabrics. The observed performance effects were

enough resistant to repeated washing. Analyses of the particle size distribution of the AquaCyl dispersion show that CNTs are susceptible to agglomeration formation. Because the dispersion includes quantities of agglomerates with diameters of around 12, 66, and 617 nm, it was filtered to remove agglomerates larger than 500 nm. Filtration allows the AquaCyl dispersion to be used in jet printing processes. The incorporation of additives (DBSA, SLS) into the aqueous dispersion improved the antistatic and antibacterial characteristics of the inks. The crosslinking chemicals (Ebecryl 2002 and Esacure DP 250) directly enhanced the dispersion viscosity. The required printing form (paste or ink) was generated by depositing the aqueous dispersion and the crosslinking component.[114]

This research looks at exploring novel material-led ways of wearable communication. CNTs/CNC (cellulose nanocrystals) designs were screen printed onto flexible textile-based substrates to better realize these innovative mediums and processes (Two distinct woven fabrics of 100% cotton (CO) and 65% cotton-35% polyester (CO-PES) were employed).

Controlled acid hydrolysis is used to recover cellulose nanocrystals (CNC) from natural cellulosic materials, and surface sulfate groups provide good colloidal stability. It has polar and nonpolar groups, which may aid dispersion in both a polar and non-polar liquid. We demonstrated a simple technique that does not require inks with a binder, solvent exchange, or high-temperature heat post-process by successfully formulating water-based screen-printing conductive inks with CNTs and CNC, and these printing steps are illustrated in **Fig 20**. Thus, by modifying the solution viscosity, these formulated inks may be applied to different textile printing methods and employed with a broad variety of flexible substrates, including fabrics with roughness. The inherent benefits of fabric properties like as lightness, flexibility, and washability were highlighted.[115]

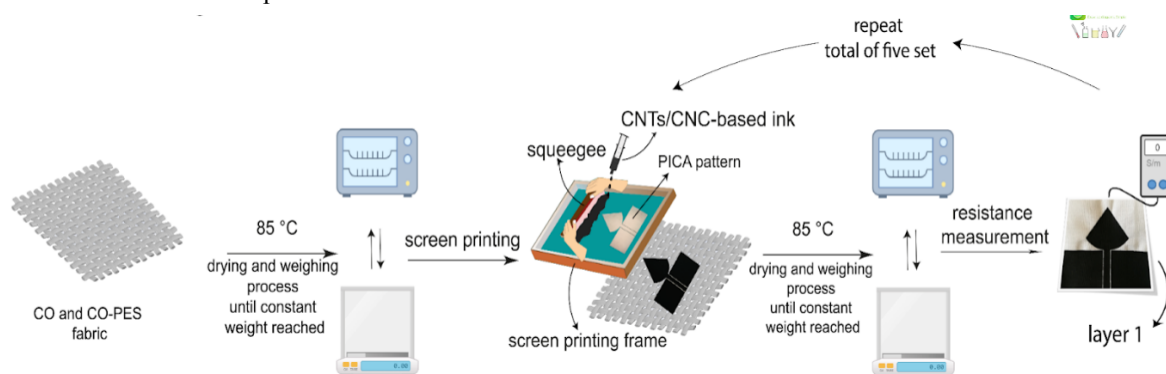


Figure 20 Schematics of screen-printing patterned textile from CNTs/CNC formulations.

Conclusion

Carbon nanotubes are extremely conductive, and lightweight, and have different characteristics, opening a new and exciting field of research in the textile industry. Some well-known CNT qualities were also studied and presented, and it was determined that CNTs had a unique combination of electrical, mechanical, and thermal capabilities. CNTs can be found in smart and electronic textiles, water-repellent textiles and UV protection fabrics, composite reinforcements, and other applications. Furthermore, by combining different types of CNT with polymers at different production methods, CNT might cover a wide spectrum of textile functionalities, from flame-retardant fabrics to antimicrobial textiles. Carbon nanotubes offer both enormous opportunities and severe challenges for fundamental science and nanotechnology research in the future.

Conflict of Interest

The authors declared no competing interests in the publication of this article

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References

- Mahmud, R. and Nabi, F. Application of nanotechnology in the field of textile, *Journal of Polymer and Textile Engineering*, **4**(1) 1-6 (2017).
- Ragheb, A., Mosaad, M., Mahmoud, S. and Abd El-Thaloth, J.I. The impact of nanotechnologies on developing the printing of natural fabrics with pomegranate peel, *Egy. J. Chem.*, **62**(7) 1249-1261 (2019).
- Nasrollahzadeh, M., Sajadi, S.M., Sajjadi, M. and Issaabadi, Z. An introduction to nanotechnology, An introduction to green nanotechnologypp. 1-27, (2019).
- Yousef, M. and Hassabo, A.G. Puncture resistance properties of natural and synthetic fabrics *J. Text. Color. Polym. Sci.*, **18**(2) 211-228 (2021).
- Hassabo, A.G., Ragab, M.M. and Othman, H.A. Ultraviolet protection of cellulosic fabric, *J. Text. Color. Polym. Sci.*, **19**(1) 51-61 (2022).
- Hassabo, A.G., Elmorsy, H., Gamal, N., Sediek, A., Saad, F., Hegazy, B.M. and Othman, H. Applications of nanotechnology in the creation of smart sportswear for enhanced sports performance: Efficiency and comfort, *J. Text. Color. Polym. Sci.*, **20**(1) 11-28 (2023).
- Hassabo, A.G., Reda, E.M., Ghazal, H. and Othman, H.A. Synthesis of agnps and znopns using tea leaves extract and their utilization to improve dyeability, printability and functionality of cotton and wool fabrics, *Inorg. Chem. Commun.*, **150** 110525 (2023).
- Abd El-Aziz, E., El-Desoky, S.S., El-Bahrawy, G.A., Ezat, H.A., Abd El-Rahman, R., abdelraouff, A. and Hassabo, A.G. Nanotechnology to improve the performance of silk fabric, *J. Text. Color. Polym. Sci.*, **21**(1) 33-38 (2024).
- Mohammed, N., Nawar, S.H., Etawy, M.S., Nassar, G.E. and Hassabo, A.G. Nanotechnology and its applications in industry and product design, *J. Text. Color. Polym. Sci.*, - (2024).
- Krifa, M. and Prichard, C. Nanotechnology in textile and apparel research – an overview of technologies and processes, *J. Text. Inst.*, **111**(12) 1778-1793 (2020).
- Liu, Z. and Liang, X.J. Nano-carbons as theranostics, *Theranostics*, **2**(3) 235-7 (2012).
- Delgado, J.L., Herranz, M. and Martín, N. The nano-forms of carbon, *Journal of Materials Chemistry*, **18**(13) (2008).
- Xu, J., Zhang, J.Y., Xu, J., Chang, Y., Shi, F., Zhang, Z. and Zhang, H. Design of functional cotton fabric via modified carbon nanotubes, *Pigment Resin Technology*, **49**(1) 71-78 (2020).
- Shaker, S., Ghazal, H. and Hassabo, A.G. Synthesis of carbon dots and their functional impact on natural and synthetic fabrics, *Egy. J. Chem.*, **67**(13) 179-188 (2024).
- Hassabo, A.G., Zayed, M., Bakr, M., Abd El-Aziz, E. and Othman, H. Applications of supercritical carbon dioxide in textile finishing: A review, *J. Text. Color. Polym. Sci.*, **19**(2) 179-187 (2022).
- Kyotani, T. Synthesis of various types of nano carbons using the template technique, *Bull. Chem. Soc. Jpn.*, **79**(9) 1322-1337 (2006).
- Saifuddin, N., Raziah, A.Z. and Junizah, A.R. Carbon nanotubes: A review on structure and their interaction with proteins, *J. Chem.*, **2013** 1-18 (2013).

18. Shahidi, S. and Moazzenchi, B. Carbon nanotube and its applications in textile industry – a review, *J. Text. Inst.*, **109**(12) 1653-1666 (2018).
19. Dai, H. Carbon nanotubes: Opportunities and challenges, *Surf. Sci.*, **500**(1-3) 218-241 (2002).
20. Ratna, U. and Gokarneshan, N. Textile applications of carbon nano tube, *International Journal of Creative Research Thoughts*, **9**(9) 148-159 (2021).
21. Brown, P. and Stevens, K. Nanofibers and nanotechnology in textiles, Elsevier, (2007).
22. Popov, V. Carbon nanotubes: Properties and application, *Materials Science and Engineering: R: Reports*, **43**(3) 61-102 (2004).
23. Mahmud, R. and Nabi, F. Application of nanotechnology in the field of textile, *IOSR J. Polym. Text. Eng.*, **4**(1) (2017).
24. Ibrahim, K.S. Carbon nanotubes-properties and applications: A review, *Carbon letters*, **14**(3) 131-144 (2013).
25. Yan, J., Fan, Z. and Zhi, L. Functionalized carbon nanotubes and their enhanced polymers, *Polymer science: A comprehensive reference* pp. 439-478, (2012).
26. Abdalla, S., Al-Marzouki, F., Al-Ghamdi, A.A. and Abdel-Daiem, A. Different technical applications of carbon nanotubes, *Nanoscale Res Lett*, **10**(1) 358 (2015).
27. Chen, J., Wei, S. and Xie, H. A brief introduction of carbon nanotubes: History, synthesis, and properties, *Journal of Physics: Conference Series*, IOP Publishing, p. 012184 (2021).
28. Eatemadi, A., Daraee, H., Karimkhanloo, H., Kouhi, M., Zarghami, N., Akbarzadeh, A., Abasi, M., Hanifehpour, Y. and Joo, S.W. Carbon nanotubes: Properties, synthesis, purification, and medical applications, *Nanoscale research letters*, **9** 1-13 (2014).
29. Zhang, M., Yang, M., Nakajima, H., Yudasaka, M., Iijima, S. and Okazaki, T. Diameter-dependent degradation of 11 types of carbon nanotubes: Safety implications, *ACS Applied Nano Materials*, **2**(7) 4293-4301 (2019).
30. Malhotra, B.D., Srivastava, S. and Augustine, S. Biosensors for food toxin detection: Carbon nanotubes and graphene, *MRS Proceedings*, **1725** (2015).
31. Hasnain, M.S. and Nayak, A.K. Classification of carbon nanotubes, *Carbon nanotubes for targeted drug delivery* pp. 11-15, (2019).
32. Aqel, A., El-Nour, K.M.M.A., Ammar, R.A.A. and Al-Warthan, A. Carbon nanotubes, science and technology part (i) structure, synthesis and characterisation, *Arabian Journal of Chemistry*, **5**(1) 1-23 (2012).
33. Pandey, P. and Dahiya, M. Carbon nanotubes: Types, methods of preparation and applications, *Carbon*, **1**(4) 15-21 (2016).
34. Hassan, M.S.B. Nano technology applications in textile to improve puncture resistant of fabrics, *International Design Journal*, **10**(1) 147-154 (2020).
35. O'connell, M.J. Carbon nanotubes: Properties and applications, CRC press, (2018).
36. Singh, C. and Song, W. Carbon nanotube structure, synthesis, and applications, *The toxicology of carbon nanotubes* pp. 1-37, (2012).
37. Venema, L., Meunier, V., Lambin, P. and Dekker, C. Atomic structure of carbon nanotubes from scanning tunneling microscopy, *Physical Review B*, **61**(4) 2991 (2000).
38. Chen, C., Chen, W. and Zhang, Y. Synthesis of carbon nano-tubes by pulsed laser ablation at normal pressure in metal nano-sol, *Physica E: Low-dimensional Systems Nanostructures*, **28**(2) 121-127 (2005).
39. Baddour, C.E. and Briens, C. Carbon nanotube synthesis: A review, *International journal of chemical reactor engineering*, **3**(1) (2005).
40. Awasthi, K., Srivastava, A. and Srivastava, O. Synthesis of carbon nanotubes, *Journal of nanoscience nanotechnology*, **5**(10) 1616-1636 (2005).
41. Paladugu, M.C., Maneesh, K., Nair, P.K. and Haridoss, P. Synthesis of carbon nanotubes by arc discharge in open air, *Journal of nanoscience nanotechnology*, **5**(5) 747-752 (2005).
42. Keidar, M. Factors affecting synthesis of single wall carbon nanotubes in arc discharge, *J. Phys. D: Appl. Phys.*, **40**(8) 2388 (2007).
43. Antisari, M.V., Marazzi, R. and Krsmanovic, R. Synthesis of multiwall carbon nanotubes by electric arc discharge in liquid environments, *Carbon*, **41**(12) 2393-2401 (2003).
44. Ando, Y. and Zhao, X. Synthesis of carbon nanotubes by arc-discharge method, *New diamond frontier carbon technology*, **16**(3) 123-138 (2006).
45. Arora, N. and Sharma, N.N. Arc discharge synthesis of carbon nanotubes: Comprehensive review, *Diamond Relat. Mater.*, **50** 135-150 (2014).

46. Anazawa, K., Shimotani, K., Manabe, C., Watanabe, H. and Shimizu, M. High-purity carbon nanotubes synthesis method by an arc discharging in magnetic field, *Appl. Phys. Lett.*, **81**(4) 739-741 (2002).
47. He, D., Zhao, T., Liu, Y., Zhu, J., Yu, G. and Ge, L. The effect of electric current on the synthesis of single-walled carbon nanotubes by temperature controlled arc discharge, *Diamond related materials*, **16**(9) 1722-1726 (2007).
48. Yogesh, G.K., Shukla, S., Sastikumar, D. and Koinkar, P. Progress in pulsed laser ablation in liquid (plal) technique for the synthesis of carbon nanomaterials: A review, *Applied Physics A*, **127** 1-40 (2021).
49. Vander Wal, R.L., Berger, G. and Tichich, T. Carbon nanotube synthesis in a flame using laser ablation for in situ catalyst generation, *Applied Physics A*, **77** 885-889 (2003).
50. Varshney, K. Carbon nanotubes: A review on synthesis, properties and applications, *International journal of engineering research general science*, **2**(4) 660-677 (2014).
51. Kuo, T., Chi, C. and Lin, I. Synthesis of carbon nanotubes by laser ablation of graphites at room temperature, *Japanese Journal of Applied Physics*, **40**(12R) 7147 (2001).
52. Ismail, R.A., Mohsin, M.H., Ali, A.K., Hassoon, K.I. and Erten-Ela, S. Preparation and characterization of carbon nanotubes by pulsed laser ablation in water for optoelectronic application, *Physica E: Low-dimensional Systems Nanostructures*, **119** 113997 (2020).
53. Kim, M., Osone, S., Kim, T., Higashi, H. and Seto, T. Synthesis of nanoparticles by laser ablation: A review, *KONA Powder Particle Journal*, **34** 80-90 (2017).
54. Ganash, E.A., Al-Jabarti, G.A. and Altuwirqi, R.M. The synthesis of carbon-based nanomaterials by pulsed laser ablation in water, *Materials Research Express*, **7**(1) 015002 (2019).
55. Pant, M., Singh, R., Negi, P., Tiwari, K. and Singh, Y. A comprehensive review on carbon nano-tube synthesis using chemical vapor deposition, *Materials Today: Proceedings*, **46** 11250-11253 (2021).
56. Manawi, Y.M., Ihsanullah, Samara, A., Al-Ansari, T. and Atieh, M.A. A review of carbon nanomaterials' synthesis via the chemical vapor deposition (cvd) method, *Materials*, **11**(5) 822 (2018).
57. See, C.H. and Harris, A.T. A review of carbon nanotube synthesis via fluidized-bed chemical vapor deposition, *Indust. Eng. Chem. Res.*, **46**(4) 997-1012 (2007).
58. Kumar, M. and Ando, Y.J. Chemical vapor deposition of carbon nanotubes: A review on growth mechanism and mass production, *Journal of nanoscience nanotechnology*, **10**(6) 3739-3758 (2010).
59. Danafar, F., Fakhru'l-Razi, A., Salleh, M.A.M. and Biak, D.R.A. Fluidized bed catalytic chemical vapor deposition synthesis of carbon nanotubes—a review, *Chemical Engineering Journal*, **155**(1-2) 37-48 (2009).
60. Ghoranneviss, M. and Elahi, A.S.J. Review of carbon nanotubes production by thermal chemical vapor deposition technique, *Molecular Crystals Liquid Crystals*, **629**(1) 158-164 (2016).
61. Wang, X.-D., Vinodgopal, K. and Dai, G.-P. Synthesis of carbon nanotubes by catalytic chemical vapor deposition, *Perspective of carbon nanotubes*, 1-19 (2019).
62. Nessim, G.D. Properties, synthesis, and growth mechanisms of carbon nanotubes with special focus on thermal chemical vapor deposition, *Nanoscale*, **2**(8) 1306-1323 (2010).
63. Abdullah, H.B., Ramli, I., Ismail, I. and Yusof, N.A. Hydrocarbon sources for the carbon nanotubes production by chemical vapour deposition: A review, *Pertanika J Trop Agric Sci*, **25** 379-396 (2017).
64. Popov, V.N. Carbon nanotubes: Properties and application, *Materials Science Engineering: R: Reports*, **43**(3) 61-102 (2004).
65. Khanna, S. and Islam, N. Carbon nanotubes-properties and applications, *Organic and Medicinal Chemistry*, **7**(1) 1-6 (2018).
66. Sun, X., Zeng, X., Shu, X. and Cheng, Z. Properties and applications of carbon nanotubes, *China Powder Technol*, **6** 29-33 (2001).
67. Brozena, A.H., Kim, M., Powell, L.R. and Wang, Y. Controlling the optical properties of carbon nanotubes with organic colour-centre quantum defects, *Nature Reviews Chemistry*, **3**(6) 375-392 (2019).
68. Pitroda, J., Jethwa, B. and Dave, S. A critical review on carbon nanotubes, *Int. J. Constr. Res. Civ. Eng.*, **2**(5) 36-42 (2016).
69. Coleman, J.N., Khan, U., Blau, W.J. and Gun'ko, Y.K. Small but strong: A review of the mechanical properties of carbon nanotube-polymer composites, *Carbon*, **44**(9) 1624-1652 (2006).
70. Hussein, L.S. and alkufi, H.K. A general review on carbon nanotubes: Advantages, disadvantages,

- biomedical applications and analytical techniques, *Azerbaijan Medical Journal*, **62**(8) (2022).
71. Alhashmi Alamer, F. and Almalki, G.A. Fabrication of conductive fabrics based on swcnts, mwcnts and graphene and their applications: A review, *Polymers*, **14**(24) 5376 (2022).
 72. Åkerfeldt, M., Strååt, M. and Walkenström, P.J. Electrically conductive textile coating with a pedot-pss dispersion and a polyurethane binder, *Textile Research Journal*, **83**(6) 618-627 (2013).
 73. Haji, A., Rahbar, R.S. and Shoushtari, A.M. Improved microwave shielding behavior of carbon nanotube-coated pet fabric using plasma technology, *Appl. Surf. Sci.*, **311** 593-601 (2014).
 74. Nafeie, N., Montazer, M., Nejad, N.H. and Harifi, T. Electrical conductivity of different carbon nanotubes on wool fabric: An investigation on the effects of different dispersing agents and pretreatments, *Colloids Surfaces A: Physicochemical Engineering Aspects*, **497** 81-89 (2016).
 75. Makowski, T., Grala, M., Fortuniak, W., Kowalczyk, D. and Brzezinski, S.J. Electrical properties of hydrophobic polyester and woven fabrics with conducting 3d network of multiwall carbon nanotubes, *Materials Design*, **90** 1026-1033 (2016).
 76. Kowalczyk, D., Fortuniak, W., Mizerska, U., Kaminska, I., Makowski, T., Brzezinski, S. and Piorkowska, E. Modification of cotton fabric with graphene and reduced graphene oxide using sol-gel method, *Cellulose*, **24** 4057-4068 (2017).
 77. Bautista-Quijano, J.R., Pötschke, P., Brünig, H. and Heinrich, G. Strain sensing, electrical and mechanical properties of polycarbonate/multiwall carbon nanotube monofilament fibers fabricated by melt spinning, *Polymer*, **82** 181-189 (2016).
 78. Govaert, F. and Vanneste, M. Preparation and application of conductive textile coatings filled with honeycomb structured carbon nanotubes, *J. Nanomater.*, **2014** 13-13 (2014).
 79. Wu, N., Hu, Q., Wei, R., Mai, X., Naik, N., Pan, D., Guo, Z. and Shi, Z. Review on the electromagnetic interference shielding properties of carbon based materials and their novel composites: Recent progress, challenges and prospects, *Carbon*, **176** 88-105 (2021).
 80. Guan, H. and Chung, D. Absorption-dominant radio-wave attenuation loss of metals and graphite, *Journal of Materials Science*, **56** 8037-8047 (2021).
 81. Li, N., Huang, Y., Du, F., He, X., Lin, X., Gao, H., Ma, Y., Li, F., Chen, Y. and Eklund, P.C. Electromagnetic interference (emi) shielding of single-walled carbon nanotube epoxy composites, *Nano Lett.*, **6**(6) 1141-1145 (2006).
 82. Orasugh, J.T. and Ray, S.S. Functional and structural facts of effective electromagnetic interference shielding materials: A review, *ACS omega*, **8**(9) 8134-8158 (2023).
 83. Jaroszewski, M., Thomas, S. and Rane, A.V. Advanced materials for electromagnetic shielding: Fundamentals, properties, and applications, Wiely, (2018).
 84. Benhamou, S. and Hamouni, M. Determination of reflection loss, absorption loss, internal reflection and shielding effectiveness of a double electromagnetic shield of conductive polymer, *J. Mater. Environ. Sci*, **5**(6) 1982-1987 (2014).
 85. Wang, C., Murugadoss, V., Kong, J., He, Z., Mai, X., Shao, Q., Chen, Y., Guo, L., Liu, C. and Angaiah, S. Overview of carbon nanostructures and nanocomposites for electromagnetic wave shielding, *Carbon*, **140** 696-733 (2018).
 86. Tran, T.Q., Fan, Z., Liu, P., Myint, S.M. and Duong, H.M. Super-strong and highly conductive carbon nanotube ribbons from post-treatment methods, *Carbon*, **99** 407-415 (2016).
 87. Bonaldi, R.R., Siores, E. and Shah, T.J. Characterization of electromagnetic shielding fabrics obtained from carbon nanotube composite coatings, *Synth. Met.*, **187** 1-8 (2014).
 88. Yang, Y., Gupta, M.C. and Dudley, K.L. Towards cost-efficient emi shielding materials using carbon nanostructure-based nanocomposites, *Nanotechnology*, **18**(34) 345701 (2007).
 89. Zhu, G., Giraldo Isaza, L., Huang, B. and Dufresne, A. Multifunctional nanocellulose/carbon nanotube composite aerogels for high-efficiency electromagnetic interference shielding, *ACS Sustainable Chemistry Engineering*, **10**(7) 2397-2408 (2022).
 90. Kundu, C.K., Li, Z., Song, L. and Hu, Y. An overview of fire retardant treatments for synthetic textiles: From traditional approaches to recent applications, *Eur. Polym. J.*, **137** 109911 (2020).
 91. Wang, X., Kalali, E.N., Wan, J.-T. and Wang, D.-Y. Carbon-family materials for flame retardant polymeric materials, *Prog. Polym. Sci.*, **69** 22-46 (2017).
 92. Kausar, A., Rafique, I. and Muhammad, B. Significance of carbon nanotube in flame-retardant polymer/cnt composite: A review, *Polymer-Plastics Technology Engineering*, **56**(5) 470-487 (2017).

93. Liu, Y., Wang, X., Qi, K. and Xin, J.H. Functionalization of cotton with carbon nanotubes, *Journal of Materials Chemistry*, **18**(29) 3454-3460 (2008).
94. Gashti, M.P. and Almasian, A. Uv radiation induced flame retardant cellulose fiber by using polyvinylphosphonic acid/carbon nanotube composite coating, *Composit.B: Eng.*, **45**(1) 282-289 (2013).
95. Im, J.S., Bai, B.C., Bae, T.-S., In, S.J. and Lee, Y.-S. Improved anti-oxidation properties of electrospun polyurethane nanofibers achieved by oxyfluorinated multi-walled carbon nanotubes and aluminum hydroxide, *Materials Chemistry Physics*, **126**(3) 685-692 (2011).
96. Harifi, T. and Montazer, M. Past, present and future prospects of cotton cross-linking: New insight into nano particles, *Carbohydrate polymers*, **88**(4) 1125-1140 (2012).
97. Hu, J., Zhu, Y., Huang, H. and Lu, J. Recent advances in shape-memory polymers: Structure, mechanism, functionality, modeling and applications, *Prog. Polym. Sci.*, **37**(12) 1720-1763 (2012).
98. Gulati, S., Kumar, S., Kumar, S., Wadhawan, V. and Batra, K. Wrinkle-resistant fabrics: Nanotechnology in modern textiles, *Handbook of consumer nanoproducts*, Springerpp. 911-928, (2022).
99. Salman, A.A., Metwally, F.A., El-bisi, M.K. and Emara, G. Applications of nanotechnology and advancements in smart wearable textiles: An overview, *Egy. J. Chem.*, **63**(6) 2177-2184 (2020).
100. Jung, K.K., Jung, Y., Choi, C.J. and Ko, J.S. Highly reliable superhydrophobic surface with carbon nanotubes immobilized on a pdms/adhesive multilayer, *ACS omega*, **3**(10) 12956-12966 (2018).
101. Zou, L., Lan, C., Li, X., Zhang, S., Qiu, Y. and Ma, Y. Superhydrophobization of cotton fabric with multiwalled carbon nanotubes for durable electromagnetic interference shielding, *Fibers Polymers*, **16** 2158-2164 (2015).
102. Shahin, A., Nabil-Adam, A., Shreadah, M.A., Elnagar, K. and Osman, H. Application of printing and finishing cotton fabrics with natural dyes (a review), *Egy. J. Chem.*, **65**(11) 341-358 (2022).
103. Hassabo, A.G. and Ragab, M. Ultraviolet protection of cellulosic fabric, *Journal of Textiles, Coloration Polymer Science*, **19**(1) 51-61 (2022).
104. Mondal, S. Nanomaterials for uv protective textiles, *J. Indust. Text.*, **51**(4_suppl) 5592S-5621S (2022).
105. Mondal, S. and Hu, J. A novel approach to excellent uv protecting cotton fabric with functionalized mwnt containing water vapor permeable pu coating, *J. Appl. Polym. Sci.*, **103**(5) 3370-3376 (2007).
106. Kang, S., Herzberg, M., Rodrigues, D.F. and Elimelech, M. Antibacterial effects of carbon nanotubes: Size does matter!, *Langmuir*, **24**(13) 6409-6413 (2008).
107. Yang, C., Mamouni, J., Tang, Y. and Yang, L. Antimicrobial activity of single-walled carbon nanotubes: Length effect, *Langmuir*, **26**(20) 16013-16019 (2010).
108. Kumar, A., Dalal, J., Dahiya, S., Punia, R., Sharma, K., Ohlan, A. and Maan, A. In situ decoration of silver nanoparticles on single-walled carbon nanotubes by microwave irradiation for enhanced and durable anti-bacterial finishing on cotton fabric, *Ceram. Int.*, **45**(1) 1011-1019 (2019).
109. Abd El-Hady, M.M., Farouk, A. and Sharaf, S. Multiwalled-carbon-nanotubes (mwcnts)-gptms/tannic-acid-nanocomposite-coated cotton fabric for sustainable antibacterial properties and electrical conductivity, *Coatings*, **12**(2) 178 (2022).
110. Verma, S., Mili, M., Sharma, C., Bajpai, H., Pal, K., Qureshi, D., Hashmi, S. and Srivastava, A. Advanced x-ray shielding and antibacterial smart multipurpose fabric impregnated with polygonal shaped bismuth oxide nanoparticles in carbon nanotubes via green synthesis, *Green Chemistry LettersReviews*, **14**(2) 272-285 (2021).
111. Mojtahed, F., Shahidi, S. and Hezavehi, E. Influence of plasma treatment on cnt absorption of cotton fabric and its electrical conductivity and antibacterial activity, *J. Exp. Nanosci.*, **11**(3) 215-225 (2016).
112. Yazhini, K.B. and Prabu, H.G. Antibacterial activity of cotton coated with zno and zno-cnt composites, *Applied biochemistry biotechnology*, **175** 85-92 (2015).
113. Krucińska, I., Skrzetuska, E. and Urbaniak-Domagala, W. Prototypes of carbon nanotube-based textile sensors manufactured by the screen printing method, *Pulse*, **11** 15 (2012).
114. Krucińska, I., Skrzetuska, E. and Urbaniak-Domagala, W. The use of carbon nanotubes in textile printing, *J. Appl. Polym. Sci.*, **121**(1) 483-490 (2011).
115. Ibanez Labiano, I., Arslan, D., Ozden Yenigun, E., Asadi, A., Cebeci, H. and Alomainy, A. Screen printing carbon nanotubes textiles antennas for smart wearables, *Sensors*, **21**(14) 4934 (2021).

الأنابيب الكربونية النانوية: الهيكل، التخليق، التثبيت، الخواص، وتطبيقات النسيج (مراجعة)

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المستخلص:

الأنابيب الكربونية النانوية هي واحدة من أبرز الابتكارات في عالم التكنولوجيا النانوية. تم دراسة أنابيب النانوتكنولوجيا الكربونية بشكل مكثف من قبل خبراء عدة حول العالم على مدى العقدين الماضيين نظرًا لإمكاناتها الهائلة في مجموعة متنوعة من المجالات التقنية مثل التكنولوجيا النانوية الإلكترونية، والتكنولوجيا الحيوية، وعلم المواد، والبوليمرات، والمركبات، وصناعة النسيج بسبب خصائصها المتقدمة في التبلور البللوري والكهربائية والميكانيكية والحرارية. يمكن تحقيق تخليق الأنابيب الكربونية النانوية باستخدام مجموعة متنوعة من الطرق، مثل عملية التفريغ بالقوس الكهربائي وترسب بخار كيميائي (CVD) وتبخير بالليزر. هناك ثلاثة أنواع من أنابيب الكربونية النانوتكنولوجيا الجدارية: مفردة، مزدوجة ومتعددة الجدران. يركز الدراسة الحالية على تخليق الأنابيب الكربونية النانوية وتثبيتها وخصائصها وتطبيقاتها.

الكلمات المفتاحية: الأنابيب الكربونية النانوية ، التثبيت، تطبيقات النسيج