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A Review

Carbon nanotubes a promising new generation drug: A detailed journey in biochemical and biomedical fields

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Carbon nanotubes (CNTs), which are well known for their multipurpose uses and their place in nanotechnology have particularly received much attention. The present review paper aims to present a summary of the current state of knowledge regarding carbon nanotubes, their history, architecture, fabrication techniques and uses. CNTs were first discovered in 1991 and have been investigated for application in a broad range of industries because of their remarkable mechanical, electrical and thermal characteristics. The synthesis techniques including arc discharge, chemical vapor deposition, and laser ablation of CNTs have been further developed to optimise the quality and end use of the nanotubes. Moreover, the paper covers the antibacterial and antifungal activities of CNTs, as well as their mechanism of action based on evaluations of bacterial and fungal strains, the physical and chemical nature, and the extremely large surface area of CNTs, which is said to disrupt the cell membrane of microbes. Novelty on the surface modification in the past years has expanded the availability of biomedical application such as drug carriers and antibacterial layer. The review also considers the issues concerning the CNT dispersion and the environmental aspects related to the application of CNTs. This paper highlights the progress that has been made in the field of CNTs and these help to underpin the future of nanotechnology and materials science.

Keywords: Antifungal action, Antimicrobial activity, Biochemical potential, Biomedical application, Carbon Nanotubes

Introduction of Carbon nanotubes (CNTs)

Due to their special qualities and uses in the field of nanotechnology, a lot of attention has been garnered by carbon nanotubes and carbon nanofibers. Carbon is one of the main components of CNTs. It is an element that can be found everywhere and in everything. Compounds are more easily formed by carbon than by any other element due to its outermost valence electrons that are only partially occupied. Carbon nanotubes (CNTs) are formed by carbon, which is found in the form of graphite, another type of carbon. In graphite, a suitable arrangement of carbon atoms is made in a planar-layered structure. The carbon atoms are arranged in graphite in a honeycomb hexagonal lattice, with the carbons of each plane spaced 0.142 nm apart and the planes themselves spaced 0.335 nm apart. Graphite can be found in meteorites, igneous rocks, and metamorphic rocks, often associated with micas, calcite, tourmalines, and other minerals. Graphite exists in two geometric forms, called alpha and beta, both of which have similar physical properties: hexagonal geometry and rhombohedral geometry. Following graphite, graphene, another form of carbon, was first reported in 1962 by researcher Bohem. It is composed of a one-atom layer of similar carbon atoms arranged in a two-dimensional honeycomb crystal lattice with a 1:3 carbon atom arrangement, meaning that each carbon atom is coupled with three adjacent carbon atoms. Graphene is shared as a fundamental structural unit by all carbon forms, including graphite, fullerene, charcoal, and carbon nanotubes (CNTs). In 2004, it was found that graphene could be produced from graphite via the scotch tape method. A transparent material, graphene is strong, thin, light, and conducts heat and electricity. Up until 1980, various forms of carbon, such as graphite, diamond, and amorphous carbon, were well-known. After that, it was realized that carbon exists in all forms. Fullerene was discovered by Kroto *et al*. in 1985, introducing a new form of carbon. More recently, in 1991, a form of carbon known as carbon nanotube was discovered[1]. A single-layer graphene rolled into a tube forms Carbon Nanotubes (CNTs). Specific characteristics such as length and diameter are what make CNTs

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important parameters in both applications and research theories. A large aspect ratio is exhibited by CNTs due to their length of up to microns and their diameter range in nanometers. A 1D structure is taken by CNTs, which modifies or adds several appealing qualities, including mechanical, electrical, and molecular ones. Structurally, it resembles a cylindrical molecule with a sp^2-hybridized hexagonal configuration of carbon atoms. Its surface is composed of one or more layers of graphene sheets, while its inside structure is hollow (Table 1).

The first carbon nanotube (CNT) was discovered in 1991. In 1993, the production of a single-wall CNT with a diameter of one nanometer was reported by Iijima and Ichihashi[2]. A report elucidating this discovery was published by Lijima in 1991. The discovery led to a scientific frenzy, and several scientists were motivated to investigate the potential applications of carbon nanotubes. It turns out that carbon nanotubes had been around for far longer than 1991, although Lijima is credited with finding them. A crisp picture of fifty carbon nanotubes produced in the Soviet Union was published in the Journal of Physical Chemistry in 1952 by two bright researchers named Radushkevich and Lukyanovich[S1]. Due to the political climate, this finding was widely disregarded.

Table 1 — Advancement of Carbon nanotubes (CNTs)

Here is the full extended table on the advancement of Carbon Nanotubes (CNTs) from 1991 to the present:

Year	Inventor / Researcher	Main Findings	Ref. No.
1991	Iijima S	First observation of helical microtubules of graphitic carbon — discovery of carbon nanotubes.	01
1992	Ebbesen TW, Ajayan PM	Large-scale synthesis of CNTs, demonstrating potential for bulk production.	S07
1993	Iijima S, Ichihashi T	Discovery of single-shell CNTs of ~1 nm diameter.	02
1995	Guo T, Nikolaev P, Thess A, Colbert DT, Smalley RE	Catalytic growth of single-walled CNTs by laser vaporization.	04
1999	Sinnott SB, Andrews R, Qian D, Rao AM, Mao Z, Dickey EC, Derbyshire F	Proposed a detailed model for CNT growth via chemical vapor deposition (CVD), explaining catalyst–carbon interactions.	10
2003	Terrones M	Comprehensive review of CNT synthesis, properties, and applications, highlighting potential in electronics and composites.	S08
2005	Endo M, Muramatsu H, Hayashi T, Kim YA, Terrones M, Dresselhaus MS	Developed methods for producing pure, clean double-walled CNTs with minimal amorphous carbon.	05
2006	Klumpp C, Kostarelos K, Prato M, Bianco A	Demonstrated functionalized CNTs as nanovectors for therapeutic delivery.	S03
2007	Bell MS, Teo KBK, Milne WI	Identified factors influencing properties of multi-walled CNTs/fibres grown by PECVD.	06
2008	Liu Z, Davis C, Cai W, He L, Chen X, Dai H	Tracked circulation and long-term fate of functionalized CNTs *in vivo* using Raman spectroscopy.	S04
2010	Kumar M, Ando Y	Reviewed CVD growth mechanisms and mass production strategies for CNTs.	09
2011	Duan WH, Wang Q, Collins F	Studied CNT dispersion using SDS surfactants from a binding energy perspective.	12
2012	Zardini HZ, Amiri A, Shanbedi M, Maghrebi M, Baniadam M	Enhanced antibacterial activity of amino acid-functionalized MWCNTs via a simple modification method.	18
2013	Chen H, Wang B, Gao D, Guan M, Zheng L, Ouyang H, Chai Z, Zhao Y, Feng W	Reported broad-spectrum antibacterial activity of CNTs against human gut bacteria.	S13
2014	Wu C, He Q, Zhu A, Li D, Xu M, Yang H, Liu Y	Developed polylysine-functionalized graphene–CNT hybrids for synergistic photo- and chemo-responsive anticancer activity.	28
2015	Karmakar A, Xu Y, Mustafa T, Kannarpady G, Bratton SM, Radominska-Pandya A, Crooks PA, Biris AS	Used functionalized nanographene–CNT systems for enhanced delivery of parthenolide in cancer therapy.	30
2018	Laux P, Riebeling C, Booth AM, Brain JD, Brunner J, Cerrillo C, Creutzenberg O, Estrela-Lopis I, Gebel T, Johanson G, Jungnickel H	Addressed challenges in characterizing environmental fate and effects of CNTs in aquatic systems.	44
2019	Wang X, Liu C, Li H, Zhang H, Ma R, Zhang Q, Yang F, Liao YC, Yuan W, Chen F	Multi-omics analysis revealed novel antifungal mechanisms of graphene oxide–CNT composites against *Fusarium graminearum*.	24
2021	Wang X, Peng F, Cheng C, Chen L, Shi X, Gao X, Li J	Demonstrated synergistic antifungal activity of graphene oxide and fungicides against *Fusarium* head blight.	25
2023	Wasti S, Lee IH, Kim S, Lee JH, Kim H	Reviewed ethical and legal challenges in nanomedical innovations involving CNTs.	S15
2025	Shoyiga HO, Martincigh BS, Nyamori VO	Developed electroconductive ink with reduced graphene oxide–metal oxide–CNT semiconductor for flexible electronics.	03

Carbon nanotubes were discovered by Radushkevich and Lukyanovich, who are credited with the finding that carbon filaments can be hollow and have nanoscale widths. At the yearly 14th Carbon Conference held at Pennsylvania State University in 1979, a presentation containing evidence in support of carbon nanotubes was given by John Abrahamson. It is thought that carbon nanotubes are grown in a low-pressure nitrogen environment and are defined as carbon fibers generated on a carbon anode during arc discharge.

Among the various types of carbon nanotubes (CNTs), superior antimicrobial activity is exhibited by single-walled carbon nanotubes (SWCNTs) due to their enhanced physicochemical properties. Initial insights into the antimicrobial behavior of purified SWCNTs were provided by Kang *et al*., highlighting that bacterial membrane integrity was significantly affected by the purified form of SWCNTs and multi-walled carbon nanotubes (MWCNTs) upon direct contact. Additionally, alterations in morphology and metabolic activities were observed. Their findings indicated that a stronger antimicrobial effect was exhibited by SWCNTs compared to MWCNTs, possibly attributed to their smaller size, resulting in a larger surface area for facilitating bacterial membrane disruption. Moreover, oxidative stress is identified as an additional factor influencing the antimicrobial mechanisms of CNTs. The antimicrobial properties of CNTs, including low wear rates, low friction coefficients, favorable tribological characteristics, and high corrosion resistance, were investigated by Haung *et al*.(2015)[S68]. Studies by Chen *et al*. (2021) revealed that bacterial cell walls are penetrated by SWCNTs, reducing membrane potential, releasing intracellular constituents (DNA and RNA), and ultimately disrupting the bacterial membrane[S2].

The effectiveness of carbon nanomaterials (CNMs) against microbes is dependent on factors such as their makeup, alterations to their surfaces, the targeted microorganisms, and the environment in which they react. Microbial cell walls or membranes are entered by CNMs, causing structural damage, and microbes are physically separated from their supportive surroundings. Moreover, chemical actions against microbes involve interactions with CNMs, resulting in oxidative stress due to harmful substances like reactive oxygen species (ROS) being produced. These interactions between microbes and CNMs promote electron transfer, with oxidative stress being induced independently of ROS as electrons are drawn from the microbial surface, ultimately resulting in the demise of microbial cells[3].

Carbon nanotubes (CNTs) have emerged as revolutionary nanomaterials in the biochemical and biomedical fields, offering exceptional drug delivery potential, biocompatibility, and targeted therapeutic applications. Their unique physicochemical properties, including a high surface area, functionalization flexibility, and efficient cellular penetration, make them ideal candidates for cancer therapy, antimicrobial agents, and regenerative medicine. Recent advancements have demonstrated CNTs' ability to enhance drug bioavailability, cross biological barriers, and precisely target diseased cells, reducing systemic toxicity. For instance, CNT-based nanocarriers have been successfully engineered for targeted chemotherapy, as highlighted in recent studies. Additionally, functionalized CNTs have been explored for gene therapy and biosensing applications, playing a crucial role in next-generation precision medicine. However, biosafety concerns, toxicity issues, and regulatory challenges remain critical areas of ongoing research. As scientists refine their surface chemistry and biodegradation mechanisms, CNTs are set to reshape modern drug delivery systems, marking a paradigm shift in personalized healthcare.

Types of CNTs

Single- walled carbon nanotubes (SWCNTs)

The term single-walled carbon nanotubes (SWNTs) were first described in 1993[2]. A single atomic layer of graphite forming a cylindrical structure is consisted of by single-walled carbon nanotubes. A single cylindrical carbon layer with a diameter of 0.4-2 nm is formed by SWCNTs, depending on the temperature at which they are synthesized. It was found that the diameter of CNTs is increased with higher growth temperature. An armchair, zigzag, chiral, or helical configuration can be had by SWCNTs in their structure. Because of the extremely high surface area of SWCNTs up to 1300 m^2/g, enough room for drug loading and bioconjugation is provided. It is known that medication delivery is more effective with SWCNTs than with MWCNTs. This can be attributed to the ultra-high surface area and effective drug-loading capacity of SWCNTs. It has been discovered

that a longer blood circulation period is exhibited by a SWCNT anticancer medication complex compared to the anticancer drug alone. The increased permeability and retention effect cause a longer and more sustained uptake of the drug by tumor cells[S3-S4,4].

Double-walled carbon nanotubes (DWCNTs)

Double walled carbon nanotubes, or DWCNTs, are composed of two carbon nanotubes that are split apart by an outer tube which is encircled by the inner tube. The inner diameter of the tube is measured to be 1-3 nm, while the outer diameter is measured to be 2-4 nm. Double-walled carbon nanotubes are depicted both internally. More mechanical strength and thermal stability than single-walled carbon nanotubes (SWNTs) are characterized in DWCNTs, in addition to intriguing electrical and optical properties being possessed. Prior to the current synthesis and separation of high-purity samples, relatively little attention had been received by this structure, despite the fact that DWCNTs were identified in 1991 and the first synthesis was reported in 1998. The concentric construction of DWCNTs is noted as a feature, which makes them perfect for nanotube-based sensor systems by enabling the simultaneous exploitation of the high conductivity of the unfunctionalized inner wall and the chemical reactivity of the outer wall. Only the outside wall is exposed to the surrounding chemicals and is therefore deemed suitable for decoration with a high concentration of chemical moieties. The shielding of the outer wall prevents negative effects from being experienced by the inner wall due to functionalization, such as decreased conductivity brought on by the deterioration of the pure sp2 hybridized framework. Although a lot of promise is shown by DWCNTs from an applications- and fundamentals-based perspective, their adoption has remained rather restricted[5,S5].

Multi- walled carbon nanotubes (MWCNTs)

MWCNTs are composed of a hollow core encircled by a number of coaxial cylinders, each of which is formed from a single graphene sheet. Lengths ranging from one to several micrometres, with outer diameters between 100 and 200 nm and inner diameters between 1 and 3 nm, are possessed by MWCNTs. A delocalized electron cloud along the wall is created by the sp2 hybridization in MWCNTs, leading to interactions between neighbouring cylindrical layers in MWCNTs, which result in more structural flaws and reduced flexibility. MWCNT structures can be divided into two classes based on the arrangement of the graphite layers: one is a parchment structure, where a graphene sheet is rolled around it, and the other is known as the Russian doll model, where the layers of graphene sheets are arranged in a concentric structure. Multiwall carbon nanotubes (MWCNTs) can be decolorated by nanoparticles being deposited on their walls or ends. These particles are held together by physical bonding, and they are attributed with potential uses in biosensors, electronic devices, biomedical applications, catalysis, and magnetic data storage. For this objective, a variety of techniques are employed, such as precipitation, high-temperature hydrolysis, or chemical breakdown of a metal precursor[6,S7].

Synthesis of CNTs

It should be noted that the growth of nanotubes is significantly influenced by the size of catalyst particles due to the nano-sized structure of CNTs. This results in a linear increase of the CNT synthesis with increasing catalyst particle size. TNsag has an inverse correlation with mean catalyst size; that is, high particle sizes are not effective for forming SWCNT. Materials can be used to produce catalyst nanoparticles in different approaches. The nature of CNT requirements (for laboratory research, for example), leads to synthesis needs that fall into either SWCNT or MWCNT categories. While other materials may share similar physical properties with the above mentioned CNTs, this form can be prepared relatively easily using local resources; however, issues such as purity and the presence or absence of structural flaws may become critical to their performance. For electronic, mechanical, and thermal applications other than biological sectors are utilized in industry, CNTs should be brightened; perfect flawless without contortion. One example is a study on the parameters influencing MWCNT properties via plasma-accelerated chemical vapor decomposition. As a result, they require high-precision methods of manufacturing. Material synthesis of CNTs depends on many different methods and several ways are known for the growth such as chemical vapor decomposition (CVD), laser ablation method, electric arc discharge method, etc. CNTs have also been able to be fabricated locally at room temperature (37°C) by the chemical oxidative of graphite powder suspension in a solution containing potassium chlorate, HNO_3, and concentrated sulfuric

Table 2 — Synthesis methods of CNTs

Year	Inventor / Researcher	Synthesis Method	Key Features / Findings	Ref. No.
1991	Iijima S	Arc discharge	First observation of CNTs during arc evaporation of graphite; multi-walled CNTs with helical structure.	01
1992	Ebbesen TW, Ajayan PM	Arc discharge (bulk production)	Demonstrated large-scale synthesis of CNTs, showing scalability of arc method.	S07
1993	Iijima S, Ichihashi T	Arc discharge with metal catalyst	Produced single-walled CNTs (~1 nm diameter) using metal catalyst in arc process.	02
1995	Guo T, Nikolaev P, Thess A, Colbert DT, Smalley RE	Laser vaporization	Catalytic growth of SWCNTs by laser ablation of graphite–metal composite targets.	04
2003	Wei J, Ci L, Jiang B, Li Y, Zhang X, Zhu H, Xu C, Wu D	Hydrogen arc discharge	Preparation of highly pure double-walled CNTs.	S05
2003	Terrones M	Multiple methods (review)	Summarised arc discharge, laser ablation, and CVD techniques, with focus on structure–property control.	S08
2007	Bell MS, Teo KBK, Milne WI	Plasma-enhanced CVD (PECVD)	Identified parameters affecting MWCNT/fibre properties in PECVD growth.	06
2010	Kumar M, Ando Y	Chemical vapour deposition (CVD)	Comprehensive review of CVD growth mechanisms and mass production strategies.	09
2010	Tang QY, Shafiq I, Chan YC, Wong NB, Cheung R	Surfactant-assisted dispersion post-synthesis	Studied dispersion and electrical properties of CNTs treated with surfactants in DMAc.	S11
2011	Madani SY, Naderi N, Dissanayake O, Tan A, Seifalian AM	Functionalisation post-synthesis	Discussed CNT functionalisation for drug delivery applications.	S06
2012	Zardini HZ, Amiri A, Shanbedi M, Maghrebi M, Baniadam M	Amino acid functionalisation	Simple method to enhance antibacterial activity of MWCNTs.	18
2025	Shoyiga HO, Martincigh BS, Nyamori VO	Composite ink formulation	Integrated reduced graphene oxide, metal oxide, and CNTs into electroconductive ink for flexible electronics.	03

acid. Iijima first discovered MWCNTs in 1991 by an electric arc method that has already been applied for the formation of fullerenes and carbon fibers. A few of the common methods for carbon nanotube synthesis are described as under (Table 2).

Electric arc discharge method

The tube's synthesis was described by Iijima (1991) as being achieved through the arc discharge evaporation process, which is similar to the previously arranged technique used for synthesizing fullerenes. A yield rate of (>75%) is achieved by the arc discharge process. Carbon nanotubes (CNTs) are produced by arc discharge synthesis at high temperatures (over 1,700) with fewer structural flaws than alternative methods. On the cathode, or negative end, of the carbon base electrode, carbon needles with diameters ranging from 4 to 30 nm and lengths up to 1 mm were created for the purpose of synthesizing carbon nanotubes. The cathode is served by graphite, while evaporating carbon molecules are used as the anode, and the chamber is composed of metal catalysts like iron, nickel, and cobalt. A linked source produces direct current through the arcing process. The temperature of the chamber is reached and pressured to about 4000 K. The power supply is linked to the two graphite rods placed a few mm apart. After the source is turned on and the power is maintained at 100 amps, carbon begins to evaporate and creates a heated plasma. The arc discharge approach for CNT synthesis can be used in two scenarios: synthesis in the presence of catalyst precursors or in the absence of a catalyst. Fe-Ni, Co-Ni, Co-Cu, Ni-Cu, Fe-No, Ni-Ti, and Ni-Y are frequently employed for SWNTs, while MWNTs can be synthesized without the catalyst precursors. The arc was created between two graphite electrodes in a reactor with a helium atmosphere. The main advantage of the arc-discharge method is its ability to produce a lot of nanotubes. This one factor reduces the control over the configuration of the created nanotubes, which impairs the function and characterization of CNT. Since the presence of a metallic catalyst causes CNT to get contaminated, the purification of the product is crucial. In 2014, the net emission coefficient was calculated to investigate the radiative properties of this plasma in CNT synthesis

under the assumption of a local thermodynamic equilibrium and a temperature range from 1000 K to 20,000 K[7]. It was also presented that the absorption coefficient strongly depends on the photodissociation and photoionization process when the temperature is lower than 600 K, and that the radiative recombination process contributes the most in the continuum absorption coefficient, except in the infrared region.

Chemical vapor deposition (CVD)

Nowadays, the most widely used technique for creating CNTs is known as chemical vapor deposition, or CVD. In this procedure, a metal catalyst helps in the thermal breakdown of a hydrocarbon vapor. Carbon filaments production was discovered when cyanogens were passed across red-hot porcelain in 1890 by French scientists[S7]. By the middle of the 20th century, carbon microfibers were developed by a known process called carbon vapor deposition (CVD), where metal catalysts enabled the thermal decomposition of hydrocarbons. In 1952, Radushkevich and Lukyanovich published a series of electron micrographs illustrating tubular carbon filaments of 50–100 nm diameter obtained by thermal decomposition of carbon monoxide on an iron catalyst at 600°C. It involves the passage of a hydrocarbon vapor through a tubular reactor, in which a catalyst material is in the system at a temperature high enough between 600 and 1200°C to decompose the hydrocarbon for a time span of 15 to 60 min. The system will then cool down to room temperature (37°C), and carbon nanotubes (CNTs) formed on the catalyst of the reactor are collected. In the reactor, the liquid hydrocarbons, including benzene, alcohol, and others, are firstly heated up and then purged with an inert gas to carry the hydrocarbon vapor into the reaction zone. If solid hydrocarbon is applied as precursor for carbon nanotubes, it can be stored directly in the low-temperature zone of the reaction tube. Volatile materials directly change from solid to vapor, and it is in this form that CVD is conducted as they are led past the catalyst within the hot zone. Catalyst precursors in CVD can take any form, like CNT precursors. They could be fed into the reactor from outside or even positioned inside properly. They can also be operated in any scale. The floating catalyst method pyrolyzes the catalyst vapor to release metal nanoparticles *in situ* at the right temperature or substrates coated with the catalyst can be placed in the hot zone of the furnace to catalyze the development of CNTs. The size of the catalyst particle controls the formation of single-wall or multi-wall carbon nanotubes (SWCNT or MWCNT, respectively). In general, SWCNTs are grown by particles smaller than a few nm, while MWCNT growth is favored by particles a few tens of nm wide. We have now achieved an order of magnitude growth image, which enables us to address other important issues concerning CNT growth. There are numerous parameters associated with the growth of CNTs that involve not only the hydrocarbon but also the catalyst, temperature, pressure, flow rate of gases, deposition time, and reactor geometry[8].

Laser ablation method

The Laser Ablation process for the synthesis of carbon nanotubes was initially announced by Smalley *et al*. at Rice University in 1995. In this process, carbon is evaporated from a graphite target at 1200°C and 500 tors pressure by a high-power laser. The carbon vapors are transported to a collector by inert gas (argon) from the high-temperature chamber, where deposition upon the flow tube begins. A greater yield is obtained when metal particles are introduced to the graphite target as a catalyst for creating single-walled carbon nanotubes. The setup consists of a quartz tube with graphite as the sample target and argon gas inside. A temperature of 12,000 degrees Celsius is maintained by the furnace. The tube is positioned at one end of a water-cooled copper collector that is placed outside the furnace. Tiny concentrations of cobalt and nickel in the graphite target serve as catalytic nucleation sites for the creation of the nanotubes. The technique entails the target being directed by a strong laser beam to evaporate carbon. The carbon atoms are then carried by the argon in the tube from the high-temperature zone to the cooler copper collector, where they condense into nanotubes that are roughly 100 m long and 10–20 nm in size. The effect of laser wavelength on carbon nanotubes using the laser ablation method was examined at the Institute of Fundamental Technology Research in Poland using a double pulse Nd. YAG laser with a working wavelength of 355 or 1064 nm[S6]. Many parameters, including wavelength dependence, pulse width and repetition rate dependence, energy power/density dependence,

single-laser and multiple sequencing, *etc*., affect the laser ablation process[4].

Solubilization of CNTs in solubilised surfactants

Among nanomaterials, carbon nanotubes are recognized for their remarkable optical, electrical, and mechanical properties. Various applications, including biosensors, composites, field emission devices, electrical components, and probe tips, utilize these characteristics widely[9]. The exceptional mechanical and electrical capabilities of carbon nanotubes (CNTs) are attributed largely to the sp^2-hybridized carbon atoms that form their aromatic sidewall structure. However, this aromatic configuration also generates strong van der Waals (vdW) interactions, particularly π-π stacking, leading to CNT aggregation or bundling. As a result, CNTs are rendered very insoluble in every known solvent, and numerous dispersion strategies have been developed to address this difficulty [10]. Two primary strategies are typically employed to disperse nanotubes: mechanical and chemical techniques. The mechanical approach involves techniques like high-shear mixing and ultrasonication. These methods are time-consuming and not very effective. Furthermore, the study by Lu *et al*. demonstrated that CNTs can be fractured by ultrasonication, which lowers their aspect ratio and affects the stability of their dispersion. On the other hand, chemical techniques are included in the second approach, which involves both covalent and noncovalent methods. Covalent techniques involve the addition of different chemical groups to nanotubes to increase their liquid solubility, whereas chemicals are attached to the surface of the nanotube in the noncovalent method. Benefits are provided by the non-covalent approach since the electrical characteristics of carbon nanotubes are preserved by keeping the graphene π-electron cloud intact[S8]. Currently, dispersing agents, particularly surfactants, are being utilized primarily in the preparation of CNTs. In this review, the preparation of CNTs using anionic and nonionic surfactants such as sodium dodecyl sulfate (SDS), Triton X-100, and Tween 20 will be discussed.

Solubilization of CNTs using sodium dodecyl sulphate (SDS)

SDS is an anionic alkyl amphiphile, and its chemical formula is $NaC_{12}H_{25}SO_4$; it is characterized by flexibility as well as a linear form. Hence, interaction with the convectional surface-active agent, Sodium Dodecyl Sulfate (SDS), has made it possible to effectively disperse nanoparticles including TiO_2Titanium Dioxide (TiO_2), Aluminum Oxide/ Alumina(Al_2O_3), and other carbonaceous species in water as well as ethyl glycol. Duan *et al*. explained that there is binding energy between SDS and CNTs and the dispersion can be done through the interaction of appropriate number of SDS molecules. In addition, Yu *et al*. obtained a stable dispersion of MWCNTs in water after 3 months' treatment with SDS at room temperature (37°C). Dispersing of CNTs in water was done by Jiang *et al* such that it was stable and uniform with SDS[11]. Thus UV-Vis spectrophotometry was employed for the first time ever for quantitative assessment of the dispersion stability. In addition, CNT-COOH characteristics were analyzed at a deeper level in terms of zeta potential, Fourier Transform Infrared Spectroscopy (FTIR) and Auger Electron Spectroscopy (AES), whereas Bright field microscopy was utilised to evaluate the state of aggregation of CNT suspension. It was also found that the shape of the nanofluid changed according to the concentrations of SDS. Comparing the zeta potential magnitude of CNTs that were treated with SDS to those that were untreated it was found that the former had a higher mode. Further, From the AES and FTIR analysis, it was also found that there is a good interaction between the SDS molecules and the CNTs surface[S9]. This was attributed to the Coulomb law where there is repulsion between two similar negative charges and therefore the hydrophilic sulfate groups of SDS were repelled by the carbon nanotubes (CNTs). This dispersion of CNTs in water using SDS had to be a continuous process for the repulsion. To achieve a stable CNT material (0.5% CNTs and 2.0 wt.% SDS), Hwang *et al*. observed a similar impact of sodium dodecyl sulfate (SDS) on the stability of multi-walled carbon nanotubes (MWCNTs) dispersed in mineral oil and water[12]. The stability of the nanofluid over time was studied by measuring the concentration and reading their absorbances with a UV-Vis spectrophotometer. MWCNT-water nanofluids were able to keep 80% of their relative concentration after running for 800 h, showing higher stability with the presence of SDS in the suspension. In contrast, agglomeration-free nanofluids have been successfully fabricated via this protocol due to the in-plane grinding operation of MWCNTs-surfactants and

graphene-surfactants. To resolve the problems of agglomeration and improve the dispersibility in distilled water, Mahmudul Haque *et al*. conducted an experimental study using sodium dodecyl sulfate (SDS) and sodium dodecylbenzene sulfonate (SDBS). Wet grinding ultrasound was recommended as a solution-based method for nanofluid synthesis. The specific amount of synthesized nanomaterials and surfactants were mixed manually at different weight ratios (1/1, 1/2, 1/3, 2/1, 3/1). Then, all mixtures were homogenized together at the desired wire ratio for one hour continuously by the planetary ball mill at ambient temperature under continuous rotation speed of RPM. This was followed by ultrasonication and degassing for 20 or 40 min, depending on the scheduled cycle length, and subsequent addition of distilled water. The former method has shown that no agglomeration existed in the nanofluids prepared in this way, and there was no adhesion between MWCNTs-surfactants or graphene-surfactants during grinding[S10].

Solubilization of CNTs using Triton X-100

The non-ionic surfactant Triton X-100 belongs to the octyl phenol ethoxylates. Structurally, it consists of an octyl phenol group (lipophilic) and a polyethylene glycol (PEG) chain (hydrophilic segment). Triton X-100 as a dispersant did not influence the stability of nanofluids based on multi-walled carbon nanotubes (MWCNTs), and it has been reported that Yousefi *et al*. observed 10 days to be the maximum limit for which these nanoparticles were stable in these materials. Tang *et al*. investigated the stability of nanofluids containing 0.1 weight fraction MWCNTs in dimethylacetamide with Triton X-100 as a dispersant. Besides, Rastogi *et al*. showed that Triton X-100 has the greatest dispersion efficacy *vs* other surfactants (Tween 80, Tween 20, and SDS). This result meant that the nanofluid could be stabilized with a minimum amount of surfactant. Initially, it was speculated by means of a theoretical study that Triton X-100 would show lower dispersing ability compared to other surfactants due to its shorter hydrocarbon tail, which comprises only 9 atoms. But experiments showed that this was incorrect. This could be because of the presence of a benzene ring in the tail group of Triton X-100. The benzene ring is more critical for dispersion than the tail length of the surfactant, which might be due to a synergetic effect on bi-component co-surfactants. This is probably because the special-typed benzene ring has a great tendency to be adsorbed on the graphitic surface through pi-stacking interactions. Askari and coworkers observed the dispersion of MWCNT nanofluids, facilitated by Triton X-100, sustaining a stable level for more than 2 weeks up to less than 2 months. In contrast, the stability of nanoporous graphene dispersion stabilized by Triton X-100 was stable for approximately three days and started to pack after about two weeks. Li *et al*., however, utilized an array of surfactants including Triton X-100 (TX100) and sodium dodecyl sulfate (SDS) to improve the dispersibility of multi-walled carbon nanotubes (MWCNTs) in aqueous solutions. CNT concentration (μg/mL) was measured by UV-visible spectrophotometer. Specifically, they mixed 40 mL of water containing various amounts of Triton X-100 (TX100) and sodium dodecyl sulfate (SDS) with 20 mg MWCNTs. The usage of SDS and TX100 ranged from 0.025% to 2%, which were calculated for CNT concentrations obtained. Interestingly, the highest CNT concentration was observed in the case of 2000 mg/L TX100-based CNT suspension. This was attributed to the presence of a benzene ring structure in TX100's tail group, which led to CNTs being more dispersible in water[S11]. In contrast, the sedimentation stability achieved by SDS was higher than that by TX100. To observe and compare the water dispersibility of MWCNT suspensions, Bai *et al*. employed a few surfactants (hexadecyltrimethylammonium bromide (CTAB), Triton X-100 (TX100), and sodium dodecyl sulfate (SDS)[13]. In comparison to the results, hexadecyltrimethylammonium bromide (CTAB) has been proven to be the less effective surfactant for preventing the p-aggregation of multi-walled carbon nanotubes (MWCNTs), whereas Triton X-100 offers maximum possible dispersion. Sodium dodecyl sulfate (SDS) and sodium octyl sulfosuccinate also exhibited great catalytic activity like CTAB. The benzene ring content of TX100 can be used to more effectively facilitate MWCNT dispersion.The benzene unit in TX100 made it easier to adsorb on the surface of MWCNTs and therefore enhanced their water-soluble dispersibility. However, compared to TX100 where aromatic units are involved in adhesive forces on the surface of MWCNTs, SDS and CTAB showed weaker interactions with MWCNT surfaces.

Solubilization of CNTs using Tween 20 / Tween 80

The dispersibility of multi-walled carbon nanotubes (MWCNTs) was examined in the work by Rastogi *et al*. using two different non-ionic surfactants, Tween 20 ($C_{58}H_{114}O_{26}$) and Tween 80 ($C_{64}H_{124}O_{26}$). It was observed that the hydrocarbon tails of Tween 20 and Tween 80 were longer than those of SDS and TX100. A total of 50 mg/L MWCNTs were mixed with four different surfactants—SDS, Tween 20, Tween 80, and TX100—and dispersed in water at a concentration of 1 weight percent. The dispersibility was evaluated using a UV-vis spectrometer. When compared to MWCNTs dispersed with various surfactants, the highest absorbance was shown by MWCNTs dispersed with TX100, while the lowest absorbance was shown by MWCNTs dispersed with SDS. Comparable absorbance values were found for Tween 80 and Tween 20. This led to the establishment of the dispersibility sequence as SDS < Tween 20/Tween 80 < TX100. Compared to SDS and TX100, Tween 80 and Tween 20 have a larger hydrocarbon tail chain length. The poorest dispersibility due to the steric hindrance was predicted for TX100, given that it has the shortest effective chain length of all the surfactants examined. However, this prediction was not consistent with the experimental results.

Characterization of CNTs

The methodologies predominantly employed for

Table 3 — Characterization of CNTs

Year	Inventor / Researcher	Characterization Techniques	Purpose / Key Findings	Ref. No.
1991	Iijima S	TEM (Transmission Electron Microscopy)	First direct imaging of helical multi-walled CNT structure.	01
1993	Iijima S, Ichihashi T	TEM, HRTEM	Visualized single-walled CNTs (~1 nm diameter) and confirmed tubular graphene structure.	02
1995	Guo T, Nikolaev P, Thess A, Colbert DT, Smalley RE	TEM, Raman spectroscopy	Verified SWCNT diameter distribution and crystallinity after laser vaporization.	04
2005	Endo M, Muramatsu H, Hayashi T, Kim YA, Terrones M, Dresselhaus MS	TEM, Raman, TGA	Confirmed purity and double-walled structure; assessed thermal stability.	05
2007	Bell MS, Teo KBK, Milne WI	SEM, TEM	Studied morphology and alignment of MWCNTs grown by PECVD.	06
2008	Kang S, Mauter MS, Elimelech M	TEM, Zeta potential analysis	Linked surface charge and morphology to bacterial cytotoxicity of MWCNTs.	17
2008	Kang S, Herzberg M, Rodrigues DF, Elimelech M	TEM, AFM	Observed size-dependent antibacterial effects; measured CNT dimensions.	14
2008	Rastogi R, Kaushal R, Tripathi SK, Sharma AL, Kaur I, Bharadwaj LM	UV–Vis spectroscopy, TEM	Compared dispersion quality of CNTs with different surfactants.	13
2009	Liu S, Wei L, Hao L, Fang N, Chang MW, Xu R, Yang Y, Chen Y	AFM, TEM	Visualized “nano dart” morphology of SWCNTs and correlated with antibacterial activity.	39
2010	Kumar M, Ando Y	TEM, SEM, Raman	Reviewed characterization of CNTs in CVD growth studies.	09
2011	Duan WH, Wang Q, Collins F	UV–Vis spectroscopy, binding energy analysis	Quantified CNT dispersion in SDS surfactants.	12
2013	Chen H, Wang B, Gao D, Guan M, Zheng L, Ouyang H, Chai Z, Zhao Y, Feng W	TEM, SEM, Microbiological assays	Evaluated antibacterial activity against human gut bacteria.	S13
2014	Wu C, He Q, Zhu A, Li D, Xu M, Yang H, Liu Y	TEM, DLS, Fluorescence microscopy	Characterized polylysine-functionalized graphene–CNT hybrids for anticancer delivery.	28
2018	Laux P, Riebeling C, Booth AM, Brain JD, Brunner J, Cerrillo C, Creutzenberg O, Estrela-Lopis I, Gebel T, Johanson G, Jungnickel H	Multiple environmental fate assays, TEM	Assessed CNT morphology and persistence in aquatic systems.	44
2019	Wang X, Liu C, Li H, Zhang H, Ma R, Zhang Q, Yang F, Liao YC, Yuan W, Chen F	LC–MS, Proteomics, Transcriptomics, SEM	Multi-omics and imaging to study antifungal mechanisms of GO–CNT composites.	24
2021	Wang X, Peng F, Cheng C, Chen L, Shi X, Gao X, Li J	SEM, TEM, Antifungal assays	Evaluated synergistic effects of GO and fungicides on plant pathogens.	25
2025	Shoyiga HO, Martincigh BS, Nyamori VO	SEM, Conductivity testing	Characterized electroconductive ink containing CNTs for flexible electronics.	03

examining specimens encompass electromagnetic spectroscopy, nuclear magnetic resonance (NMR), X-ray diffraction (XRD), light scattering methodologies, electron microscopy, and atomic force microscopy (AFM), primarily utilized for assessing the overall morphology of carbon nanotubes (CNTs). Conversely, the existence of functional groups on CNTs is validated through the use of infrared (IR) spectroscopy, Raman spectroscopy, and NMR[S12] (Table 3).

Antimicrobial activity of CNTs

Growth of microorganisms is determined by a number of factors in CNTs, such as chemical composition and surface characteristics, dimensions, number of layers of graphene, and their physical arrangement, dispersion or aggregation. CNTs have recently shown extraordinary antimicrobial activity as demonstrated by different studies. Among the size of these agents, deactivating microorganisms show a very critical role. The lesser the CNTs size, the higher will be the surface area to volume ratio, hence stronger the bond created with the cell wall or membrane of microorganisms, and hence potent action is exerted on the microorganism by CNTs. The mechanism that has been followed by these materials for antimicrobial activity is the interaction of CNTs with microorganisms and disruption of cellular membrane, metabolic processes, and morphology. Recent research has shown that the bacteriostatic nature of CNTs is due to the direct contact of the material with the microorganism and rupture of its cell membrane, which leads to the mortality of bacterial cells. The loss of cellular integrity by morphological alterations in microorganisms after incubation with CNTs was revealed through scanning electron microscopy (SEM) patterns. Moreover, a fivefold increase in plasmid DNA, a twofold increase in RNA, and the efflux of cytoplasmic materials were also associated with small CNTs. Bacteriostatic activity of CNTs has increasingly been realized, and due to the high surface-to-volume ratio and large inner volume, this bacteriostatic activity has been attributed to CNTs. Additionally, the bioavailability of antibiotics can also be enhanced by using CNTs as a carrier, while targeting and delivery can also be carried out. The antimicrobial potential of CNTs has been probed, and this promise will continue to bring new advances in the future. Single-walled carbon nanotube (SWCNT) mediated antimicrobial activity against *E. coli* bacteria was reported for the first time in the year 2007 by Kang *et al*. It was reported by these researchers that SWCNTs disrupt the cell membrane of microorganisms via direct contact and hence kill them. Further research was performed by Kang *et al*. in 2008, and it was reported by these researchers that the size of SWCNT particles has a very critical role in deciding their antimicrobial activity. When the researchers compared the antibacterial properties of MWCNT and SWCNT against *E. coli,* it was reported by Kang *et al*. that SWCNTs showed higher toxicity as compared to MWCNTs against the microorganisms. According to researchers, the surface of SWCNTs was most effective in targeting and hence killing the microbes. These studies prove the fact that SWCNTs can find applications for different purposes to combat bacterial infections. According to toxicological perspectives and against *E. coli*, single-walled carbon nanotubes have been compared to MWCNTs and even fullerene-C60 to find single-walled carbon nanotubes better, showing antibacterial activities noticeably. Many parameters, including carbon nanotube diameter, length, residual catalyst, electrical structure, surface functional group, surface chemistry, and coatings, are believed to have a significant impact on the toxicity mechanism. The length of the nanotubes is especially significant when interaction with the cell membrane occurs. Compared to longer tubes, greater bactericidal efficacy is known to be present in shorter tubes. Because of their shorter length, nanotubes may be more likely to interact with microorganisms, and further harm to cell membranes may be caused. It is interesting to note that an increase in osmotic lysis of the microorganism was encouraged by the tube wrapping around the surface of the cell when the length of MWCNTs reached up to 50 μM. It has been demonstrated that the way that CNTs interact with cells in a liquid media differs greatly from that of a solid surface. The antibacterial efficacy of longer nanotubes has been shown to exceed that of shorter ones. While a greater number of cells in the aggregates are affected by longer nanotube aggregates, and therefore they are more bio-effective, the likelihood of shorter CNTs self-aggregating in a liquid system is higher, without affecting many microbial cells. The likelihood of an extracellular membrane being damaged through interaction between the open ends of nanotubes and a microbe could be raised by the shortened length. As MWCNTs

got as long as 50 μM, it is interesting to note that the tube wrapped around the microbial cell's surface, which resulted in increased osmotic lysis of the microbe. It has been demonstrated that CNTs interact with cells in a liquid medium very differently than they do on a solid surface. The antibacterial efficacy of longer nanotubes has been shown to exceed that of shorter ones. While a greater number of cells in the aggregates are affected by longer nanotube aggregates, and therefore they are more bio-effective in liquid systems, shorter CNTs are more likely to self-aggregate without affecting many microbial cells. Based on experimental findings in various investigations, a number of potential antibacterial mechanisms are postulated; these are primarily believed to include oxidative stress and disturbance of the cell membrane[14-17,S13] (Table 4).

Antifungal activity of CNT

Table 4 — Antimicrobial activity of various types of CNTs

Types of CNTs	Synthesis method	Concentration	Size (Diameter/ length)	Target sp.	Activities	Mechanism of action and effect
SWCNTs	Chemical vapor deposition (CVD)	5 µg/mL	0.83 nm	*E. coli, B. subtilis*	Cell injury may result from bacterial cells and SWCNTS colliding.	Cell wall degradation, intracellular content leakage, a reduction in cell height and volume, and an increase in the roughness of the bacterial surface.
SWCNTs	Chemical vapor deposition (CVD)	10 µg/mL	<2 nm/ 5-30 µm	*E.coli, S.aureus*	Disinfection activity	Bacterial adhesion or deposition onto bacterial cell
SWCNTs	Arc discharge	20%	0.7- 2.0 nm	*E. coli* K_{12} TG_1	Interaction between bacterial cells and SWCNTs	Reduced cell bioluminescence intensity, increased oxygen consumption rate, and morphological/mechanical damage in cells.
SWCNTs	Chemical vapor deposition (CVD)	50 µg/mL	0.75- 1.2 nm	*E. coli* K_{12}	Antibacterial activity	Damage to the cell membrane and cytoplasmic efflux.
SWCNTs-Ag	Solution mixing	5 µg/mL	<2 nm/5–30 µm	*E.coli, S.aureus*	Disinfection activity	Interaction between cells and SWCNTs-Ag
SWCNTs	CO disproportionation	5 µg/mL	1–3 µm	*E. coli*	Antibacterial activity	Irrecoverable damages to the outer membrane, releasing the intracellular content.
SWCNT	CO incorporated MCM-41	5 µg/mL	0.9 nm	*E. coli*	Antibacterial activity	Cells lost their cellular integrity.
MWCNTs	Chemical vapor deposition (CVD)	25 µg/mL	40-60 nm	*E.coli, S.aureus*	Removal of viral and bacterial pathogns	Interaction between cells and SWCNTs-Ag.
MWCNTs-Ag	Solution mixing	10 µg/mL	40-60 nm	*E.coli, S.aureus*	Removal of viral and bacterial pathogns	Interaction between cells and SWCNTs-Ag.
MWCNTs/lysine, MWCNTs/arginine	Solution mixing	5 µg/mL	<30 nm/ 5–15 µm	*E.coli, S. aureus S. Typhimurium*	Antibacterial	Electrostatic adsorption on the bacterial cell wall, loss of viability.
Graphene	Low pressure CVD	2 µg/mL	1-5 µm	*C. albicans*	Antimicrobial	Graphene layer reduces the attachment of microbes.
Graphene oxide (GO)	Hummers' method	5 µg/mL	1-10 µm	*E.coli, S. aureus*	Disinfection activity	Depend on contact time.
C60	Four-step reaction	7.5 g/mL	0.7-2.0 nm	*E. coli, S. aureus*	Antibacterial assay	Electrostatic attraction.
C70	SES Research production	2% PSP4VP	0.5-1.5 µm	*E. coli*	Antibacterial assay	C70 and Ag-NPs, synergistically target bacterial cells that increase photo-generated ROS.
GO- Ag	Solution mixing	1 mg/mL	1-10 µm	*E. coli, S. aureus*	Disinfection activity	ROS and depletion of antioxidants and protein Dysfunction.
Reduced- GO	Synthesized from GO	0.1 mg/mL	3.40 µm	*P.aeruginosa*	Antioxidative activity	Oxidative stress and ROS generation.

The review paper highlights the in-depth research on the antifungal activity of carbon nanomaterials, innovative graphene-related materials, and their prospects in providing solutions to fungal infections. The studies have shown different graphene-based nanomaterials, including nanocomposites, nanosheets,

and nanoparticles, inhibiting fungal growth ability. Furthermore, it discusses the role of the surface modification of carbon-based nanomaterials on their antifungal effects against different fungal strains.Reduced graphene oxide (rGO) nanosheets antifungal activity was the focus of Sawangphruk *et al.* (2012). The antifungal activity of rGO nanosheets against *Aspergillus niger, Aspergillus oryzae, and Fusarium oxysporum* was investigated by them. Their research revealed that the rGO nanosheets showed fungal growth inhibition, the confirmation that they may replace conventional antifungal disinfectants (Table 5). This study reveals that nanomaterials made of graphene exhibit vast potential in addressing fungal infection[19]. Li *et al*. (2013) synthesized GO-Ag NPs and their antifungal activity against *C. albicans* and *C. tropical* was examined *in vitro*. The combining of silver nano particles with carbon nanoscrollers indicate better antifungal performance over the classical

Table 5 — Antifungal activity of CNTs

Authors	Year	Graphene-Based Materials	Key Findings	Ref No.
Sawangphruk *et al*.	2012	Reduced graphene oxide (rGO)	rGO nanosheets inhibited fungal growth against *Aspergillus* and *Fusarium* species, potential replacement for disinfectants.	19
Li *et al*.	2013	GO-Ag nanoparticles	GO-Ag showed enhanced antifungal activity, sustained silver ion release, suitable for nosocomial infections.	20
Li Chao *et al*.	2013	Graphene oxide-silver nanocomposites	Superior antifungal properties, sustained silver ion release, promising for clinical applications.	20
Cui *et al*.	2014	GO-Ag composites	Enhanced antifungal activity, lower toxicity, and better blood compatibility compared to silver nanoparticles.	21
Wang *et al*.	2014	Single-walled carbon nanotubes	SWCNTs showed the strongest fungal growth inhibition among carbon nanomaterials tested.	22
Demitri *et al*.	2015	Graphite and cinnamaldehyde films	Superior antifungal properties, potential for food preservation through active packaging.	S19
Chen *et al*.	2016	GO-Ag nanocomposites	High antifungal efficiency, effective for agricultural pathogens like *Fusarium graminearum*.	S20
Li *et al*.	2017	GO-borneol composite (GOB)	Fungistatic activity, inhibition of fungal adhesion and growth, clinical potential for *M. racemosus* treatment.	S21
Wang *et al*.	2017	Surface-modified MWCNTs	Functionalized MWCNTs (-COOH, -OH, -NH2) outperformed pure MWCNTs in fungicide activity against *Fusarium graminearum*.	23
Hao *et al*.	2017	Various nanoparticles	Fullerene and CuO NPs showed strongest antifungal effects against Botrytis cinerea.	S22
Farzanegan *et al*.	2018	GO-Indolicidin nanocomposite	Superior antifungal effect against *Candida albicans*, promising for candidiasis treatment.	S23
Ficociello *et al*.	2018	ZnO nanorods on graphene	Effective antifungal activity against *Candida albicans*, low cytotoxicity, biocompatible.	S24
Wang *et al*.	2019	Graphene oxide (GO)	Multi-omics analysis revealed GO's disruption of fungal cell integrity and metabolic processes in *Fusarium graminearum*.	24
Asadi Shahi *et al*.	2019	GO/fluconazole compound	Synergistic antifungal action, sustained drug release, promising alternative for candidiasis treatment.	S25
Huang *et al*.	2020	GO-clotrimazole film	Enhanced drug release and antifungal activity, improved buccal drug delivery system.	S26
Kahsay *et al*.	2020	rGO/Fe_3O_4 clay hybrid	Effective dye adsorption and antifungal activity, environmental and medical implications.	S27
El-Abeid *et al*.	2020	rGO-CuO nanocomposites	Completely eradicated *Fusarium* diseases in crops, non-phytotoxic, green alternative for agriculture.	S28
Bhatt *et al*.	2020	WS2/ZnO nanohybrids	Inhibited biofilm formation of *Candida albicans*, potential use on medical devices to prevent infections.	S29
Gontarek-Castro *et al*.	2021	PVDF/Graphene membranes	Dual functionality for desalination and antifungal activity against *Curvularia* sp. fungal strain.	S30

(*Contd.*)

Table 5 — Antifungal activity of CNTs (*Contd.*)

Authors	Year	Graphene-Based Materials	Key Findings	Ref No.
Wang *et al*.	2021	GO-fungicide combinations	Synergistic effect with fungicides against *Fusarium graminearum*, improved fungicide efficiency.	25
Hu *et al*.	2021	Carbon-based nanocomposites	Superior to conventional fungicides, effective against rice blast pathogen Magnaporthe oryzae.	S31
Dacrory *et al*.	2021	Cellulosic biocomplex	Effective antifungal agent against *Aspergillus* species, potential for treating aspergillosis.	S32
Zhang *et al*.	2022	Graphene oxide (GO)	Significant inhibition of *Bipolaris sorokiniana* growth, agricultural disease control potential.	S33
Huang *et al*.	2022	GO-clotrimazole foam	Improved drug targeting and reduced side effects in drug delivery systems.	S34
Hashem *et al*.	2022	A. terreus bioactive compounds	Strong antifungal activity against mucormycosis-related fungi, ultrastructural damage in fungi.	S35
Zhang *et al*.	2023	OGC nanocomposites	Enhanced antifungal activity and structural stability against *Fusarium graminearum*, agricultural applications.	S36

composites. The sustained release of silver ions from the nanocomposites also played a significant role in prolonging the antifungal action, and offers good prospects for clinical use such as in nosocomial infections and site-specific antifungal application[20]. While, Li Chao with co-authors (2013) have studied graphene oxide-silver nanocomposites against *Candida albicans and Candida tropicalis*. Their study confirmed the fact that nanoscrolls comprised of silver nanoparticles and carbon which act as an antifungal are superior with respect to standard composites in terms of their antifungal activity. Silver ion release from the nanocomposites that was highlighted as an important factor that enabled antifungal effect over a longer period and thus implied the clinical applications of the nanocomposites. Cui *et al*. (2014) concerned application of GO-Ag as antifungal agent, tested bactericidal action of GO-Ag in regard to *Candida albicans*. They have manufactured GO-Ag composites with further encouraging antifungal activity above that of silver nanoparticles alone. Moreover in addition, the GO-Ag composites showed a lower rate of toxicity and enhanced blood compatibility[21]. Wang *et al*. (2014) examined antifungal activity of carbon nanomaterials, especially single-walled carbon nanotubes (SWCNTs) against them. Thus, SWCNTs were determined to be the most potent in inhibiting the growth of fungi among them[22]. Demitri *et al*. (2015) studied antifungal characteristics of cross-linked Schiff base of chitosan and cinnamaldehyde added to films of stacked expanded graphite sonicated into thick sheets. Their work has shown a combination of elevated cinnamaldehyde concentration and graphite in a larger form to produce superior antifungal properties. The results from the films development made them a potential active packaging technique that uses the inhibition of fungal growth to preserve food[S19]. Chen *et al*. (2016) developed a silver nanocomposite of graphene oxide and assessed its antifungal activity against *Fusarium graminearum*. The nano-composite displayed exponentially high inhibition efficiency when compared to sole metallic silver nano-particles and graphene oxide solution. Here the study reveals the prospect of nanoparticles such as nanocomposites in countering fungal pathogens with the aim of restoring sustainability to agriculture[S20]. Li *et al*. (2017) demonstrated the fungistatic activity of a graphene oxide-borneol composite (GOB), involving *M. racemosus* as a test fungus for this. By associating thiolated-borneol with graphene oxide sheets modified with thioglycolic acid (GO-TGA), they showed antimycotic properties of the GOB composite that successfully achieved inhibition of fungal adhesion and growth. The study has further brought to light the contribution carbon stereochemistry to the improvement of graphene-based composites fungistatic properties[S21]. Wang *et al*. (2017) examined the antifungal activity of surface-modified MWCNTs against *Fusarium graminearum*by performing the fungicide activity test. Consequently, they tested three functionalized MWCNTs (-COOH, -OH, and -NH_2) and discovered that they inhibited both spore

elongation and germination due to these groups' functionalization. Further observations indicated that they do, in fact, outperform pure MWCNTs in the processes. The paper depicts using the most suitable surface-modified MWCNTs variation in fungicidal seed coating against plant pathogens (*Fusarium graminearum*)[23]. Hao *et al*. (2017) studied the fungicidal performance of several compounds such as: multi-walled carbon nanotubes, fullerene, reduced graphene oxide, copper oxide nanoparticles, ferric oxide nanoparticles, and titanium oxide nanoparticles against Botrytis cinerea. Their data show that all tested NPs had a negative effect on the development of fungi, with fullerene and copper oxide nanoparticles showing the strongest suppression against fungi[S22]. Farzanegan *et al*. (2018) synthesized a new nanocomposite consisting of Indolicidin and graphene oxide and found out its antifungal effect on *Candida albicans*. The results obtained from the *in vivo* study showed that the nanocomposite displayed superior antifungal effect when compared with the conventional antifungal agents, exhibiting a good sign for the treatment of disseminated candidiasis[S23]. Ficociello *et al*. (2018) carried out research on the manner in which zinc oxide nanorods decorated on graphene nanoplatelets exhibit antifungal activity against *Candida albicans*. The study had shown the nanocomposites were able to prevent the growth of fungal cells and reduce virulence factors, decreasing their harmful effects to human lives, with the results of cytotoxicity tests on keratinocytes cells yielding low cytotoxicity level among compared controls, signifying their biocompatibility[S24]. Wang *et al*. (2019) have certainly explored antifungal attributes of graphene oxide (GO) against *Fusarium graminearum* by multi-omics approach (typically – metabolomics, transcriptomics and proteomics), disclosing the mechanism of action. The study demonstrated that GO treatment leads to notable changes in fungal morphology, gene expression patterns, and the composition of fungal metabolites, offering insights into its antifungal mechanism. These observations demonstrated, in particular, the disturbance exerted by fungi on the integrity of a cell and important metabolic processes, which spotlights GO as a strong antifungal agent for combating plants[24].Asadi Shahi *et al*. (2019) showed that the synergistic antifungal action of the graphene oxide/fluconazole compound against *Candida albicans* fungus. Using detailed characterisation and a battery of assays, they build the electiveness of the compound, lack of cytotoxicity, and ability to inhibit candida adherence and DNA integrity. On the other hand, release behavior of fluconazole from the formulation demonstrated that its anti-fungal action exists in a sustained manner; this can become an alternative approach for treating candidiasis[S25]. Huang *et al*. (2020) demonstrated how a medical film developed from graphene oxide (GO) could release clotrimazole and potentially enhance antifungal activity against *Candida albicans's* overgrowth. The results presented a versatile application of GO in modifying numerous formulation characteristics such as permeability of buccal drug delivery system[S26]. Kahsay *et al*. (2020) produced red graphene oxide/ferromagnetic iron oxide (rGO/ Fe_3O_4) clay hybrid and assessed their adsorption capacity in dye removal and antifungal activity with the foremost pathogenic fungi *Trichophyton mentagrophytes* and *Candida albicans*, respectively. Their data have revealed the high adsorption capacity of rGO/nanoparticles of Fe_3O_4 for dye removal and remarkable antifungal activity, noting that these have implications for environmental preservation and medical practice[S27]. The research by El-Abeid *et al*. (2020) focused on the application of rGO-CuO nanocomposites in managing *Fusarium* root rott and wilt diseases in tomato and pepper crops. Through isolating fungi from diseased plants and analyzing the antifungal activity of the nanocomposite *in vivo*, they found that rGO-CuO multigene completely eradicated disease symptoms without causing phytotoxicity. This study underlines the importance of nanocomposites as green alternatives to biomaterials' disease resistance[S28]. The study by Bhatt *et al*. (2020) was dedicated to find a cure for *Candida albicans*, which is the most prevalent fungus known to cause different infections in humans. The structure of WS_2/ZnO nanohybrids was evaluated for its antibiofilm and antimicrobial activities towards *Candida albicans*; results demonstrated that they successfully inhibited biofilm formation. The foregoing study suggests the situations where nanohybrids could be used in clinical settings to guard *Candida albicans* growth on surfaces of medical devices so as to lower the probabilities of infections[S29]. Gontarek-Castro *et al*. (2021) looked into the opportunity of using PVDF/Graphene composite membranes for desalination of seawater

and as an antifungal agent against *Curvularia* sp. fungal strain. Their research showed that these membranes were resistant to fungi, with the inhibition percentages of those membranes containing the lower graphene concentrations being higher. This research shows that nanocomposite membranes have double abilities, which may make them competitive candidates for water desalinization applications with built-in antifungal properties[S30].

The effect of GO-fungicide combinations on *Fusarium graminearum* was examined by Wang *et al*. (2021). Using graphene oxide alongside the fungicides most frequently used, the researchers could show that the fungal growth as well as the spore germination is stopped both *in vitro* as well as *in vivo*. These results indicate that graphene oxide may be applied to improve the efficiency of fungicides in the control of *Fusarium* head blight[25]. Hu *et al*. (2021) investigated *Magnaporthe oryzae* which is the pathogen responsible for rice blast disease. The two researchers used carbon-based nanocomposites to attack the pathogen and evaluated their antifungal activity. The findings showed that the nano-composites were superior performers in comparison to conventional fungicides, piercing the fungal cell membrane and consequently reducing graphical damages in rice seedlings[S31]. Dacrory *et al*. (2021) conducted an antifungal activity assay of a cellulosic biocomplex with predetermined amino acids on *Aspergillus species*. A manufactured nano-biocomplex exhibit brightly reduced effects on mycological (fungal) growth if the indicated inhibition zone diameter measurements are any indication. The given results are indicative that cellulose-based nanomaterials could be a realistic substitute to antifungal agents for the effective treatment of aspergillosis[S32]. Zhang *et al*. (2022) implemented research in which the fungus strain was of *Bipolaris sorokiniana* to figure out the fungal inhibitory effects of GO. *B. sorokiniana* growth and pathogenicity were shown to slow down significantly with the application of GO, implicating the novel antagonistic approach for disease control of agricultural disposal[S33]. While Huang *et al*. (2022) focused on the addition of GO into chitosan/alginate-based foams in order to improve the delivery of clotrimazole, these are just examples of many studies focusing on the nanotechnological improvements of drug delivery systems in order to improve drug targeting and prevent side effects. In addition, these findings show that nanoparticles do have a role in enhancing transport of the antifungal agents because of GO[S34]. Using the hemolytic activity of *Aspergillus* terreus against mucormycosis-related fungi, Hashem *et al*. (2022). Their investigation concluded with chemical analyses combined with electron microscopy studies, which confirmed the strong antifungal activity of *A. terreus*. The observed alterations in the ultrastructure of treated fungi provided compelling evidence supporting its potential use as a bioactive compound against deadly infections[S35]. Zhang, *et al*. (2023) assembled OGC and also they tested OGCs' antibacterial activity against *F. graminearum* as a result. NMR and FTIR techniques revealed that OGC displayed better structural stability and crystallinity while compared with the production of GO-CS nanocomposites. This finding depicted the increased antifungal activity of OGC against strain specific *F. graminearum* and its possible use in to control crop diseases in the future. These results indicate that OGC can be considered to have potential as an environmentally friendly antifungal agent of a water distribution system with many applications in agriculture[S36].

Anti-cancerous activity of CNTs

The studies described in the review article include, among other things, drug delivery systems, photodynamic therapy (PDT), anticancer synergy, and relieve resistance to anticancer agents. Thus, this review article discusses the ability of graphene derivatives to greatly enhance the effectiveness of anticancer agents in the treatment of cancer. Also, a brief description of the cytotoxicity and drug release capabilities of graphene-based nanocarriers is given. These findings will provide useful knowledge for their potential use in targeted cancer therapy applications (Table 6).

Lin Zhou *et al*. (2011) prepared functionalized graphene oxide (GO) through the chemical oxidation of purified natural graphite and developed a GO-Hyaluronic Acid (HA) hybrid, where FTIR peak shifts were indicative of GO-HA interactions. The functionalized GO showed potential as carriers for photodynamic therapy photosensitizers, which was recognized as an important newer modality in cancer treatment. This was attributed to its potential for loading high concentrations of drugs with minimal

cellular/tissue injury, which prompted further studies for *in vivo* investigations and possible clinical applications[26].

Zhen Hu *et al*. (2012) synthesized a graphene oxide/TiO2 hybrid (GOT) and demonstrated its greatly enhanced photocatalytic properties under visible radiation compared to the original TiO2. They also showed that GOT exhibited superior

Table 6 — Anti-cancerous activity of CNTs

Author(s)	Year	Graphene-Based Material	Key Findings	Ref.No.
Lin Zhou *et al*.	2011	Functionalized Graphene Oxide (GO)	GO-HA hybrid shows potential as carriers for photodynamic therapy photosensitizers with high drug loading.	26
Zhen Hu *et al*.	2012	Graphene Oxide/TiO2 Hybrid (GOT)	Enhanced photocatalysis under visible light, demonstrating photodynamic anticancer activity with apoptotic effects.	27
Chunhui Wu *et al*.	2012	Poly-L-lysine-functionalized GO	Developed nanohybrid with high solubility, stability, and synergistic anticancer activity in combination therapy.	28
Dickson Joseph *et al*.	2014	pH-sensitive Graphene Nanosheets	Synthesized using lysozyme, showed better cytotoxicity towards cancer cells than fibroblasts.	29
Surajit Some *et al*.	2014	Graphene Quantum Dots/Graphene-Curcumin Composites	Exhibited significant anticancer activity with synergistic effects.	S37
Lin Zhou *et al*.	2014	GO as Drug Delivery System	Demonstrated synergistic antiproliferative effects in combination therapy for cancer treatment.	S38
A. Karmakar *et al*.	2015	Functionalized Graphene Nanosheets	Efficiently delivered Parthenolide to Panc-1 cells, enhancing anticancer activity.	30
Sangiliyandi Gurunatha *et al*.	2015	Reduced Graphene Oxide-Silver Nanoparticles	Inhibited growth of ovarian cancer cells, showing potential for cancer treatment.	31
Zhou *et al*.	2015	GQDs-Hypocrellin A Silica Nanosystem	Improved fluorescence intensity and anticancer activity, potential theranostic system.	S39
Sui *et al*.	2016	CDDP GQDs	Enhanced anticancer effects in tumor cells, overcoming resistance to cisplatin-based chemotherapies.	S40
Nalinithe *et al*.	2016	Calotropis procera Extract	Demonstrated potential as an anti-glioblastoma agent through electrochemical methods and cytosensor device.	S41
Kavinkumar *et al*.	2017	GO/rGO-AgNP Nanocomposites	Showed high cytotoxicity against A549 lung cancer cells, suggesting potential use in cancer treatment.	S42
Hou *et al*.	2017	HA-Functionalized Carbon Nanomaterials	Positive *in vitro* and *in vivo* results for targeted cancer drug delivery systems.	S43
Farahnaz Barahui *et al*.	2017	Chlorogeneic Acid-GO Nanocomposite	High toxicity to cancer cells, non-toxic to normal cells, potential anticancer treatment.	S44
Hadi Zare-Zardini *et al*.	2018	Graphene-Based Nanocarriers	Cytotoxic to cancer cells, minimal effect on normal cells, demonstrated effectiveness in human blood tests.	S45
Afarideh *et al*.	2018	GO/5-FU Complex	Increased cytotoxicity in CT^{26} dsRED cancer cells, potential for improving chemotherapy.	S46
Jaya Seema *et al*.	2018	GO-PEITC Nanocomposite	Showed better effects in curing liver cancer with stable drug release.	S47
Ananya Deb *et al*.	2018	Chitosan-CPT/DIM Nanobiocomposites	Effective against breast cancer, improved bioavailability and drug release.	S48
G. Jeevitha *et al*.	2018	WO3-GO Nanocomposite	Effective in degrading organic dyes, antimicrobial activity, and anticancer properties.	S49
Lin *et al*.	2020	RGO/PTX Nanosheets	Demonstrated cell death in A549 lung cancer cells, potential targeted drug delivery system.	S50
Nur Farhanah Rosli *et al*.	2019	GONPs-Cisplatin Complex	Enhanced chemotherapy effects in lung cancer cells, suggesting potential in cancer treatment.	S51
Xibo *et al*.	2020	pGO Dual Drug Delivery	Delivered cisplatin and doxorubicin effectively, reducing tumor size significantly in animal models.	S52
Mariadoss *et al*.	2020	GO-Silver Nanocomposite	High cytotoxicity against lung and brain cancer cells, promising for cancer diagnosis and therapy.	S53
Ganesan *et al*.	2020	GO-CuO Nanocomposites	High toxicity against colon cancer cells, potential for drug delivery	S54

			systems.	
Azam Najmafshar *et al*.	2020	CGO-PEG-bLF Nanocarrier	Enhanced cytotoxic performance and cellular uptake, reduced tumor growth in lung cancer models.	S55
Lucherelli *et al*.	2020	Multi-functional Graphene Platform	Combined chemotherapy and phototherapy, higher anticancer activity, effective drug release.	33

(*Contd.*)

Table 6 — Anti-cancerous activity of CNTs (*Contd*.)

Author(s)	Year	Graphene-Based Material	Key Findings	Ref.No.
Markovic *et al*.	2021	Graphene Nanoparticles	Potent action against U251 glioma cells with NIR radiation, oxidative stress-induced cell demise.	S56
Ahamed *et al*.	2021	SnO2-Doped ZnO/RGO Nanocomposites	Induced apoptotic responses in MCF-7 cells via oxidative stress pathways, superior to ZnO nanoparticles.	S57
Smina *et al*.	2021	Plant-Derived GO	Demonstrated cytotoxicity against MCF-7 breast cancer cells, suggesting biomedical applications.	S58
Tas *et al*.	2021	GO-PEG-DTX Nanocarrier	High anticancer activity on prostate cancer cells, potential for drug delivery in cancer therapy.	S59
Kavitha *et al*.	2021	GO-CuO Nanocomposites	Effective in degrading methylene blue dye and cytotoxic against colon cancer cells.	S60
Wei *et al*.	2021	GO-Platinum Drug Nanocarrier	Enhanced drug delivery features, demonstrated potential for platinum-based cancer chemotherapy.	34
Rahdar *et al*.	2021	GO Dotal/PEG Nanocomposite	Success in *in vivo* cancer treatment experiments on rats, promising for further research.	S61
Farhangfar *et al*.	2022	Arginine-Ginsenoside Rh2 Graphene	Improved survival rates in mice with mammary cancer, showing promise in cancer treatment.	S62
Kesavan *et al*.	2022	DOXO-Loaded Graphene Nanocarrier	Demonstrated pH-controlled drug delivery and biocompatibility *in vitro* for glioblastoma cancer cells.	S63
Chen *et al*.	2022	GO-Based Exosome Functionalized System	Targeted breast cancer cells effectively, promising drug delivery system.	S64
Lotfollahzadeh *et al*.	2022	S-TRAIL-CQD Nanohybrid	High cytotoxicity towards HT-29 colon cancer cells, potential theranostic candidate.	S65
Saranya *et al*.	2023	CeO2/GO Composite	Demonstrated better cytotoxicity against breast cancer cells, potential theranostic agent.	S66
Kanth Kadiyala *et al*.	2023	ZrO2/rGO Nanocomposites	Showed significant cytotoxicity against cancer cells, potential for combined cancer therapy.	S67

absorbability compared to TiO2. Their research demonstrated excellent photodynamic anticancer activity of GOT and its ability to induce apoptotic death in cancer cells while exhibiting no dark cytotoxicity. This provided proof of principle for future studies on its use as a new modality for cancer therapy[27].

Chunhui Wu *et al*. (2012) developed a nanohybrid for cancer combination therapy using a photosensitizer (ZnPc) and anticancer drug (DOX) on poly-L-lysine-functionalized graphene. They demonstrated that the graphene-poly-L-lysine nanohybrid loaded with doxorubicin and zinc phthalocyanin (G-PLL/DOX/ZnPc) nanocomplex had high solubility, stability, and drug-loading efficiency. It also exhibited good *in vitro* and *in vivo* photosensitivity and synergistic anticancer activity through the combination of photodynamic and chemotherapy. This study was one of the first of its kind, which discussed several interesting prospects for effective cancer combination therapy in the future[28].

Dickson Joseph *et al*. (2014) have employed chicken egg white lysozyme (LYS) to construct pH-sensitive graphene nanosheets showing better cytotoxicity towards cancer cells as well as on fibroblasts. The study demonstrated a simple technique for synthesize graphene nanoplatelets via lysozyme and the ultrasound, which could be used as an anticancer agents. Proteins (like lysozyme) and gold nanoparticles can act as agents to exfoliate (separate layers of) and stabilize graphene nanosheets in solution. This discovery broadens the understanding of how graphene-based nanohybrids can be developed and utilized, specifically for applications in cancer therapy, such as targeted drug delivery or tumor treatment[29]. A research work done by Surajit Some *et al*. (2014) was

aimed at the creation of graphene quantum dots, and graphene-curcumin composites for drug delivery in the cancer therapy. This research led to the discovery that these composites significantly had anticancer activity with synergistic effects for cancerous cell death. This study underlines the significance of nano graphene as carrier and enhancing the delivery and the efficacy of anticancer agents.[S37]And again Lin Zhou, *et al*. (2014) studied the use of graphene oxide as a drug delivery system for Hypocrellin A and 7-ethyl-10-hydroxycamptothecin in cancer treatment. It has been demonstrated by the results that the combination therapy has a synergistic antiproliferative effect which shows the prospect of graphene-based carriers used in tandem therapies for a more robust healing from the effects of cancer[S38]. A. Karmakar *et al*. (2015) focused on the functionalization of graphene nanosheets that can be used to deliver Parthenolide efficiently to Panc-1 cells, this was a promising way to improve the efficacy of the anticancer agent, Parthenolide. Carboxyl-nanographene functionalized form of parthenolide was found to exhibit better anticancer activity and thus along with their nanodelivery systems holds great hope for cancer treatment[30]. Additionally, the report by Sangiliyandi Gurunatha *et al*. (2015) delved into the development of reduced graphene oxide–silver nanoparticles from natural extracts as an anticancer therapeutic agents for the growth inhibition of ovarian cell lines. The results of this study demonstrated the efficiency of these nano-based agents in cancer treatment that can serve as the base for the future research in this field in order to further discover the practical applicability of these agents in cancer treatment[31].The cancer cells were detected with the use of HeLa cells by Zhou *et al*. (2015) in their study. Various multicolor imaging and PDT were performed *via* isolating a complex of GQDs and hypocrellin A that are encapsulated with a silica nanosystem helper[S39]. The study has indicated that the nanosystem had high fluorescence intensity and its anticancer activity was improved, clearly explaining it as a hopeful theranostic system for the PDT of superficial cancer cells cells on the bas relie *F.* In the article (Sui *et al*., 2016), PI staining of bacteria is used as a visualization method and combined with CDDP - GQDs were used for cancer therapy. The authors showed that cisplatin/ cis-Diamminedichloroplatinum (II)(CDDP) in combination with gadopentetic acid (Gd-DTPA) nanoparticles, specifically graphene quantum dots (GQDs) exert more powerful anticancer effects in different types of tumor cells which may be a novel treatment modality to overcome cisplatin-based chemotherapies resistance through cooperation effects[S40]. Nalinithe *et al*. (2016) investigated the anticancer mechanism of some phytochemical components of Calotropis procera represented by electrochemical methods and a cytosensor device they fabricated. That shows its potential as a health product, not just decorative one. The results of the research fully showed up the potency of Calotropis procera extract as an anti-glioblastoma agent opening the way to the role of novel anti-glioblastoma methods[S41]. In this connection, An examination of apoptosis in A^{549} lung cancer cells as done by Kavinkumar *et al*. (2017) was carried out through using dyes including Acridine Orange (AO) and Ethidium Bromide (EB). GO (graphene oxide) and rGO (reduced graphene oxide) nanostructures, and nanocomposites with AgNP embedded in them were made. The study confirmed that rGO\–AgNPs showed high cytotoxicity against A549 cell line(human lung adenocarcinoma) and therefore gave a possibility of their use in cancer treatment by virtue of improved anticancer activity and biocompatibility[S42].The study conducted by Hou and colleagues (Hou *et al*., 2017) explored the potential of the photothermal and photodynamic responses of hyaluronic acid-modified carbon nanomaterials like HA-SWNT, HA-GO, and HA-C60 for the therapeutic treatment of cancer. The *in vitro* and *in vivo* experiments showed positive results that suggested that those functional materials were able to be used as tumor targeted drug delivery systems which made it possible to design therapy for cancer patients[S43]. Farahnaz Barahui *et al*. (2017) carried out a study on the blending of chlorogeneic acid and graphene oxide nanomaterial, which ultimately made this mixture more toxic to cancer cells and non-toxic to normal cells. Researchers selected a certain strain of bacteria and a wide variety of techniques that include UV-visible spectrophotometry, HRTEM, Raman spectroscopy, FTIR spectroscopy, XRD, and thermal analysis. The results of this study revealed that the nanocomposite might possess a huge property directed to therapeutic anticancer treatment with its ability to release an accurate dosing of anticancer drugs and its high toxicity to cancer cells[S44].With regards to the following paper, Hadi Zare-Zardini and colleagues (2018) explain the harmful effects of graphene-based carriers as well

as of cargos made of ginsenoside Rh_2, lysine, and arginine respectively. They synthesized the creation of these nanostructures and tested the different cell lines by using MTT method. What they found out was that the nanostructures were definitely cytotoxic to cancer cells, but had minimal cytotoxic action on normal cells. Besides that they investigated the process of hemolysis using whole human blood of healthy donor which did not result in serious hemolysis[S45]. The challenge can be utilized and is confirmed by the dose-dependent increasing in the TUNEL apoptotic assay cells A new strategy as developed by the group of Afarideh *et al*. (2018) to boost the effect of chemotherapy was found using 5-fluorouracil (5-FU) loading on the GO nano-carriers. The research demonstrated that the formation of a graphene oxide (GO)/ 5-fluorouracil (5-FU) complex increased the probability of CT[26] dsRED cancer cells (murine colon carcinoma) being affected by them almost two times more in comparison with the regular 5-FU. The results of the research have demonstrated a new mechanism of a GO-based nanosensing and drug molecules interaction, which could lead to an increase of hepatotoxicity of chemotherapy which were used in cancer treatment now and it would be a promising strategy for improving the therapeutic result of cancer treatment[S46]. Another thing, Jaya Seema along group (2018) have used graphene oxide to transport phenethyl isothiocyanate (PEITC), which was a cancer killer helper molecule. Any specificity in the characterization process of the nanocomposite through the help of XRD, Raman, UV/Vis, FTIR, DLS and TEM techniques have showed its better effect in curing liver cancer than only drug. Simultaneously, this nanocomposite presents steady releases within the simulated conditions for the human body which proves its suitability for the development of drug delivery systems in cancer medicine transportation[S47]. The study conducted by Ananya Deb *et al*. (2018) incorporated carbon nanotubes (CNTs) as a crucial element of the nano-biocomposites. These composites, which included chitosan, camptothecin (CPT), and diindolylmethane (DIM), were designed using CNTs for their exceptional drug-loading capacity, sustained drug release properties, and enhanced bioavailability. The CNTs were utilized as nanocarrier platforms, leading to improved delivery and therapeutic efficacy of the anticancer agents against breast cancer in both *in vitro* and *in vivo* models[32].On the other side, an experiment by Ananya Deb *et al*. (2018) used camptothecin that was coupled to polyethylene glycol and folic acid for targeted drug delivery to MCF-7 breast cancer cells via GNPs (graphene oxide nanoparticles). The outputs revealed the enhanced cell toxicity in comparison with the free camptothecin demonstration, thus it can be concluded that the drug delivery system has significant potential in cancer treatment.G. Jeevitha *et al*. (2018) examined the WO3-graphene oxide by hydrocarbon (GO) nanocomposite with regard to the efficiency in degrading organic dyes, antimicrobial activity against *Escherichia coli* and *Bacillus subtilis*, and anticancer properties on human lungs cancer cell lines. The study pointed at the composite's functionality aspects, including its potential use in the environmental and biomedical sectors[S48]. Lin *et al*. (2020) fabricated nanosized sheets of RGO via using a natural tea leaf extract of *Euphorbia milii* and then loaded it with paclitaxel molecule to be used as a carrier for targeted chemotherapy in lung cancer. The results of the *in vitro* cytotoxicity assay demonstrated a pronounced cell death of the human alveolar basal epithelial cells line (A549) exposed to the RGO/PTX nanosheets, confirming their promising character as targeted drug delivery system[S50]. The article of Nur Farhanah Rosli *et al*. 2019 directed towards graphene oxide nanoplatelets (GONPs) coulpled to CisPlatin as well as the way it influences human lung cancer cell line *in vitro*. The investigation is reflected in that GONPs acted in the same manner as drug carriers and cisplatin's medicinal properties are potentiated in A549 cell lines, which suggests that these might be helpful in improvement combinational chemotherapy[S51]. Xibo *et al*., (2020) used hydrophilic NGO (Nanographene Oxide) for dual drug delivery in which PEGylated graphene oxide (pGO) delivered cisplatin and doxorubicin effectively to tumor cells. They carried out experiments both in the laboratory and the animal (mice) world in which they noticed that the tumor dramatically went down and cell death was initiated. This brought forth the efficacy of this system in improving the treatment of cancer[S52]. Mariadoss *et al*. (2020) assessed the toxicity of graphene-oxide/silver nanocomposite against human lung cancer cells and brain cancer cells. In their study, the displayed the values of the samples' cytotoxicity and photothermal conversion efficiency, pointing to the nanocomposite material as a promising potential innovative approach

to cancer diagnosis and therapy[S53]. For instance, Ganesan *et al*. (2020) demonstrated the ability of GO-CuO nano-composites synthesized using Acalypha Indica leaf extract to effectively degrade methylene blue dye and also showed a high toxicity level against human colon cancer cell lines. The results advocate for the applicability and effectiveness of the nanocomposites for cancer tumors and drug delivery systems based on the nanocomposites[S54]. Azam Najmafshar *et al*. (2020) evaluated the use of Chitosan Graphene Oxide-Polyethylene Glycol-bovine Lactoferrin (CGO-PEG-bLF) as a nanocarrier to enhance the therapeutic outcome in anticancer-related treatments. The result of their research significantly enhanced cytotoxic performance and cellular intake which led to the reduction of tumor growth in the animal model (mice) for lung cancer, finally implicating CGO-PEG as the potential nanocarriers used in cancer therapy[S55]. Lucherelli *et al* (2020) have designed a novel multi-functional graphene platform - capable of combining both - chemotherapy and phototherapy to give cancer treatment. Platform showed higher anticancer activity than cancer cells, outstanding targeting ability towards cancer cells, and effective drug releasing properties than other cancer therapy applications, which confirm its prospect for advanced future cancer therapy applications[33]. As reported by Markovic *et al*. in 2021, the photothermal cancer-busting effect of graphene nanoparticles was set against U251 human glioma cells. The investigators came to the conclusion that graphene nanoparticles possessed an added advantage of showing more potent action targeted at NIR radiation than carbon nanotubes. We were able to understand mechanistically oxidative stress-induced cancer cell demise by implicating mitochondrial depolarization and a mixture of programmed cell death and necrotic pathway[S56]. Ahamed with his study colleagues (2021) made a composite by doping SnO_2-Doped ZnO/Reduced Graphene Oxide Nanocomposites and examined the anticancer mechanism that happen inside MCF-7 cells. ZnO-based nanocomposites were demonstrated as potent bioactive agents inducing apoptotic responses via oxidative stress pathways that proved to be much better than pure ZnO nanoparticles[S75]. Application of characterization techniques that airfield electron microscopy (FETEM) and X-ray diffraction (XRD) were carried out in order to shed light on the in nanocompositesIn the study conducted by Smina *et al* (2021) the performance of the decreased graphene oxide liquid made by the plant extract was measured and also the impact of it against MCF-7 breast cancer cells was measured. The results gave important evidence of the cytotoxicity, which suggested that as a result, plant-derived compounds could be used in the synthesis of nanomaterials with biomedical applications[S58]. Tas *et al*. (2021) selected PEGylated nanographene oxide (GO-PEG) as a versatile nanocarrier for the anticancer drug docetaxel. This innovative approach aimed to enhance the therapeutic efficacy of docetaxel by improving its stability, bioavailability, and targeted delivery to cancer cells. The study revealed that the Graphene Oxide-Polyethylene Glycol-Docetaxel (GO-PEG-DTX) had a high anticancer activity on prostate cancer cell lines and thus, confirms its potential as a drug delivery system. The stability testing and the cell viability assays collaboratively validated the therapeutic potential of GO-PEG-DTX in cancer therapy[S59]. Kavitha *et al*. (2020) developed GO-CuO nanocomposites via the synthesis of Acalypha Indica leaf extract-derived copper oxide nanoparticles (CuO-NPs) and their combination with graphene oxide (GO). Utilizing these techniques, including FTIR, UV-vis, XRD, SEM, EDAX, XPS, and TEM, they showed that the nanocomposites degrade the methylene blue dye efficiently under the photocatalytic process. Moreover, the nanocomposites showed considerable cytotoxic activity against HCT-116 Human colon cancer cell lines and the ability to be used for both photocatalytic and anti-cancer applications[S60]. The primary objective of Wei *et al*. (2021) was in the development and characterization of therapeutic nanoparticles encapsulating Platinum antiketogenic drugs using with Graphene Oxide and further decorated with different polymers and Folic Acid. Their study showed enhanced drug delivery features for different platinum drugs and demonstrated the ability of the functionalized Graphene Oxide nanocarrier system for platinum cancer chemotherapy[34]. The study of 'Rahdar *et al*. (2021)' focused on the synthesis of graphene oxide dotal/PEG b-poly(HEMA-g-LA)2 nanocomposite for cancer treatment was conducted. The success of the *in vivo* experiments on rats, combined with biochemical and histological analyses, proved that the safety, and effectiveness of these nanocomposites were applicable for cancer therapy[S61]. Farhangfar *et al*. (2022) doped graphene with the

amino acid arginine and ginsenoside Rh2 by modifying this carrier, and they showed that this graphene-based material has the capacity to act on a growth of tumors and to improve the survival rate in mice with mammary cancer. The authors in their team confirmed the therapeutic purpose of using graphene-based nanocomposites in cancer treatment[S62]. Kesavan *et al*. (2022) fashioned a DOXO-loaded nanocarrier system based on graphene nanosheets for the eradication of human glioblastoma cancer cells. Their system showed pH-controlled drug delivery, biocompatibility, and cancer therapy *in vitro* but *in vivo* experiments will be required to fully assess the potential of graphene -based nanocomposites for targeted drug encapsulation and cancer therapy[S63]. Chen *et al*. (2022) innovated the graphene oxide-based exosome functionalized composite bionic smart-drug-delivery system that could specifically attack the breast cancer cells. Through using the tumor exosomes from the breast cancer, the team of the researchers displayed enviable drug release properties and a great increase of effectiveness of the manufactured system of drug delivery[S64]. This clairvoyant, nano-intelligence-enabled drug delivery system demonstrated the unique one-dimensional characteristics of the drug mitoxantrone, enhancing its potential as a transformative treatment for breast cancer, positioning it as more than just a standard therapeutic option.This nanohybrid system developed by Lotfollahzadeh *et al*. (2022) was made up both of S-TRAIL (Soluble Tumor Necrosis Factor-Related Apoptosis-Inducing Ligand) and GQDs and can eradicate colon cancer. This way maintains the safety level and high-grade cytotoxicity of S-TRAIL-CQD compound particles towards HT-29 human colon cancer cells. This creative approach explains its potential of being a theranostic candidate for the colon cancer therapy as it offers multitudinous methods of diagnosis and treatment[S65]. Saranya *et al*. (2023) explored the therapeutic value of the CeO_2/GO [Cerium oxide] composite as a breast cancer therapeutic agent. After anticancer properties were established by hybrid combination and presentation, the scientific quarter completed an apoptosis inducing of MCF-7 cells[S66]. The hybrid material of CeO_2/GO that has been fabricated has demonstrated better cytotoxicity than the Cis- CeO_2/GO, a platform for breast cancer therapy, which therefore, is a promising theranostic agent.The latest study headed by Kanth Kadiyala *et al*. (2023) focused on the dose-dependent cytotoxic impact of ZrO_2/rGO nanocomposites on human cancer cell lines (A^{549} and HCT116). Through careful selection of the types of polymers and synthetization of nanocomposites, the researcher illustrated that it could have some considerable cytotoxicity against cancerous cells, which caused them to commit apoptosis and generation of reactive oxygen species. In this case these results again show the wide range of favorable characteristics of ZrO_2/rGO nanocomposites. This makes them valuable for use in cancer therapy combine cancer cell killing and generation processes of reactive oxygen species[S67].

Functionalization of CNTs

Silver nanoparticle-coated SWCNTs

Research has consistently demonstrated the antimicrobial efficacy of silver nanoparticles (AgNPs) and various metal oxides, along with their ability to inhibit infections. Additionally, the production of reactive oxygen species (ROS) may also be led by the process. Antimicrobial effects on various fungi, bacteria, and viruses have been exerted by antimicrobial peptides (AMPs). It was observed by Chaudhari *et al*. that the antimicrobial activity of silver-coated single-walled carbon nanotubes (SWCNTs) could be enhanced by the addition of antimicrobial peptides (AMPs) when applied against *S. aureus* in a skin infection model. It was found in their study that bacterial growth was significantly inhibited by treating skin with silver-coated functionalized carbon nanotubes (CNTs) by 105 CFU/g [35]. Single-walled carbon nanotubes (SWCNTs) were attached to silver nanoparticles (AgNPs) by Chaudhary *et al*., and they were combined with antimicrobial peptides (AMPs) TP^{359} to examine the antimicrobial efficacy of SWCNTs-adsorbed AgNPs against *S. aureus*, *Streptococcus pyogenes*, *Salmonella enterica* serovar Typhimurium, and *E. coli*. It was found that a strong synergistic antibacterial effect of TP^{359} (Tachyplesin 359) with SWCNTs-adsorbed AgNPs was yielded by the combination. The antibacterial effectiveness of SWCNTs adorned with AgNPs on cotton fabrics against *S. aureus* and *E. coli* was highlighted by another study by Kumar *et al*. [36]. Robust antibacterial properties were exhibited by fabrics coated with SWCNTs-AgNPs against the tested pathogens. Moreover, bacterial growth (*E. coli*) was notably inhibited by AgNPs on silica-coated SWCNTs

substrates compared to AgNPs on plasma-treated SWCNTs substrates, which lost hydrophilicity during AgNPs deposition [37]. Antioxidant and antimicrobial activities against *S. aureus*, *E. coli*, and *E. faecalis* were demonstrated by silver-based biohybrids in a separate study. Greater reductions in microbial growth rates and increased antioxidant capacity were shown by these silver-based biohybrids, composed of phyto-nanosilver, CNTs, and liposomes with cholesterol. Carbon nanotubes (CNTs) and graphene oxide with silver nanoparticles (AgNPs) were produced using a simple, one-step synthesis method by Chang *et al*. to be tested against *E. coli* and *S. aureus*. It was found that antibacterial activity was displayed by the resulting nanomaterials, with graphene oxide AgNPs having the strongest disinfecting properties. It was confirmed by lipid peroxidation assays and antioxidant enzyme activity measurements that oxidative stress *via* O_2- could be induced by the nanomaterials, damaging the bacterial cell membranes and leading to cell death. The antimicrobial effects against *E. coli* and *S. aureus* of single-walled carbon nanotubes (SWCNTs) coated with Ag-doped TiO2 nanoparticles were examined in another study. It was revealed that strong antibacterial properties against both bacteria were shown by the nanocomposites, though *S. aureus* was less sensitive than *E. coli* when exposed to UV light. Pegylated single-walled carbon nanotubes (pSWCNTs) coated with AgNPs were synthesized by Park *et al*., which enhanced their antibacterial activity and were evaluated against foodborne pathogenic bacteria including *Listeria monocytogenes*. A significant decrease in proteins related to bacterial biofilm formation, quorum sensing, cellular structure, and motility in surviving pathogens was observed. Additionally, a hybrid nanocomposite was synthesized using SWCNTs, Ag, and polypyrrole (PPy) in a simple, cost-effective one-pot method by Singh *et al*. The growth of bacterial strains such as *S. aureus*, *P. aeruginosa*, *E. coli*, and *B. cereus* was completely inhibited by the prepared nanocomposites within 24 h. The antibacterial properties of carbon nanotubes (CNTs) with silver (Ag) and graphene oxide (GO) with Ag against both gram-positive and gram-negative pathogens were demonstrated by Yun *et al*. It was found that stronger antimicrobial activity was exhibited by CNTs-Ag compared to GO-Ag nanocomposites, which could be attributed to the superior dispersion of silver nanoparticles (AgNPs) within the CNTs.

Silver nanoparticle-coated MWCNTs

Strong antibacterial properties were demonstrated by silver-coated multiwalled carbon nanotubes (MWCNTs). It was shown that bacterial growth rates of *S. epidermidis* and *E. coli*, *S. aureus*, *Sphingomonas* and *Methylobacterium* species, and *P. aeruginosa* species were suppressed by 93.7–99%, 56.7%, and 100%, respectively, by the silver/MWCNTs complex. When silver-coated MWCNTs were combined with amphiphilic dendrimers, including poly (propyleneimine), bacterial inactivation rates for *S. aureus*, *B. subtilis*, and *E. coli* were observed to exceed 90%. Similarly, effective inhibition of *S. aureus* and *E. coli* was achieved by polymer colloids immobilized with the silver/MWCNTs combination. On the other hand, microbial growth suppression rates of 55.7% for *S. aureus*, 97.8% for *E. coli*, and 78.5% for *P. aeruginosa* were observed when poly(amidoamine)-grafted MWCNTs were incorporated with silver sulfide (Ag_2S) quantum dots. Additionally, superior antibacterial activity was demonstrated by Ag2S-MWCNTs when compared to MWCNTs coated with cadmium sulfide quantum dots [38].

Modified with carboxyl, hydroxyl, and amine groups

The surface functionalization such as addition of carboxyl, hydroxyl, and amine groups modify single-walled carbon nanotubes (SWCNTs), improved properties for biomedical uses. The solubility, compatibility with biological environments, and interactions of SWCNTs are increased by these changes. The antimicrobial effectiveness is enhanced by the functionalization, making SWCNTs more capable of targeting and stopping the growth of different microbial strains. Specific binding to certain types of microorganisms is allowed by the functional groups, improving the potential for targeted antimicrobial treatments. Carbon nanotubes (CNTs) can be applied with different functionalization methods, such as covalent and non-covalent techniques. CNT-bacterial aggregates can be formed by acid or carboxyl group modifications, enhancing interactions with pathogens. The binding to microbial cells by functionalized CNTs has been improved, as demonstrated by prior research. The effects of various surface functional groups on single-walled carbon nanotubes (SWCNTs), including -NH_2, -COOH, and -

OH, on their microbial inhibitory effects against *S. aureus*, *B. subtilis*, and *Salmonella typhimurium* were examined in this study. It was shown that bacterial growth was inhibited by SWCNTs with cationic -NH_2 groups only at higher concentrations, while strong inhibitory effects (7-log reduction) were produced by those functionalized with anionic -COOH and neutral -OH groups against the pathogens tested. The implication of the strong inhibitory effects is that some or all of the population's cells were rendered inactive upon exposure to SWCNTs functionalized with -COOH and -OH groups. While a lengthy carbon chain $CH_3(CH_2)16CH_2$-NH_2 was used to modify the -NH_2 group, the other groups were directly produced from the surface of SWCNTs. It was hypothesized by this group that bacterial cell death is probably caused by direct interaction with the SWCNTs. The interaction of SWCNTs-NH2 with microbial cells might be affected by the extended carbon chain. The inhibitory effects would be lessened by the prevention of close contact between the cylindrical form of the SWCNTs and the microbial cell walls. Moreover, selective inhibitory effects against various pathogens are shown by functionalized SWCNTs, and bacterial contacts with the nanotubes are promoted, irrespective of the surface functional group[37].

Antimicrobial activities of functionalized SWCNTs

Functionalized single-walled carbon nanotubes (SWCNTs) offer notable antibacterial properties, proving effective in hindering microbial growth on different biomedical surfaces. It's important to explore their interactions with various types of microorganisms. Consequently, this section will primarily focus on the impact of functionalized SWCNTs with various nanocomposites in augmenting their antibacterial efficacy against a spectrum of microbial strains, as detailed in the following (Table 7).

Antimicrobial activities of functionalized MWCNTs

Table 7 — Antimicrobial activities of Functionalized SWCNTs

Material blend	Concentration	Species	Main findings
f-SWNTs with functional groups (-OH, -COOH, -NH_2)	50-200 µg/mL	*S. aureus, B. subtilis, and S. typhimurium*	SWNTs functionalized with -OH and -COOH functional group showed more microbial inhibition rate (7-log reduction) against selected pathogens, while SWNTs with -NH2 displayed antimicrobial activity only at high concentrations
Silver-SWNTs functionalized with peptides (TP226, TP359, TP557)	5 µg/mL	*S. aureus*	The viability of bacteria increased by 4-log in non-treated skin model, whereas treated skin with functionalized silver-SWNTs showed antimicrobial activity only 1-log reduction.
Functionalized SWNTs with DNA and lysozyme (LSZ)	~25 mg/L	*S. aureus, and M. Lysodeikticus*	Layer by layer coating of DNA- and LSZ-SWNTs displayed high antimicrobial activity (with 84% microbial reduction).
SWNTs incorporated inside poly(lactic-co-glycolic acid)	<2% by weight	*E. coli, and S. Epidermidis*	The metabolic activity of bacteria was considerably decreased (98%) with SWNTs-PLGA, while 15-20% reduction rate observed with pure PLGA.
SWNTs-polyvinyl-N-carbazole (PVK) nanocomposite	3 wt.%	*E. coli, and B. subtilis*	SWNTs-PVK nanocomposite induced a higher rate of bacterial inactivation (90% for *B. subtilis* and 94% for *E. coli*) in the planktonic cells and showed a significant reduction of biofilm formation.
SWNTs assembled with poly (L-glutamic acid) (PGA) and poly(L-lysin)(PLL) (layer-by-layer)	<2% by weight	*E. coli, and S. Epidermidis*	SWNTs/PGA/PLL showed a higher rate of antimicrobial activity (90%) against selected pathogens than non-treated samples of PGA/PLL (with 20% reduction rate).
Oxidized SWNTs with poly (vinyl alcohol) (PVOH) nanocomposite	0-10% (w/w)	*Pseudomonas Aeruginosa*	The viability of cell deposited on the surface of O-SWNTsPVOH gradually decreased with increasing in nanotubes loading.
SWNTs/porphyrin composite	0.04 mg/mL	*S. aureus*	In the presence of visible light, SWNTs/porphyrin induced damage to the cell membrane.
Functionalized-SWNTs/ poly (ethylene glycol) (PEG) and poly (ε caprolactone) composites	0.5-1.0 wt.%	*P. aeruginosa, and S. aureus*	The proliferation of tested bacteria inhibited by f-SWNT/copolymer complex to a lower extent as compared to pure polymer complex.
SWNTs bound with polyamide membranes	0.1-0.2 mg/mL	*E. coli*	The complex of nanocomposite inactivated the microbial cells by 60% after 1 h of contact time.

Numerous studies and applications in a variety of sectors had been focused on multi-walled carbon nanotubes (MWCNTs) because of their special physicochemical characteristics and potential as antibacterial agents. Highly efficient antimicrobial surfaces have been created by extensively examining and using functionalized MWCNTs made of various materials. Earlier research on the biocidal properties of MWCNTs and their interactions with a variety of bacteria is provided in (Table 8).

MWCNTs modified with functional groups

Functional groups were added to the surface of multi walled carbon nanotubes (CNTs) to decrease unexpected molecule absorption from the biological environment and prevent desorption processes. The prevention of microbial growth was determined by the rate at which different functional groups were adsorbed onto the surface of carbon nanotubes (CNTs). The connection between microbial cytotoxicity and functional group adhesion to carbon nanotube surfaces was assessed by The relationship between toxicity and the physicochemical characteristics and aggregation state of functionalized

Table 8 — Antimicrobial activities of functionalized MWCNTs

Material blend	Concentration	Species	Main findings
f-MWNTs with functional groups (-OH, -COOH, NH_2)	*50-200 µg/mL*	*S. aureus, B. subtilis, and S. typhimurium*	*MWNTs functionalized with -OH and -COOH functional group did not significantly induce antimicrobial activity on selected pathogens.*
	-25 µg/mL	*E. coli, B. subtilis, and S. aureus*	MWNTs-COOH inactivated the bacterial cells by 30% for *B. subtilis*, 40% for *E. coli*, and 50% for S. aureus, respectively
	20 µg/mL	*S. aureus, E. coli, and P. aeruginosa*	MWNTs-COOH inactivated the bacterial cells by 26.9% for *P. aeruginosa*, 34.1% for *E. coli*, and 22.8% for *S. aureus*, respectively.
	20 mg/20 mL	*S. aureus, E. coli, and P. aeruginosa*	MWNTs-COOH inactivated the bacterial cells by 26.8±1.1 for *P. aeruginosa*, 20±0.8 for *E. coli*, and 14.7±0.5 for S. aureus, respectively.
	20 µg/mL, 50 µg/mL, 100 µg/mL	*E. coli, S. aureus, E. faecalis, L. acidophilus, and B. adolescentis*	MWNTs-COOH and MWNTs-OH induced dose dependent microbial inhibition against selected pathogens.
	1000 µg/mL	*V.parahaemolyticus*	Antimicrobial activity of functionalized-MWNTs was time-dependent. Functionalized nanotubes that did not pierce into the cell membrane, rather wrapped around the surface of the pathogen.
	0–100 mg/mL	Group A *Streptococcus*	Carboxylated-MWNTs functionalized with antibodies may have the potential to mitigate the bacterial infections of soft tissue.
	20 µg/mL – 100 µg/mL	*Staphylococcus aureus, P. aeruginosa, K. pneumoniae,* and*C. albicans*	Microbial growth was inhibited by non-covalently dispersed CNTs and relied heavily on the treatment time and concentration. MWNTs demonstrated higher antimicrobial effect on selected pathogens.
Surfactant- functionalized MWNTs with sodium dodecylbenzene sulfonate (SDBS), sodium cholate (SC), sodium dodecyl sulfate (SDS), triton X-100 (TX-100), dodecyltrimethylammonium bromide (DTAB), cetyltrimethylammonium bromide (CTAB), and polyvinylpyrrolidone (PVP)	1.0, 0.5, 0.25 and 0.125 mg/mL 0.1, 0.5, 1 mg/mL	*S. mutansE. coli*	Functionalized-MWNTs caused cell membrane rupture via direct contact. Functionalized-MWNTs penetrated the bacterial cell membrane due to electrostatic forces between bacterial membrane and surfactant.
AgNPs-coated MWNTs	2-30 wt%	*E. coli*	The cell membrane of bacteria damaged via direct contact.
f-MWNTs with lysine	0.01875 to 0.6	*S. aureus, E. coli, S.*	Electrostatic adsorption presented between the bacterial membrane

	mg/mL	*agalactiae, S. typhimurium, S. dysgalactiae,* and *K. pneumoniae*	and positive charges lysine groups on MWNTs.
MWNTs functionalized with amphiphilic dendrimer poly (propyleneimine)	25 µg/mL	*E. coli, B. subtilis,* and *S. aureus*	MWNTs-nanocomposite inactivated the bacterial cells by 96.5% for S. aureus, 96.6% for *B. subtilis*, and 87% for *E. coli*, respectively
MWNTs functionalized with aromatic dendrimer polyamide	20 µg/mL	*S. aureus, E. coli,* and*P. aeruginosa*	MWNTs-nanocomposite inactivated the bacterial cells by 35.5% for S. aureus, 65.2% for *P. aeruginosa*, and 72.6% for *E. coli*, respectively

SWCNTs was also investigated by researchers; however, no connection was found between the thermal, physicochemical, or structural characteristics of functionalized SWCNTs and bacterial cytotoxicity. Instead, nanoparticle aggregation was found to be a far more significant factor in determining the cytotoxicity of functionalized SWCNTs. Furthermore, a substantial reduction in the survival of microorganisms such as *B. subtilis* by 30%, *P. aeruginosa* by 27%, *E. coli* by 20–40%, and *S. aureus* by 15–50% was observed when MWCNTs functionalized with carboxyl (-COOH) groups were used[18]. It was also shown by Chen *et al*. that MWCNTs functionalized with hydroxyl (-OH) and carboxyl (-COOH) groups had a dose-dependent antibacterial impact on pathogens such as *E. coli*, *S. aureus*, *E. faecalis*, *L. acidophilus*, and *B. adolescentis*. A comparable outcome was observed by Ding *et al*. regarding *Vibrio parahaemolyticus*. According to research by Arias *et al*., less antibacterial efficacy was shown by MWCNTs functionalized with hydroxyl (-OH), amine (-NH_2), and carboxyl (-COOH) groups compared to SWCNTs. Numerous studies have been conducted on the antibacterial properties of non-covalently dispersed CNTs (DWCNTs and MWCNTs) against *S. aureus*, *K. pneumoniae*, *P. aeruginosa*, and *C. albicans*. A significant impact was observed on the ability of non-covalently distributed CNTs to inhibit microbial growth by the length and concentration of the treatment. Inhibition of microbial growth was observed to be greater by ethanolamine-functionalized MWCNTs compared to pure MWCNTs. Stronger antibacterial effects were observed by different researchers when MWCNTs modified to include oxygen-containing groups[19].

MWCNTs combined with elevated metals

To enhance antibacterial activity, MWCNTs have been combined with other noble metals, such as copper nanoparticles, leading to a 75% decrease in bacterial viability. Similarly, substantial antibacterial action was obtained when *E. coli* was treated with MWCNTs covered with zinc oxide. Significant suppression of microbial growth had been shown against *B. subtilis*, *K. pneumoniae*, *S. aureus*, *C. albicans*, *Streptococcus pneumoniae*, *Proteus vulgaris*, and *Shigella dysenteriae* by a nanocomposite complex consisting of MWCNTs, titanium, and gold. Furthermore, effective inhibition of biofilm development was achieved for a maximum of five days by Rifampicin in combination with MWCNTs coated with titanium alloy[17].

Antimicrobial mechanisms of CNTs

Several antibacterial processes using carbon nanotubes (CNTs) have been postulated in numerous investigations. These mechanisms include (1) the enhancement of transmembrane electron transfer, damaging the membrane and cell wall, by CNTs attaching to the surface of the microbial cell; ang, S., Herzberg, M., Rodrigues, D. F., & Elimelech, M. (2008). Antibacterial effects of carbon nanotubes: Size does matter! *Langmuir, 24*(13), 6409-6413. (2) damage to DNA and proteins by CNTs penetrating bacterial cells;and (3) cell damage caused by the generation of secondary substances like reactive oxygen species (ROS). It has been revealed by many studies that microbial cell death is eventually caused by the leakage of internal substances due to the disruption of the pathogen's cell membranes. For example, the first concrete proof that leakage of internal components, including DNA, RNA, and proteins, was caused by direct interactions between pathogens and single-walled carbon nanotubes (SWCNTs) was presented by Kang *et al*. While it was originated by some researcher that 60 min of interaction between bacteria and SWCNTs was

enough to cause membrane damage, other investigations required longer contact times, up to several days, to produce comparable effects[14]. The physical interactions between aggregated SWCNTs and microbial cells were investigated by Arias *et al*. using scanning electron microscopy (SEM), and it was found that the side walls of SWCNTs interacted with *Salmonella* cells. Frequently, bacterial cell death is initiated by the rupture of the membrane, which is followed by the extrusion of intracellular components. The proton motive force, membrane permeability, and cellular structure of the cellular membrane are all affected by carbon nanotube adhesion. The leakage of cytoplasmic contents was validated by Kang *et al*. by quantifying RNA and DNA, and the loss of bacterial (*E. coli*) cellular integrity was investigated using scanning electron microscopy (SEM). Significant cellular membrane damage was suggested by the two-fold rise in RNA and the five-fold increase in plasmid DNA that were discovered in the solutions. Similarly, the antibacterial efficacy of CNTs with double and multiple walls against *S. aureus*, *P. aeruginosa*, *K. pneumoniae*, and *C. albicans* was investigated by Saleemi *et al*. It was observed that severe damage to the cell wall and membrane of the pathogens was caused by the CNTs' wrapping around both kinds of infections. According to Liu *et al*., "nano darts" were formed by scattered single-walled carbon nanotubes (SWCNTs) in aqueous solutions, targeting and killing both Gram-positive and Gram-negative bacteria [39]. Additionally, when Ralstonia solanacearum was exposed to CNTs, similar results were detected.

Production of ROS and oxidative stress

Oxidative stress is one of the vital process that might explain why bacteria are harmed by carbon nanotubes (CNTs). Harmful reactive oxygen species (ROS) such as superoxide anion (O_2), hydroxyl radicals (OH), hydrogen peroxide (H_2O_2), and organic hydroperoxides can be produced by CNTs once bacterial cells are penetrated by them. The unsaturated phospholipids in the cell membrane start to peroxide when these ROS are present, producing peroxyl radical intermediates that can harm nucleic acids and lipoproteins. By causing modifications in membrane proteins and changing the fluidity and integrity of the membrane, lipid peroxidation can also impact the characteristics and activities of membranes, which can eventually result in microbial cell death. The quantity of ROS generated in microbial cells is influenced by the physicochemical characteristics of carbon nanotubes (CNTs), including their surface area and electrophilicity. Many genes linked to the bacterial oxidative stress response, such as the soxRS and oxyR systems, are activated when bacteria are exposed to single-walled carbon nanotubes (SWCNTs) and multi-walled carbon nanotubes (MWCNTs). Furthermore, the toxicity of SWCNTs was investigated by Vecitis *et al*. (2010) by analyzing the *in vitro* oxidation of glutathione, a non-enzymatic antioxidant that aids in bacterial defence against oxidative stress, by SWCNTs. Higher proportions of metallic SWCNTs were observed to promote glutathione oxidation, which may indicate that lipid peroxidation in the bacterial membrane has risen. Increased oxidative stress was experienced by microbial cells as a result of this imbalance between oxidants and antioxidants. Excessive ROS generation was found to interfere with the actions of antioxidant enzymes, thereby harming bacterial cells.Although oxidative stress and carbon nanotube (CNT) toxicity have been linked, other research indicates that oxidative stress might not be the only factor leading to microbial cell death. For instance, in an investigation on the redox potential of single-walled carbon nanotubes (SWCNTs), it was discovered by Liu *et al*. that treatment of *Bacillus subtilis* and *E. coli* with SWCNTs resulted in the loss of thiol groups (-SH) on proteins present on both the outside and inside of the cell membranes. Thiol oxidation did not occur under anaerobic circumstances, suggesting that the SWCNTs remained outside the microbial cells and did not pass through the cell membrane to oxidize intracellular proteins. These results imply that oxidative stress induced by SWCNTs may not be a significant factor in the antibacterial activity of the particles[39,40].

DNA degradation

It has been suggested that the surface of bacteria like *S. mutans* may be gripped to by CNTs through entanglement without causing damage to the bacterial cell membrane. It was found by Simon-Deckers *et al*. that DNA damage and protein malfunction can be caused by CNTs by studying the adsorption of bacteria (*Cupriavidus metallidurans* and *E. coli*) onto multi-walled carbon nanotubes (MWCNTs) using transmission electron microscopy. The integrity of the DNA may be threatened by single-strand breaks caused by direct interactions between CNTs and

DNA. Furthermore, it has been suggested that conformational changes in DNA structure and the degradation of supercoiled DNA base stacking can be caused by CNTs. In general, antimicrobial effects can be provided by nanomaterials targeting internal components, including proteins, RNA, and DNA, or by damaging the membranes surrounding bacterial cells. CNTs can potentially interact with DNA in an indirect manner without going inside the cell. Secondary effects include the production of reactive oxygen species (ROS), which may interact with DNA and obstruct DNA repair pathways, might cause this. Protein thiol (-SH) groups and side chains of amino acids may attach to CNTs, changing the electrical characteristics of the protein. Furthermore, the production of hydroxyl radicals that react with protein molecules can be catalyzed by the metallic catalytic residues (such as nickel) found in CNTs during their manufacture[41].

CNT mediated drug delivery

In the early stages, the potential of carbon nanotubes for biomedical applications was identified by Iijima (1991), who discovered multi-walled carbon nanotubes. This foundational work set the stage for future research, although drug delivery applications were not explored immediately.The feasibility of using carbon nanotubes for drug delivery was first demonstrated by Bianco *et al*. (2005), where CNTs were functionalized to improve biocompatibility and drug loading capacity. It was found that functionalized CNTs could be employed to transport therapeutic molecules effectively into cells. A significant advancement was made by Singh *et al*. (2008), where multi-functional carbon nanotubes were developed. These were designed for targeted drug delivery, and it was shown that they could be directed towards specific cancer cells, enhancing the therapeutic outcomes while minimizing side effects.Further refinement in targeting efficiency was reported by Liu *et al*. (2011), who engineered carbon nanotubes with peptide sequences that specifically recognized cancer cells. The targeted delivery was facilitated by these peptides, which led to increased uptake by tumor cells.The role of carbon nanotubes in overcoming multidrug resistance was explored by Zhou *et al*. (2013). It was observed that CNTs could be used to co-deliver anticancer drugs and siRNA, effectively silencing drug resistance genes in cancer cells.Recently, the biocompatibility issues associated with carbon nanotubes were addressed by Smith *et al*. (2020), who developed a new coating technique that significantly reduced the cytotoxicity of CNTs. This improvement was critical for advancing the clinical applications of CNT-based drug delivery systems.As the field continues to evolve, the latest research by Huang *et al*. (2024) introduces a novel hybrid CNT system combined with liposomes for dual drug delivery. This hybrid system was reported to enhance the therapeutic efficacy through synergistic effects, providing a controlled release of two different drugs.This review highlights that the journey of carbon nanotube-mediated drug delivery has been marked by significant innovations and improvements, which have progressively enhanced their application in targeted therapy[1,32,S3,4,6].

In vivo study on CNT-Related Toxicity

Lam *et al*. (2004) conducted one of the early studies that raised concerns over the pulmonary toxicity of CNTs. Their investigation demonstrated that CNT exposure led to the formation of granulomas in rats' lungs, suggesting significant inflammatory responses (Lam *et al*. 2004) Shvedova *et al*. (2005) conducted further investigations of CNTs' potential health impacts and reported that single-walled carbon nanotubes (SWCNTs) induced oxidative stress and inflammation in mice's lungs due to single-walled CNT exposure. Their research demonstrated dose-dependent toxicity as well as cell damage (Shvedova *et al*. 2005). Donaldson *et al*. (2006) raised concerns regarding the similarities between CNTs and asbestos fibers. Their study suggested that similar to asbestos exposure, CNTs may lead to mesothelioma or related illnesses if inhaled (Donaldson *et al*. 2006). Their results led to further inquiries regarding potential long-term risks from CNT exposure. Poland *et al*. (2010) investigated the structural similarities between CNTs and other fibrous materials known to cause harmful effects, like asbestos fibers. Their findings demonstrated how CNTs may penetrate mesothelial lining of lungs similar to asbestos fibers and cause mesothelioma (Poland *et al*. 2010). Zhang *et al*. (2012) conducted research that shed light on the genotoxic effects of CNTs. Their investigation revealed that exposure could lead to DNA damage in human lung cells, raising concerns regarding potential carcinogenicity of these materials (Zhang *et al*., 2012). Li *et al*. (2018) examined the cytotoxic effects of multi-

walled carbon nanotubes (MWCNTs) on human epithelial cells and rats in their experiment. Their findings indicated that prolonged exposure led to significant cell death, providing further evidence that CNTs may pose considerable health risks (Li *et al*., 2018). Their research concluded that prolonged exposure led to significant cell death, providing further proof that CNTs may pose potential health risks (Li *et al*. 2018).Yamashita *et al*. (2022) recently conducted an in-depth analysis of the immunotoxicity of CNTs using mice as the model organism. Their research concluded that CNTs could influence immune responses, leading to chronic inflammation and tissue damage (Yamashita *et al*., 2022)[S69-S75].

Ethical Issues of Carbon Nanotubes in Biomedical Applications

Carbon nanotubes (CNTs) have emerged as promising nanomaterials in biomedical and biochemical applications, from drug delivery to biosensors. Their unique properties (high surface area, conductivity, strength) enable innovative therapies and diagnostics. However, these same properties raise complex ethical issues that must be addressed as CNT-based technologies move from lab to clinic. This review examines recent findings (2019–2024) on key ethical concerns surrounding CNTs in biomedicine, including toxicity and biocompatibility, environmental and occupational risks, informed consent and patient awareness, regulatory challenges, and potential solutions like Responsible Research and Innovation (RRI). We integrate updated evidence and perspectives, aiming to guide responsible development of CNT-enabled healthcare.

A primary ethical concern is the potential toxicity of CNTs to patients and research participants. CNTs are increasingly produced at large scale for diverse applications, including medicine, yet studies have shown some forms can behave like hazardous fibers in the body. For example, multi-walled carbon nanotube MWCNT-7 has been linked to malignant transformations in animal models, using mechanisms akin to asbestos-induced tumorigenesis. Long, biopersistent CNT fibers can lodge in lung tissue, causing chronic inflammation, fibrosis, and even mesothelioma-like pathology in rodents.

While many researchers functionalize or coat CNTs to improve biocompatibility, results remain mixed. Some *in vivo* studies report minimal acute toxicity or organ damage when CNTs are properly functionalized or administered in moderate doses. For instance, mice injected with well-dispersed CNTs showed no immediate harm to major organs and normal blood counts in one study. However, other experiments show that inhaled CNTs can elicit strong inflammatory responses: mice exposed to CNT aerosols developed neutrophil influx and elevated cytokines in their lungs. The length, rigidity, and dose of CNTs appear critical factors – longer, stiffer CNTs often being more toxic. Given these uncertainties, it is ethically imperative to thoroughly assess CNT toxicity profiles before clinical use. Patients and participants must be protected from unintended harm, honoring the principle of *nonmaleficence*. Until clear evidence of long-term safety is established, using CNTs in humans demands caution and robust oversight.

Beyond patient safety, CNT-based innovations pose ethical concerns for environmental and occupational health. The production, handling, and disposal of CNTs may expose workers and ecosystems to unknown risks. Occupational studies indicate that manufacturing or lab personnel who handle CNT powders or aerosols could inhale nanoparticles that deposit in the lungs. Indeed, few occupational exposure limits (OELs) exist for nanomaterials, and standard dust limits may not be adequate for nanoscale particles. The U.S. National Institute for Occupational Safety and Health (NIOSH) has recommended an exposure limit of 1.0 $\mu g/m^3$ (8-h TWA) for respirable CNTs and fibers. This guidance reflects early evidence that CNT inhalation can lead to lung fibrosis and possibly cancer in animals, echoing the need to protect workers from an "asbestos-like" hazard.

Environmental release of CNTs is another concern. CNTs are extremely stable (highly persistent) and could accumulate if released into air, soil, or water. Recent reviews highlight challenges in tracking CNTs in the environment: lack of standardized methods makes it difficult to determine their fate and toxicity in ecosystems. Nonetheless, CNTs embedded in composites or electronics *can* leach out or wear down, becoming a source of environmental contamination. Once in aquatic systems, CNTs might be taken up by organisms and biomagnify through food chains. The uncertainty around long-term ecological effects poses an ethical dilemma. The *precautionary principle* suggests that until more is known, stringent

regulations should control CNT disposal and emissions.

When CNTs are used in a clinical trial or therapy, informed consent and patient awareness become paramount ethical issues. Nanomedicine interventions often carry *unknowns* – their nano-scale behavior in the human body may lead to unexpected interactions or side effects. For instance, nanoparticles can interact with cellular organelles in atypical ways, potentially causing unforeseen cellular damage. Patients considering a CNT-based treatment (such as a drug delivery system for cancer) must understand that while the technology is promising, it also "can pose unexpected or even unprecedented harms" beyond the familiar side effects of traditional treatments.

Ethicists emphasize that participants should be clearly told when an intervention is experimental and what distinguishes nanotech-based treatments. A 2023 scoping review found that informed consent in nanomedicine remains one of the top concerns in bioethics, second only to potential harm exposure. This underscores the need for ethical nanomedicine communication, balancing excitement about breakthroughs with honest discussion of uncertainties, so patients can make informed decisions.

CNT-based biomedical applications challenge existing regulatory frameworks. Current drug and medical device regulations struggle to classify CNT therapies, as they often function at the intersection of pharmaceuticals, biologics, and materials science. The European Medicines Agency (EMA) and FDA have yet to establish specific CNT-focused guidelines, leading to ambiguity in product approvals. Without clear regulations, some manufacturers might exploit loopholes to avoid rigorous testing, while others face delays due to uncertainty in classification.

The EU considered banning CNTs outright in 2019, citing toxicity risks, but this was met with opposition from experts who argued that a blanket ban would be scientifically unjustified. Instead, many advocate for a risk-based approach, differentiating between low-risk functionalized CNTs and high-risk long-fiber CNTs. As CNT-based therapies grow, global standardization of safety protocols is necessary.

Experts advocate for Responsible Research and Innovation (RRI) to address these ethical issues. RRI promotes transparency, ethical foresight, and public engagement in emerging technology development[42-44,S14-18].

Conclusion

Carbon nanotubes (CNTs) represent a cornerstone of modern nanotechnology, offering unsurpassed versatility and superior properties that make them indispensable in numerous scientific and industrial applications. This review has shed light on significant advances made in their synthesis, functionalization, and applications; underscoring their role in material science advances. From their unique mechanical strength and electrical conductivity properties to thermal stability characteristics; CNTs remain at the forefront of research due to their potential to revolutionize fields like electronics medicine and environmental technology.CNTs' antimicrobial properties have opened new avenues for biomedical applications, showing their efficacy against various pathogenic microbes. Their ability to interact with cell membranes of bacteria and fungi, leading to structural disruption of those membranes is a valuable trait when developing antimicrobial agents; yet challenges still exist with regard to dispersion, scalability, and environmental impacts of CNT production; ongoing research and development will need to take place as a result.Future efforts must address these challenges by improving synthesis processes and exploring environmental consequences associated with wide CNT usage. Innovation and interdisciplinary research must continue in order to harness their full potential and ensure sustainable technological advances are realized with them. It is equally essential that we balance technological benefits associated with carbon nanotubes against environmental stewardship practices as we move forward, so as not to neglect ethical considerations in their application. while carbon nanotubes (CNTs) hold significant promise in biomedical applications due to their unique properties, addressing ethical concerns such as potential toxicity, environmental and occupational risks, informed consent, and regulatory challenges is crucial. Implementing Responsible Research and Innovation (RRI) principles can guide the development of CNT-enabled healthcare technologies, ensuring they are safe, effective, and ethically sound.

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