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CARBON NANOTUBES AS DUAL-ACTION NANOMATERIALS: REACTIVE OXYGEN SPECIES-MEDIATED ANTIFUNGAL AND ANTICANCER MECHANISMS

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Abstract *Carbon nanomaterials, especially CNTs, have drawn much attention over the past decade due to their versatile biomedical engineering and pharmaceutical sciences applications. Such materials have distinct mechanical, electrical, and physicochemical properties, which render them applicable to a wide range of diagnostic and therapeutic applications. CNTs have been investigated widely for their antimicrobial properties due to their ability to interfere with the cell membranes and produce ROS, which makes them toxic. As far as biomedical applications are concerned, CNTs are also being probed for promoting drug delivery, particularly in cancer treatment, by leveraging the possibility of ROS generation inside the cancer cells. The bioproliferation of ROS is important for tumorigenesis and treatment alike, as CNTs can result in oxidative stress, which can cause cell apoptosis or facilitate the onset of cancer by damaging DNA. The paper reports CNTs that are interacting with cells, their opportunities for nanomedicine, drug delivery, and the damage caused by CNTs in cancer therapy. However, the safety and biocompatibility of CNTs are still a major issue, and further studies are required to improve their application in therapeutic settings. In this review, CNT-mediated cellular damage is reviewed in detail, as well as their potential in medical and biotechnological applications.*

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Introduction

The rapidly expanding field of nanotechnology has revolutionized numerous industries with its ground-breaking implications for biology, electronics, pharmaceutical delivery, beauty products, material research, aviation engineering, and biosensors. The exceptional intrinsic qualities of metal-based nanoparticles (NP) and carbon nanotubes (CNT) among all nanomaterials have attracted significant commercial interest because they satisfy the requirements of the particular application for which they are planned (Moradi et al., 2017). Because of the extreme diversity of NM's physical and chemical characteristics, including dimensions, form, framework, and element contents, determining their hazardous consequences is difficult and complex. The suppression of cell division and death, cellular oxidative stress, inflammatory processes, and genetic damage are a few of the possibilities for nanoparticle-mediated toxicity. The majority of research so far has indicated that NP toxicity is commonly associated with ROS production, which can be beneficial or detrimental during biological interactions and the oxidative stress that results. Since many of these NP intrinsic features may stimulate the creation of ROS, the Physical and Chemical Characterization of NP, including its particle size, surface charge, and chemical makeup, is a significant predictor for the subsequent ROS response and NP-induced damage (Takhar and Singh, 2025). Through their interactions with many components of the cell, CNTs cause oxidative stress and excessive production of ROS. ROS are produced when immune cells fail to fully phagocytose CNTs, which is a form of defense. ROS generation can be accelerated by the presence of reactive groups or transition metals on the surface of carbon nanotubes (CNTs). These metals can engage in redox metabolism, which produces ROS continuously and harms biological components (Manke et al., 2013). ROS can degrade lipids in cell membranes, compromising membrane integrity. This lipid peroxidation can lead to increased cell permeability and, ultimately, cell death (Nasim et al., 2024). Because of their unusually large surface area per unit mass, small size, and high surface reaction activity (Auffan et al., 2009), nanoparticles are innately toxic. This physico-chemical reaction is often associated with the potential of nanoparticles, particularly metal-based nanoparticles, to directly or indirectly cause the formation of free radicals (i.e., reactive oxygen species (ROS) such as superoxide radical anions and hydroxyl radicals) or to activate oxidative enzymatic pathways that result in a state of oxidative stress (Shvedova et al., 2012).

Antimicrobial Properties and Biomedical Applications of Carbon Nanotubes

Carbon nanomaterials are widely exploited in biomedical engineering and pharmaceutical sciences in modern years due to their distinct structure and mechanical capabilities. The physical and chemical characteristics of carbon, a frequently accessible element, have drawn a lot of interest recently. Carbon nanotubes (CNTs), one of the many carbon nanostructure materials that have been found for a range of uses, are a common material in the biomedical industry. The spherical, circular cylindrical structures known as carbon nanotubes (CNTs) are composed of a large aspect ratio of folded graphene sheets. Depending on the rolling angle, they may have semi-conductive or metallic characteristics. The quantity of graphene sheets on their surfaces determines their classification (Figure 1), such as single-walled carbon nanotubes (SWCNTs) and multi-walled carbon nanotubes (MWCNTs). The second type is made up of many single-walled nanotubes that are grouped within the tubes (Liu et al., 2024). Because of its superior physicochemical characteristics, SWCNTs have the strongest antibacterial activity among the many forms of CNTs (Asaftei et al., 2023).

The decay of microbes is really significantly influenced by the size of these substances. In fact, the CNMs' surface-to-volume ratio rises with decreasing size, strengthening their interaction with the microorganisms' cell wall or membrane and enabling them to work more efficiently. The interaction between CNTs and microbes, as well as the disruption of their cellular membrane, metabolic processes, and structure, is the basis for this activity's process (Kulanthaivel and Mishra, 2021). The structure, modification of the surface, target microbes, and reactive environment of CNMs all affect their antimicrobial activity (Ifijen and Omonmhenle, 2024). The mechanisms include biological separation of microbial cells from their supporting environment, harm to the structure, and penetration of microbial cell membranes. The third category of processes, known as chemical antimicrobial activities, relies on the interaction of CNMs with microbes and the creation of oxidative stress conditions through the generation of harmful substances such as reactive oxygen species (ROS). Electron transfer results from CNM-microorganism contacts; as the electrons are removed from the microbiological surface, ROS-independent oxidative stress develops, which causes biological mortality (Azizi-Lalabadi et al., 2020).

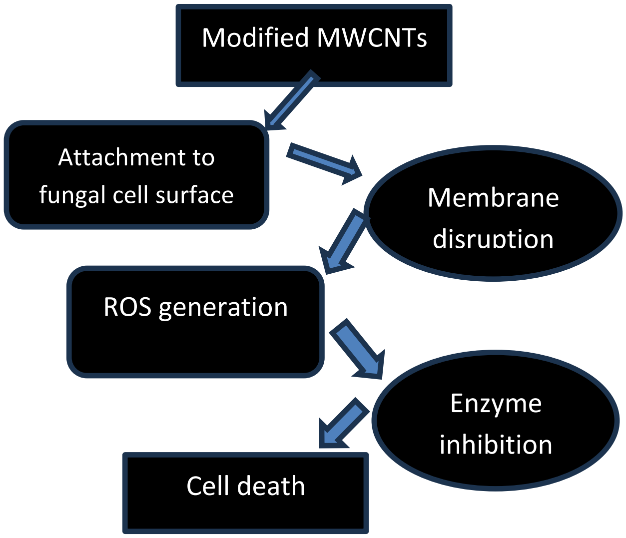

Figure 1. The antifungal activity of modified carbon nanotubes (MWCNTs) is shown in the flowchart. It emphasizes important approaches, such as the attachment to fungal cells and membrane disruption by antimicrobial peptides, reactive oxygen species (ROS) production, enzyme inhibition, and blockage of nutrient intake, which leads to fungal cell death and simultaneously prevents host cell lysis.

The Dual Role of Reactive Oxygen Species in Cellular Physiology and Pathology

The term ROS, which stands for reactive oxygen species, is widely used in various fields, including medicine (Figure 2). It refers to oxygen-containing atoms and molecules, both radical and non-radical, such as superoxide anion ($O_2−$), singlet oxygen ($1O_2$), peroxide (O_2^{-2}), hydrogen peroxide (H_2O_2), hydroxyl radicals (OH•), and hydroxyl anions (OH−), which are continuously produced as byproducts of the aerobic metabolism of physiologic cells (Alfei et al., 2024). Proper cellular physiology must maintain a balance between the beneficial and negative effects of ROS because they are both critical signaling molecules and powerful drivers of macromolecular damage. The utilization of oxygen to boost energy production occurs at a substantial price, as seen by the reactive oxygen species (ROS) that cause damage to lipids, proteins, and nucleic acids, among other cellular macromolecules. These molecules are highly toxic and chemically unstable. Because of this, ROS are involved in a number of pathogenic processes in practically all aerobes (Sies and Jones, 2020).

While ROS have historically been associated with negative outcomes, more recent studies have revealed their dual function as essential signaling molecules involved in controlling multiple cellular processes. At healthy levels, ROS play a critical role as signaling molecules in many different cellular processes, such as immune system response, stress adaptation, proliferation, growth, differentiation, and death. Once they surpass the typical physiologic range, they cause damage to cells and the onset of pathology. By modifying the activity of many enzymes, gene transcription factors, and signaling pathways, ROS serve as a second messenger. Consequently, comprehension of ROS's dual character as hazardous and regulating molecules offers a crucial understanding of the complicated interactions among oxidative stress, cellular metabolism, and physiological process control (Hong et al., 2024).

The role of carbon nanotubes in antifungal strategies and fungal pathogenicity

The proportion of patients susceptible to persistent fungal infections has grown dramatically during the past ten years, in addition to the rise in antibiotic resistance (Chandra et al., 2023). Among the different nanoparticles, particularly multi-walled Carbon nanotubes (MWCNTs) have been shown to be important in fungal biology and pathogenicity because they have antifungal activity.

Physical Disruption: Fungal cell walls can be broken down by CNTs, causing mechanical harm. Cell integrity is compromised by this penetration, which leads to intracellular component leakage and, eventually, cell death. CNTs' size and shape improve their capacity to function as "nano-darts," efficiently locating and penetrating fungal membranes. The relationship between ligninolytic enzymes and CNTs was the subject of several investigations. White rot fungal enzyme activity was enhanced by CNTs with metal impurities or carboxyl groups, but not by unaltered, high-purity CNTs (Ming et al., 2018).

Mechanisms of ROS Generation in Fungi Induced by CNTs

Fungi can directly interact with CNTs, and ROS generation is closely linked to the inherent oxidative properties of carbon nanotubes. The uptake of CNTs by fungal cells disrupts cellular membranes and metabolic processes, leading to elevated ROS levels as a result of cellular stress and damage (Maksimova et al., 2023). One major form of ROS, superoxide anions, is produced by NADPH oxidase when fungal cells activate oxidative stress response pathways in the presence of CNTs. This effect is more pronounced in phagocytic cells exposed to nanoparticles (Shvedova et al., 2012). Additionally, in fungal cells, mitochondria serve as a key source of ROS. During ATP synthesis, the mitochondrial respiratory chain can generate superoxide, a process that may be amplified by CNTs due to increased metabolic demand or stress (Abdal Dayem et al., 2017).

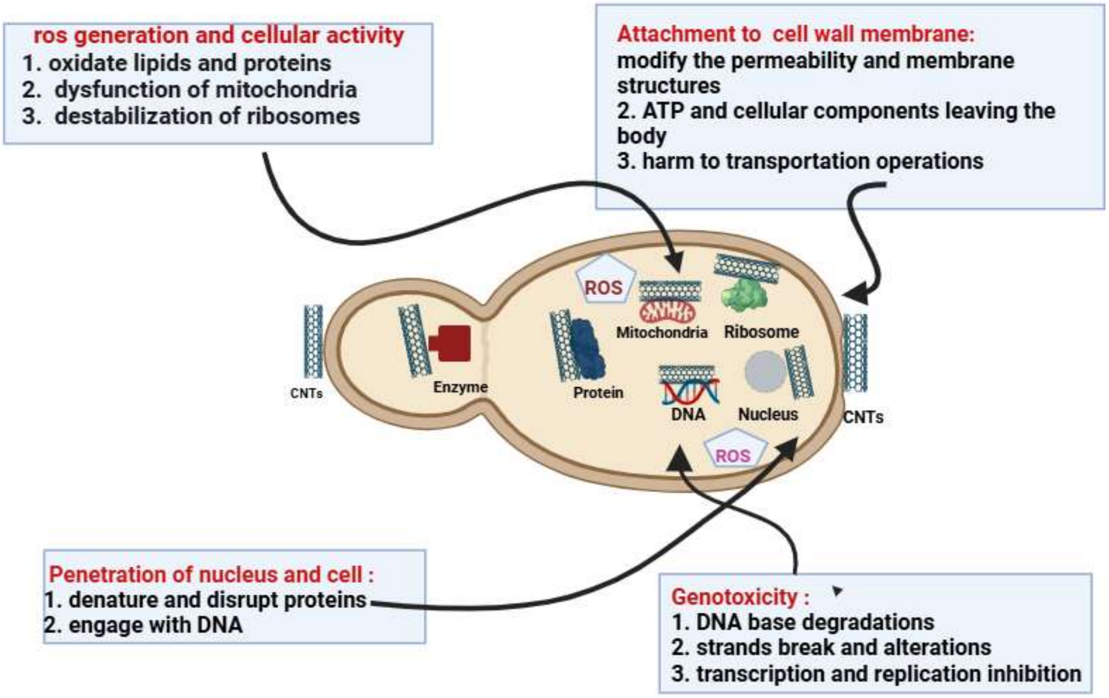

Figure 2. Mechanisms of Genotoxicity and Cellular Damage Caused by CNTs. ROS generated by CNTs disrupts lipids, proteins, mitochondria, and ribosomes. They result in transport deficiencies, ATP leaks, and modifications to membrane permeability. When CNTs penetrate cells and nuclei, they disrupt proteins and interact with DNA, resulting in genotoxic consequences, including transcription inhibition, DNA deterioration, and strand breaks. The complex cytotoxic and genotoxic effects of CNTs on cellular function are illustrated in this figure.

Antifungal Mechanisms of Surface-Modified MWCNTs

By attaching to different functional groups, functionalization allows CNTs to generate CNT-based hybrid materials (CNT-HMs), which are then utilized to connect other useful molecules. Combining these inorganic and organic hybrids in different ways improves the characteristics of CNTs, which are important for biological uses such as antibacterial usage, drug transport, and cancer treatment. CNTs have antibacterial properties that protect against a variety of pathogens, including bacteria, fungi, and viruses (Maghimaa et al., 2024). Surface modification of MWCNTs with chemicals like surfactants or polymers enhances their interaction with fungal cells, making them effective against plant pathogens such as *Fusarium graminearum*. This improved interaction increases ROS generation, leading to oxidative stress that damages fungal cell membranes, destroys their contents, and inhibits growth. (Asefi and Moghimi, 2023)The mechanism involves direct contact with fungal spores, causing structural changes that prevent germination and growth. While the charge of CNTs has minimal influence on their antifungal activity, their effectiveness is primarily attributed to ROS generation and disruption of cellular structures. Modified CNTs exhibit higher affinity for fungal cells, further improving their antifungal properties (Wang et al., 2017).

Rathore et al. (2000) utilized MWCNT and chitosan derivatives to exhibit antifungal activity in vitro, utilizing the agar well diffusion technique. Against A. niger, C. trobicalis, and C. neoformans, they discovered that chitosan nano-composites prevented the spore germination process, germ tube elongation, and radial growth (El Ghaouth et al., 1992). The antifungal properties of the polymer derivative containing MWCNT were distinct from those of the parent chitosan. MWCNTs have the capacity to alter the permeability of the cell membrane through electrostatic contact. In comparison to C. neoformans, chitosan derivatives and MWCNTs have been reported to be more effective against C. trobicalis, with A. niger exhibiting the highest efficacy. Research has shown that modified carbon nanotubes are effective against strains of Candida (Anzar et al., 2020).

A study was carried out by Zari and his colleagues (Zare-Zardini et al., 2013) to demonstrate the antifungal action against a variety of fungi, including *A. niger*, *A. fumigatus*, *C. albicans*, *P.chrysogenum*, *S. cerevisiae*, *F. culmorum*, *M. canis*, *T. mentagrophytes*, *T. rubrum*, and *P. lilacinum*. To demonstrate antifungal efficacy against *E. coli*, *S. aureus*, and *Candida albicans*, single-walled carbon nanotubes disseminated with a tetra-arylbimesityl derivative activated by adding a carboxy group were employed (Ursu et al., 2019).

Chronic plant disease is caused by hyphae, which infiltrate plant tissues and the vascular system (Seong et al., 2008).SWCNTs, MWCNTs, GO, rGO, C60, and AC were among the nanoparticles that did not affect the mycelial growth rate of F. graminearum. Nevertheless, F. graminearum treated with CNMs showed a drop in hyphae density, suggesting that the biomass of the species was impacted. As the concentration of CNM increased, the total number of F. graminearum hyphae dropped, especially that of SWCNTs, MWCNTs, GO, and rGO, which considerably reduced the biomass of *F. graminearum*. It is yet unknown how precisely CNMs impact the branching of fungal hyphae. A critical phase in the developmental cycle of filamentous fungi, spore germination is essential to comprehending the relationship between infections and hosts. Six different types of CNMs were tested for their antifungal properties against the germination of F. graminearum spores. For three hours, spores were cultured with various CNMs at varying concentrations. The maximum dosage of SWCNTs prevented spore germination by more than 95.2%, although spores that germinated under control conditions produced germ tubes. Spore germination was decreased by 85.1%, 84.3%, and 50% by MWCNTs, GO, and rGO, respectively (Harris, 2008).

When compared to non-encapsulated pesticides, fungicides that were encapsulated in functionalized MWNTs showed greater toxicity against *Alternaria alternata* fungi. Although studies reveal that nanoparticles (NPs) have negative impacts on organisms and cells, they have potential applications in many industries. Size and shape determine the hazardous potential, which results in the production of reactive oxygen species (ROS). Overexposure to ROS can result in a variety of physiopathologic effects, including inflammatory conditions, cancer development, death, and genotoxicity. Moreover, NPs alter cellular processes and upregulate the expression of proinflammatory cytokines, both of which can have lethal effects (Yu et al., 2020). Cancer is characterized by unregulated proliferation of cells that damages healthy organs and tissues (Bandyopadhyay et al., 2015). One of the deadliest illnesses that has seen a rise in death rates in recent decades is cancer (Siegel et al., 2020). Cancer cells can develop characteristics including self-reliance in proliferation signals, infinite chances of proliferation, and resistance to markers that halt proliferation or cause apoptosis in normal cells due to a variety of abnormalities and unchecked development and division of malignant cells(Luo et al., 2009). Through associations with nearby stromal cells, the stimulation of blood vessel development, eluding immune detection systems, and organ metastasis, tumors have developed to make use of new supports(Son et al., 2016). Although the treatment of cancer has become much better and patient survival times have been prolonged by the development of treatment options such as surgery, chemotherapy, radiation, endocrine therapy, immunotherapy, phototherapy, and genetic therapy, there are still obstacles to overcome, especially in the treatment of metastatic disease (Wilson et al., 2025).

Nanotechnology is transforming a number of industries, including manufacturing and medical therapies. Because of their exceptional and distinctive mechanical, electrical, and physicochemical qualities, carbon nanotubes (CNTs), a viable therapeutic candidate in nanomedicine, have garnered interest. Over the past ten years, this novel nanomaterial has piqued the interest of numerous scientists. Anticancer medications can be delivered by carbon nanotubes, which allow for tailored release to increase the effectiveness of therapy and lessen side effects on normal tissues (Gao et al., 2024). Moreover, carbon nanotubes can be used in conjunction with other treatment modalities, such as photodynamic and photothermal therapies, to eliminate cancer cells synergistically. In the field of nanomedicine, carbon nanotubes hold enormous promise as promising nanomaterials, providing new possibilities and qualities for possible cancer treatments in the future (Gao et al., 2024). Oncology therapeutic techniques directly destroy tumor parenchyma by targeting the tumor cells and their environment. However, by interfering with the tumor cells' ability to survive, attacking the tumor's surrounding environment indirectly eradicates the tumor cells. Because of their exceptional physicochemical qualities, drug-carrying surfaces, and capacity to enter tumors, carbon nanotubes (CNTs) are becoming a rising star in the treatment of cancer. The processes by which CNT-based nano-delivery systems may precisely travel and bind to different targets for therapy will be explained in this discourse(Son et al., 2016).

Carbon Nanotubes' Use in Cancer Treatment

Medication Administration Methods

CNTs have a high drug loading potential and are capable of targeting specific cancer cells; they are useful nanocarriers for anticancer medications. Some of the therapeutic medicines they can carry include proteins, genes, and tiny compounds like doxorubicin and paclitaxel. The ability to target and release CNTs at tumor sites under controlled conditions with minimal harm to healthy tissues is improved by functionalization (Gao et al., 2024; Kushwaha et al., 2013; Son et al., 2016).

Combination Treatments

CNTs can be combined with photodynamic therapy (PDT) and photothermal therapy (PTT), among other therapeutic methods. For example, CNTs can selectively eliminate tumor cells by absorbing near-infrared light and turning it into heat. This synergy approach combines numerous modes of action to improve the total efficacy of cancer treatment (Naief et al., 2023).

Diagnostic imaging

CNTs are used not just for therapeutic purposes but also for the diagnosis of cancer. Their distinct optical characteristics make it possible to use sophisticated imaging methods like Raman and fluorescence imaging. By enabling real-time disease diagnosis through near-infrared fluorescence emission spectra, recent research has shown the promise of CNTs in the development of very sensitive diagnostic tools that can surpass conventional biomarker tests (Wang et al., 2022).

Safety Issues and Biological Compatibility

There are many benefits to using CNTs; studying their possible toxicity and biocompatibility is still crucial despite these issues. Research has demonstrated that altering the surface of carbon nanotubes (CNTs) can improve their biocompatibility, minimizing harmful effects while preserving their therapeutic effectiveness (Akturk, 2023).

The method by which carbon nanotubes trigger the synthesis of reactive oxygen species (ROS) in cancerous cells:

Since carbon nanotubes (CNTs) may stimulate cancer cells to produce reactive oxygen species (ROS), they have become important players in the field of cancer treatment. This process is essential to the control of cancer cell behavior as well as the effectiveness of therapy (Jabir et al., 2023).

Studying ROS and How They Affect Cancer

Extremely reactive chemicals known as reactive oxygen species have the potential to induce oxidative stress and consequent damage to cells. ROS have two potential uses in cancer therapy: at modest concentrations, they can stimulate carcinogenesis, but when their concentration rises above predetermined limits, they can also cause apoptosis. Because of their disrupted redox state and increased metabolism, cancer cells frequently have greater ROS levels, rendering them more vulnerable to oxidative damage in comparison to normal cells (Li et al., 2021).

Mechanisms of CNT-Generated ROS Production

There are multiple processes by which carbon nanotubes produce reactive oxygen species (ROS).

Surface Reactions: Particularly near margins or defective areas, CNTs can interact with molecules of oxygen and other components of cells. The production of superoxide radicals (O_2•−O_2•−) and hydroxyl radicals (• O H•OH), two important ROS implicated in oxidative stress, is facilitated by this interaction (Zhang et al., 2021).

Photodynamic therapy (PDT): When exposed to light, carbon nanotubes (CNTs) can function as photosensitive compounds, resulting in the production of singlet oxygen (1O21*O*2). Through this process, energy is transferred from the charged state of carbon nanotubes to molecular oxygen, thus promoting the generation of reactive oxygen species (ROS) in cancer cells (Murakami, 2017).

Fenton-type Reactions: Specific CNT formulas can trigger reactions that result in the production of hydrogen peroxide (H 2 O 2 H 2 O 2), which then undergoes Fenton chemistry to break down into more reactive species like hydroxyl radicals. This technique works especially well in tumor microcosms that are acidic (Liu et al., 2022).

Effect on Cancerous Cells

Several biological reactions are brought on by the buildup of ROS that CNTs generate.

Damage from oxidation

The damage caused by oxidation. *Apoptotic* processes in cancer cells can be initiated by elevated ROS levels through peroxidation of lipids, oxidation of proteins, and damage to DNA. The redox equilibrium required for cancer cells to survive is upset by this oxidative stress (Perillo et al., 2020).

Signal Transmission

Reactive oxygen species (ROS) function as messenger molecules that can initiate many pathways linked to both mortality and growth of cells. To further encourage apoptotic processes, they can, for example, affect the pathway of calcium and activate kinases like protein kinase C (PKC)24 (Perillo et al., 2020; Tang et al., 2021).

Resistance to therapy

The activation of survival pathways by moderate amounts of ROS may lead to therapeutic resistance, even though high ROS can cause cell death. Because of its dual function, ROS levels must be carefully regulated during therapy (Xiao et al., 2023).

The Dual Role of Carbon Nanotubes-Induced ROS in Cancer Progression and Treatment

Several factors have drawn the attention of cancer researchers towards carbon nanotubes (CNTs), especially the property of generating reactive oxygen species. The controversial role of reactive oxygen species as an oncogenic agent as well as a treatment aspect makes it relevant to draw a relation between oxidative stress and cancer (Xu et al., 2024). Though their toxic effect, especially their cancer-causing potential, has been of great concern, carbon nanotubes (CNTs) have shown promise in cancer therapy. CNTs cause cancer by oxidative stress, inflammation, genotoxicity, and disruption of cellular signaling pathways. They are more readily absorbed by cells than particles the size of microns (Yaşayan et al., 2024). The epithelial-mesenchymal transition (EMT), which increases cell motility and invasive properties, is stimulated by exposure to CNTs and leads to the promotion of tumor spread. Moreover, the integrity of the endothelium is compromised by CNTs, which increases blood flow and leak and promotes the extravasation and spread of cancer cells (Ding et al., 2024).

ROS

Carbon nanotubes (CNTs) are one type of nanomaterial that can cause intrinsic oxidative stress. Numerous investigations have demonstrated that short- and long-term exposure to CNTs increases the quantity of ROS that cells produce. Oxidative stress can damage DNA and cause mutations in genes that regulate tumor suppression (Rana, 2025). This breakdown of antioxidant and oxidative systems can cause oxidative stress, which can raise calcium levels in the cytosol and cause transcription factors like NF-κB to migrate to the nucleus, where they stimulate genes that cause inflammation, such as TNF-α and iNOS. Long-term inflammation can lead to malignancy, fibrosis, and granuloma (Houldsworth, 2024).

The detoxification of ROS and aerobic respiration depend on mitochondria. MWCNTs both increase and destroy ROS production in cells, impeding their elimination and upsetting the oxidative balance (Lin et al., 2024). A basic mechanism of CNT toxicity and carcinogenesis is this imbalance, which leads to damage to DNA and the death of cells. Mitochondrial malfunction is indicated by vacuolation, bruising, and uneven lamellar ridge in cells treated with self-assembled carbon nanotubes (SWCNTs) (Ghanbari et al., 2017).

Therapeutic Impact of ROS Induced by CNTs

Radiation therapy is a commonly used treatment for cancer; it can be difficult to maximize harm to tumor cells without raising radiation dosages. Radiosensitizers that influence the cell cycle and induce breaks in double-stranded DNA, like capecitabine and nitroimidazole, can increase tumor sensitivity (Gong et al., 2021). Small-molecule radiosensitizers, however, frequently exhibit undesirable effects and inadequate specificity. By building up in tumor tissues and increasing cell radiosensitivity, nanomaterials provide a novel method for creating radiosensitizers. Because of their superior drug loading, permeation, biocompatibility, and targeted specificity, modified carbon nanotubes (CNTs) are the preferred material. By combining CNTs with metallic nanomaterials that contain high atomic number elements, radiosensitizers can be created that increase the susceptibility of cancer cells to X-rays and boost the efficacy of radiation (Viswanath et al., 2024). Carbon nanotubes (CNTs) are thought to be essential in photothermal therapy (PTT) and photodynamic therapy (PDT), where their spectral properties enable targeted cancer treatment by heat generation or ROS production (Makki et al., 2024), as seen in the figure 2. The possible uses of CNT-based nanomaterials in oncology are therefore included in these pathways.

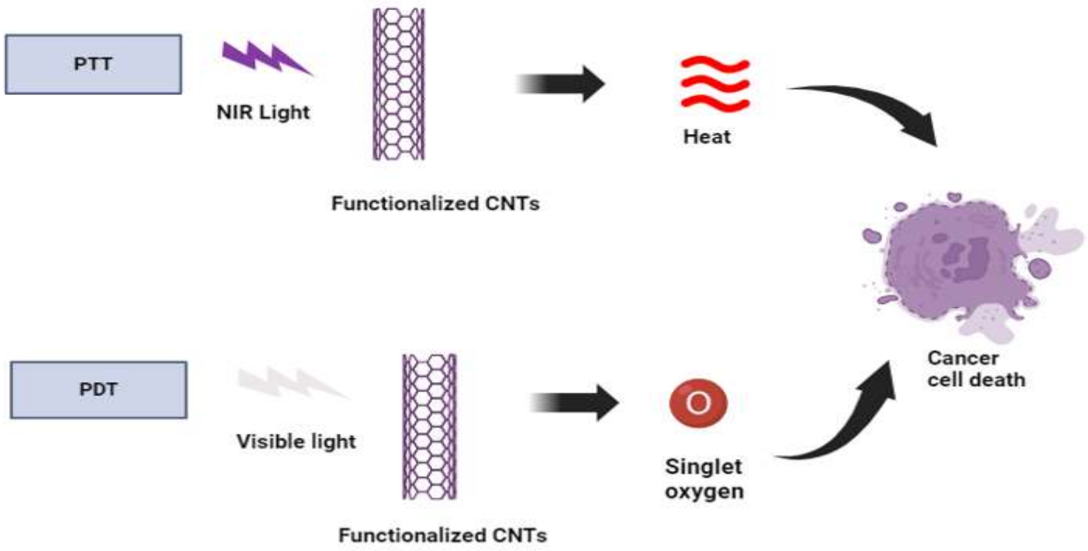

Figure 3. An example of how functionalized carbon nanotubes (CNTs) are used in photothermal therapy (PTT) and photodynamic therapy (PDT) to cure cancer. NIR-activated functionalized CNTs generate localized heat during PTT, which causes hyperthermia and kills the cancer cells. Through the activation of oxidative stress and apoptosis, visible light interacts with the functionalized CNTs in PDT to form reactive singlet oxygen species, which kill the malignant cells. The potential of employing CNT-based nanomaterials as a tool for light-activated treatments is thus clarified by both approaches.

In photodynamic therapy (PTT), a non-invasive therapeutic modality for a number of disorders, including cancer (Figure 3), CNTs have demonstrated potential. Because of their remarkable optical qualities and strong NIR light absorption, CNTs can effectively target and kill cancer cells by turning light energy into heat (Gao et al., 2024). When doxorubicin and MWCNTs were used for PTT, the tumor damage was permanent. In order to increase lymphocytes and macrophage recruitment and raise the rate of survival, oxidized MWCNTs were utilized in the treatment of breast cancer. Via photochemical interactions, CNTs can also react with other photosensitizers to destroy cells (Radzi et al., 2022).

Altering the microenvironment of tumors

Activation of the immunological Response

Through the regulation of immunological responses, CNT-induced ROS can affect the tumor surroundings. Elevated levels of oxidative stress could facilitate the penetration of immune system cells such as macrophages and T cells, which could result in enhanced immunity against tumors (Table 1). This impact is dependent on context, though, as chronic inflammation brought on by elevated ROS levels may also hasten the growth of tumors if improperly controlled (George and Abrahamse, 2020).

Using CNT-Induced ROS to Target Cancer Cells

The capacity of CNTs to specifically raise ROS levels in cancer cells is essential to the therapeutic approach of employing them to target these cells. Increased ROS can cause apoptosis and damage to DNA, especially in cancerous cells that are already experiencing stress due to metabolism. Studies show, for instance, that CNTs can be engineered to co-deliver siRNA and chemotherapy medications, increasing the total lethal effect by producing more ROS. This combo strategy targets particular pathways implicated in tumor survival in addition to increasing treatment efficacy (**Habib and Singh, 2022**).

Effects in Concert with Other Therapies

Combination therapy can incorporate CNTs to take advantage of their capacity to alter ROS levels. In conjunction with photodynamic treatment (PDT), for example, CNTs can increase the production of singlet oxygen, a powerful ROS that kills cells in tumor tissues. By increasing oxidative stress selectively within tumor microenvironments, CNT-based delivery devices have been shown in numerous studies to have a synergistic effect that improves the therapeutic effects of current cancer treatments (Li et al., 2024; Tang et al., 2021).

Table 1. An analysis of the functionalization of carbon nanotubes (CNTs), the processes by which ROS are produced, and the effects that have been shown on various types of cancer

Cancer type	Type of CNT	Functionalization	Mechanism of ROS induction	Effect on cancer cells
Head and Neck Squamous Carcinoma (HNSCC)	Single-walled Carbon	Modified with EGF and cisplatin	When EGF binds, internalization and ROS generation occur quickly.	Increased cytotoxicity and prevention of tumor growth

	Nanotubes (SWCNTs)			
Malignant Melanoma (A375)	SWCNTs	RGD peptide with camptothecin (CPT)-encapsulated	Increased ROS levels in cancer cells due to targeted delivery	Lowest cell viability and highest apoptosis-related proteins expression observed
Lung Cancer (A549, NCI-H460)	Functionalized SWCNTs (PEG)	Loaded with paclitaxel (PTX)	increases PTX activity by working in concert with CNTs in a ROS-dependent manner.	Increased cell death compared to free PTX treatment

Consequences for Drug Sensitivity

Because antioxidant defenses remove excessive ROS, cancer cells frequently become resistant to treatments. CNTs can assist in overcoming this impediment, though, by transferring substances that either block antioxidant pathways in tumor cells or further exacerbate oxidative stress. CNTs can make resistant cancer cells more sensitive to treatment and encourage cell death by upsetting the equilibrium between ROS generation and clearance (An et al., 2024; Arfin et al., 2021).

Applications of CNTs induced ROS in cancer therapy

Various immunological responses can be triggered by carbon-based nanomaterials, which ultimately result in necrosis and apoptosis, which kill cells. ROS generation, lysosomal membrane destabilization (LMD), permeation of 3T3 fibroblasts, bronchial epithelial cells, and RAW macrophages are all responses induced by MWCNT, which ultimately result in their demise. ROS and the MAPK and TGF-β signaling pathways are triggered by graphene. SWCNTs cause cancerous mesothelioma cells to produce ROS and activate NF-kB and p38 (Hosseini et al., 2023). When exposed to light or another stimulus, CNTs can directly create ROS, particularly when modified. For example, by altering important signaling pathways like AKT and JNK, single-walled carbon nanotubes (SWCNTs) can produce too much ROS, which causes cellular death and autophagy in tumor cells like Hep-G2 (liver cancer) (Rhoomi et al., 2024). To improve their capacity to produce ROS, CNTs can be mixed with substances like silver (Ag) and titanium dioxide (TiO2). By raising ROS levels and lowering liver cancer cell survival and growth, the SWCNTs@Ag–TiO2 nanocomposite material has demonstrated potent anti-cancer activity (Jabir et al., 2023). Additionally, CNTs are used in sonodynamic therapy (SDT) and photodynamic therapy (PDT), where they act as mediators that generate ROS in response to exposure to ultrasound or light activation. This focused strategy minimizes harm to nearby normal tissues while enabling the localized elimination of tumor cells (Huang et al., 2018; Ozog et al., 2016). Increased ROS can cause cancer cells to undergo phagocytosis and programmed cell death (apoptosis). To overcome the resistance frequently shown in malignancies, this dual process is essential.

Through a combined action caused by ROS, it has been demonstrated that CNTs increase the efficacy of conventional chemotherapy medications. For instance, through a ROS-dependent system, SWCNTs enhanced the effectiveness of paclitaxel (PTX) against lung cancer cells (Arya et al., 2013). Low oxygen levels are frequently present in the tumor microenvironment, which might raise the generation of ROS. By increasing ROS levels even more, CNTs can take advantage of this milieu and aggravate oxidative stress only in tumor cells while preserving healthy tissues (Aboelella et al., 2021).

Future perspectives and challenges

Enhancing biological compatibility and targeting capabilities will be the main goals of future studies on carbon nanotubes (CNTs) in cancer treatment, specifically their function in producing reactive oxygen species (ROS). Although CNTs show promise for targeted medication administration and the generation of reactive oxygen species (ROS) to destroy cancer cells, their clinical application is limited by problems such as secondary harm from persistent CNTs in the body and a lack of knowledge about their toxicity.(Sajjadi et al., 2021) To make CNTs less hazardous and more efficient, future research must investigate functionalization strategies to lower toxicity and improve biodegradability. Researchers must look at the effects of CNTs on both normal and malignant tissues. Designing safer treatments that cause the least amount of damage to healthy cells will be made easier with knowledge of the mechanisms underlying CNT-induced ROS generation. Enhancing the effectiveness of medication administration is still a major obstacle (Sonowal and Gautam, 2024). To guarantee that medications are administered and released precisely at the tumor site, more accurate targeting techniques are required, such as the use of stimuli-responsive equipment. Additionally, CNTs may be used in dual-purpose theranostic systems that integrate imaging and therapy. This could improve personalized therapy by enabling real-time monitoring of treatment effects. However, issues like pharmacokinetics—the way CNTs are metabolized in the body—and toxicity evaluation need to be resolved (Sonowal and Gautam, 2024). To completely comprehend the effects of CNTs on human health, longer-term research is required. It is also necessary to overcome the difficulty of producing in large quantities functionalized CNTs for usage in medicine. Expanding their use will depend on how to simplify their production without compromising therapeutic efficacy. To enhance the spread of drugs in the body, researchers might potentially look into different nanodelivery technologies, like oral or intravenous techniques (Zheng et al., 2021).

Conclusion:

The unique characteristics of carbon nanomaterials, particularly carbon nanotubes (CNTs), have made these materials one of the most promising options for various applications in the field of biomedical engineering and pharmaceutical science. Due to their capacity to interact with biological systems at the molecular level, these nanoparticles can be used in different applications, such as drug delivery and treatment of microbial infections. The physicochemical properties of CNTs, including the large surface area, functionalization capability, and mechanical strength, allowed the successful design integration in therapeutic regimens, mainly related to cancer therapies. Their binary character in reactive oxygen species (ROS) production reveals the potential ability to augment or abate cellular behavior and, hence, is useful for drug delivery as well as for cancer treatments. Despite the potential of CNTs, biocompatibility and toxicity are major challenges that must be surmounted. Their capability to produce ROS, having a particular mechanism of cancer therapy by oxidative stress, can also cause some disadvantages, including DNA damage and inflammation in the normal tissues. Clearly, the use of CNTs in the clinic will necessitate a judicious balance of benefiting from their therapy while reducing their toxicity. The surface functionalization of CNTs for improved stability and targeting is a step in the right direction towards a safer use of these materials for medical purposes. Further investigations are required to achieve perfection in these modified CNTs for application in CNTs without compromising human health. In the case of microbial infection, CNT possessed great antimicrobial activity against bacteria and fungi. CNTs act as antimicrobial agents through various modes of action, such as cell membrane degradation, ROS production, and enzyme pathways blockage, which are essential for microbial survival. This is of particular importance in the context of a global increase in resistance to antimicrobials in medical care. The wide range of applications of CNTs, along with their capacity to penetrate and interrupt microbial cells, render them potential candidates for future antimicrobial agents in the treatment of resistant infections.

Nevertheless, there are several barriers to overcome before CNTs can be routinely used in commercial and clinical settings with respect to production volume, regulatory clearance, and long-term safety. Existing work has set the stage for potential applications of CNTs in medicine and biotechnology, but more research is required to develop protocols for their utilization. Critical areas for attention would be to elucidate the long-term health impact of CNTs on human health, safe manufacturing practices for CNTs, and the minimization of CNT environmental impact. Further progress in nanotechnology and material sciences will probably enhance the safety of CNTs, making them the tools that they were expected to be for both clinical and industrial purposes, shaping the future of precision medicine and targeted therapies. The surface modification of single-walled carbon nanotubes (CNTs) with polymers or macromolecules can improve their biological compatibility and biodegradable properties (Gao et al., 2024). Enzyme-mediated breakdown, namely myeloperoxidase from neutrophils, can mitigate persistence issues (Gao et al., 2024). Integrating CNTs with biodegradable substances can optimize durability and biological compatibility (Huang et al., 2025). In therapeutic techniques, the integration of carbon nanotubes (CNTs) with photosensitizers for photothermal or photodynamic treatment facilitates the amplification of reactive oxygen species (ROS) under light exposure, hence augmenting antifungal and anticancer effectiveness. CNT-based Fenton catalysts can also be utilized in chemodynamic treatment to transform hydrogen peroxide in the tumor microenvironment into hydroxyl radicals, therefore generating oxidative stress (Huang et al., 2025). The simultaneous administration of immune checkpoint antagonists with CNTs may enhance the immunity against tumors while using ROS-mediated toxicity (Sabir et al., 2025).

Conclusions

This potential makes CNTs a promising tool in agricultural biotechnology for managing fungal infections, although further research is needed to ensure their safe and sustainable use in various environments. Thus, CNTs can affect fungi both beneficially and detrimentally depending on the context of their use.

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Statements and Declarations

Data Availability statement

All relevant data are within the manuscript file.

Author's Contribution Statement

HMS, SM, and SY conceived the study, collected and analyzed data, wrote the manuscript. MS supervised, provided resources. GZJ and BN critically reviewed, edited, and provided resources. All authors have read the final manuscript and approve its submission.

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Not applicable

Conflict of interest

No conflict of interest.