# Filled Carbon Nanotubes: Synthesis, Characteristics and Applications

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**ABSTRACT**

Carbon nanotubes (CNTs) are hollow graphitic nanostructures with unique physical properties and the ability to encapsulate foreign materials inside their cores, forming hybrid nanostructures called filled CNTs. Filling CNTs improves their mechanical strength and combines the properties of both CNTs and filled materials. Due to their high surface area and quantum confinement effects, filled CNTs exhibit enhanced electrochemical properties. Various inorganic and organic materials can be encapsulated into CNT cavities, enabling applications in batteries, cancer therapy, nanoreactors, and catalysis. This article reviews recent advances in the synthesis, properties, and applications of filled CNTs along with their future aspects.

## INTRODUCTION

Carbon nanotubes are a type of allotropic nanocarbon that have received worldwide scientific attention. They are single-walled (SW) or multiple-walled (MW) tube-shaped structures with diameters less than 100 nm, and their walls are made of coiled graphene sheets. The hollow interior of CNTs can be used to store various materials, including fullerenes, metals, alloys, compounds, and biomolecules. This creates unique nanocomposites with combined properties of different materials. This article aims to offer a detailed description of various filling materials, encapsulation techniques, the benefits of filling CNTs, and the potential applications of filled CNTs in various fields.

1. **Filled carbon nanotubes:** Filled CNTs are a special class of CNTs in which the hollow inner cavity (core) is intentionally filled with other materials such as metals, metal oxides, salts, molecules, or even other nanostructures. Filling enhances the properties of pristine CNTs by creating multifunctional nanostructures with improved electrical, magnetic, and thermal properties. Sensitive materials can be shielded from oxidation, corrosion, and deterioration by filling them into CNTs. Furthermore, Catalytic materials filled inside CNTs will show higher activity and better stability (Bangar et al., 2025).

2. **Types of filling material:**

i. **Metals:** Fe, Co, Ni, Cu, etc.

ii. **Metal oxides:** $Fe_3O_4$, $TiO_2$, etc.

iii. **Salts:** KI, KCl, etc.

iv. **Organic molecules:** fullerenes, metallocenes, etc.

3. **Methodologies for filling CNTs:**

i. ***In situ* filling:** In this technique, the desired material is encapsulated within carbon nanotubes during their growth, rather than after synthesis. The filling and CNT formation occur simultaneously in a single step. The commonly used techniques for this kind of filling are arc discharge and chemical vapor deposition, and metals, metal oxides, and carbides are the frequently used materials that are filled into CNTs using the *in-situ* method.

ii. ***Ex situ* filling:** In this filling technique, the CNTs are first prepared, and then they are opened, purified, and filled with desired materials such as metals, salts, organic molecules, and drugs.

- **Opening of CNTs:** CNTs are treated with acids (like $HNO_3$ or $H_2SO_4$) or oxidizing agents, which remove caps and create openings for the entry of materials.

- **Filling processes:** four major filling processes are:

a) Capillary filling: CNTs are immersed in a liquid solution containing the material; due to capillary action, the material enters the nanotube cavity.

b) Melt filling: Material is melted, CNTs are mixed with it, and then the molten substance flows inside the nanotubes.

c) Vapor phase filling: Material is vaporized and diffuses into CNTs at high temperature

d) Solution-based filling: CNTs are soaked in a solution, followed by drying, leaving the material inside the tube (Poudel & Li, 2018).

4. **Applications of filled CNTs:**

i. **Filled CNTs in cancer therapy:** Combining the unique structure of carbon nanotubes with therapeutic or diagnostic materials encapsulated inside them makes them powerful tools for cancer therapy. The cytotoxicity of CDDP-loaded SWCNTs was studied for *in vitro* drug delivery with prostate cancer cells PC3 and DU145, and in human liver cancer cells Hep3B and HepG2. Drug-filled CNTs enabled safe transport and accumulation at the therapeutic site, providing gradual delivery of therapeutic doses and consequently minimizing the risks of side effects. Recently, *in vivo* bioluminescence imaging of mice on Day 10 and Day 16 was conducted. Where three experimental groups are compared: Untreated, $^{153}$Sm@SWNT, and $^{153}$Sm@MWNT ($^{153}$Sm = Samarium 153 isotope), where $^{153}$Smloaded CNTs demonstrate significant anticancer potential *in vivo*.

ii. **Lithium, sodium, and potassium ion batteries:** Filled CNTs are widely explored in lithium (Li), sodium (Na), and potassium (K) ion batteries because they improve electrical conductivity, ion transport, and structural stability of electrodes. CNTs also act as conductive frameworks that reduce volume expansion during charge–discharge cycles. Metal sulfide- and oxide-filled CNTs are considered highly promising anode materials due to their improved electrochemical performance. Researchers are still working on developing new filling materials, but the main benefits include reduced polysulfide shuttle effect, improved stability, protection from external deterioration, and better control over crystal morphology.

iii. **Gas storage and separation:** Due to their unique morphological and chemical properties, carbon nanotubes (CNTs) are promising materials for gas storage and separation applications. Their hollow structure and large surface area allow efficient diffusion and storage of various gases. Additionally, the conjugated walls of CNTs can be functionalized to enhance gas capture and strengthen interactions with encapsulated molecules, improving system stability. Chiral CNTs can also selectively encapsulate certain gas molecules, making them useful for gas separation processes. Studies on the physisorption of gases such as $O_2$, $N_2$, $CO_2$, $H_2$, and $CH_4$ on SWCNT surfaces show that interactions between the gas molecules and CNT walls are very weak at large distances. As the molecules move closer to the CNT surface, van der Waals (vdW) forces stabilize the system by lowering its energy.

iv. **Nanoreactors:** Carbon nanotubes (CNTs) are highly attractive as nanoreactors because of their unique structural and intrinsic properties. Their $sp^2$-carbon network provides excellent chemical, electrical, and thermal stability, along with exceptional mechanical strength. CNTs can withstand very high temperatures, possess conductive or semiconductive behavior, and offer varying inner diameters suitable for hosting molecules or ions. Reactions occurring within CNT cavities can significantly alter the behavior of reactants, influencing the course of chemical reactions and the properties of the final products.

v. **Thermocatalysis:** Heating at temperatures of about 300-800 °C increases the movement and collision probability of reacting species, promoting reactions. When thermocatalysts are encapsulated within carbon nanotubes (CNTs), their performance is enhanced by the confinement effect. CNTs protect the catalysts from sintering, agglomeration, and oxidation, while their excellent thermal stability and conductivity ensure efficient and uniform heat distribution. Encapsulation also reduces catalyst leaching into the reaction medium, thereby increasing reaction yields and preventing catalyst deactivation (Sandoval et al., 2026).

**Key challenges to filled CNTs:**

Although extensive research has been carried out on filled CNTs, several challenges remain. One major issue is the heterogeneity of CNT samples, as variations in diameter, length, chirality, defect density, and impurities can strongly affect their physicochemical properties. Even CNTs obtained from the same source may show batch-to-batch differences. In addition, many studies lack sufficient details about filling conditions and post-processing steps, such as the removal of non-encapsulated materials. The absence of such experimental information makes it difficult for other researchers to reproduce the results and further develop the field.

## CONCLUSION and Future Remarks:

This article reviews the synthesis, properties, and applications of filled carbon nanotubes (CNTs). Over the past few decades, many organic and inorganic materials have been successfully encapsulated inside CNTs using two main methods, i.e., *in situ* and *ex situ* filling. The study highlights that, besides the properties of the filling materials, several factors influence the growth and filling of CNTs. Filled CNTs are considered promising materials for various applications because of their unique physicochemical properties.

However, the growth and filling mechanisms of CNTs are still not fully understood in terms of kinetics, thermodynamics, and nanoscale chemical transformations. This creates a need for more detailed research, especially on filling single-walled carbon nanotubes (SWCNTs), to bridge the gap between theoretical and experimental studies. It may also allow the encapsulation of new exotic materials inside CNTs, leading to novel and useful applications in the future (Teng et al., 2023).

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