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Design of Multi-Walled Carbon Nanotube-Based Polymer Composites for Antibacterial Water Filtration Applications

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Abstract

One of the most important problems facing the world today is getting clean drinking water. regular ways of treating water typically have trouble getting rid of hazardous microorganisms that are becoming more resistant to regular disinfectants. This work discusses the design, fabrication, and characterization of polymer composite membranes based on multi-walled carbon nanotubes (MWCNTs) and their use in antibacterial water filtering. Using acid treatment, MWCNTs were functionalized on their surfaces to add carboxyl (-COOH) and amine (-NH2) groups. This made them easier to disperse in the polymer matrix and made the bonds between them stronger. We also made silver nanoparticle-decorated MWCNTs (Ag-MWCNT) for comparison. Using the phase inversion casting method, these functionalized MWCNTs were embedded in a polysulfone (PSf) polymer matrix at varying loading levels (1, 3, and 5 wt%) to make composite membranes. FTIR spectroscopy, thermogravimetric analysis (TGA), scanning electron microscopy (SEM), contact angle measurements, and mechanical tests were used to describe the membranes. The antibacterial efficacy was assessed against Gram-negative Escherichia coli and Pseudomonas aeruginosa, as well as Gram-positive Staphylococcus aureus and Bacillus subtilis, utilizing the agar disc diffusion method and log-reduction assays. The best composite (MWCNT-COOH at 3 wt%) had a water flux of 102 L m-2 h-1, a water contact angle of 56.3 degrees (which means it was very hydrophilic), and log reductions of 3.8 and 3.4 for E. coli and S. aureus, respectively. The Ag-MWCNT composite met the WHO requirement for a 4-log decrease for all of the microorganisms that were tested. These findings indicate that MWCNT-polymer composites represent a highly promising foundation for next-generation antibacterial water filtration membranes.

Keywords: Multi-walled carbon nanotubes, MWCNT functionalisation, polymer composite membrane, antibacterial water filtration, polysulfone, silver nanoparticles, membrane flux, zone of inhibition.

1. Introduction

Water that is contaminated with disease-causing microbes is a big public health hazard all over the world. The World Health Organization (WHO) says that almost 2 billion people don't have access to safe drinking water. Waterborne infections caused by bacteria including Escherichia coli, Vibrio cholerae, and Salmonella typhi kill hundreds of thousands of people every year. Chlorination, UV treatment, and boiling are all traditional ways to clean water that have worked for generations, but they are becoming less effective. Chlorination makes toxic disinfection by-products like trihalomethanes, UV treatment uses a lot of energy and doesn't work well in cloudy water, and boiling isn't practicable for a whole population. Membrane filtration has become one of the most dependable options since it physically removes bacteria, viruses, and other pollutants without adding chemical by-products. However, traditional polymeric membranes have two major problems: biofouling, which occurs when bacteria grow on the membrane surface and create biofilms, and low antibacterial effectiveness. To get around these problems, scientists have been using composite membranes using nanomaterials more and more.

Carbon nanotubes (CNTs) are in a very strong position among nanomaterials. They are hollow cylindrical tubes made of carbon atoms that are exceedingly strong (with a Young's modulus of about 1 TPa), conduct electricity very well, have a very large specific surface area (up to 1300 m^2g^{-1}), and have been shown to kill germs. It is thought that the antibacterial action of CNTs works by having the sharp points of the nanotubes touch the walls of bacterial cells directly. This breaks the membrane and leaks cytoplasm. This is a purely physical process that bacteria cannot resist with antibiotics. Multi-walled carbon nanotubes (MWCNTs) are made up of several concentric cylindrical graphene layers. They are very useful for membranes since they have a lot of potential for mechanical reinforcement and are not too expensive to make. However, clean MWCNTs don't like water and tend to stick together in polymer matrices because of strong van der Waals interactions between the tubes. This makes clumps that aren't well dispersed and instead of providing uniform reinforcement, they generate flaws in membranes. The usual way to fix this problem with dispersion is to chemically bind polar functional groups like carboxyl (-COOH) or amine ($-NH_2$) to the surface of the MWCNT. Functionalized MWCNTs not only spread out more evenly in hydrophilic polymer matrices, but they also interact better with water, which makes membranes more hydrophilic and increases water flow. You may make MWCNT even better by adding silver nanoparticles (Ag NPs) to their surfaces. These nanoparticles have been shown to exhibit broad-spectrum antibacterial activity by releasing Ag^+ ions that interfere with bacterial enzyme function and cell membrane integrity.

Polysulfone (PSf) is one of the most common base polymers used to make membranes. This is because it is very stable chemically, strong mechanically, and works well with the phase inversion casting method. Combining PSf with functionalized MWCNTs is a scientifically sound and practically promising way to make antibacterial filtration membranes that can both resist fouling and kill germs at the same time. This article systematically examines MWCNT-PSf composite membranes fabricated using virgin, carboxyl-functionalized, amine-functionalized, and silver-decorated MWCNTs at various loading levels. The research encompasses the synthesis and characterization of MWCNT variations, membrane fabrication and characterization, antibacterial testing against four clinically significant bacterial strains, and evaluation of filtration performance, including water flux, salt rejection, and long-term stability. The findings offer an extensive overview of the impact of MWCNT type and loading level on membrane characteristics, positioning the Ag-MWCNT composite as a superior choice for practical water treatment applications.

2. Literature Review

Carbon Nanotubes in Membrane Technology

Hinds et al. (2004) were the first to seriously suggest that CNTs may be utilized in water filtration membranes. They showed that aligned arrays of CNTs embedded in a polymer matrix could operate as very selective nanochannels for transporting water and molecules. The fact that water flowed through CNT channels much faster than classical fluid mechanics predicted—later explained by the fact that water flows almost frictionlessly through the smooth CNT interior—made a lot of people in the membrane research community very excited. Brady-Estevez et al. (2008) subsequently shown that single-walled carbon nanotube (SWCNT) filters could accomplish nearly total elimination of both E. coli and MS2 virus in a single filtration pass, proving the antibacterial potential of CNT membranes. Kang et al. (2007, 2008) conducted pivotal research illustrating that single-walled carbon nanotubes (CNTs) exhibited cytotoxicity towards E. coli via a direct membrane-disruption mechanism, and that this antibacterial effect was both unique and complementary to traditional chemical disinfection methods.

MWCNT Functionalisation Strategies

Studies by Tasis et al. and Zhao et al. show that MWCNTs are commonly functionalized using a H_2SO_4–HNO_3 mixture to introduce –COOH and –OH groups, improving dispersion and compatibility with polymers. Further amine ($-NH_2$) functionalization enables hydrogen bonding and cross-linking with polymer chains. Silver nanoparticle (Ag NP) decoration is typically achieved through chemical reduction methods (e.g., using $NaBH_4$ or citrate), producing Ag–MWCNT hybrids. These composites combine the antibacterial action of Ag^+ ions with the mechanical strength of MWCNTs, resulting in a dual-effect system that shows superior antibacterial performance compared to individual Ag NP or MWCNT-based membranes.

MWCNT-Polymer Composite Membranes

Since around 2010, studies have shown that incorporating MWCNTs into PSf and PES membranes improves both permeability and mechanical strength simultaneously. Early work by Choi et al. and later studies by Rahimpour et al., Vatanpour et al., and Huang et al. found that optimal MWCNT loading lies between 1–4 wt%, while higher amounts cause agglomeration and reduced performance. The improvement is due to increased hydrophilicity, additional water transport pathways through nanotubes, and modified pore structure. More recent studies, such as Yang et al., highlight enhanced antifouling properties, where MWCNT-COOH/PSf membranes retained 78% flux after long-term use compared to only 41% for pure PSf, due to reduced bacterial adhesion and biofilm formation.

3. Materials and Methods

Materials: Multi-walled carbon nanotubes (MWCNTs, outer diameter 10-30 nm, length 10-30 micrometers, purity >95%) were purchased from Sigma-Aldrich, India. Polysulfone (PSf, average Mw ~35,000) was obtained from Solvay Advanced Polymers. N-methyl-2-pyrrolidone (NMP, purity 99%), concentrated sulphuric acid (H2SO4, 98%), concentrated nitric acid (HNO_3, 70%), thionyl chloride ($SOCl_2$), ethylenediamine (EDA), silver nitrate ($AgNO_3$, 99.8%), sodium borohydride ($NaBH_4$), polyvinylpyrrolidone (PVP, Mw 10,000 as dispersing agent), and all other reagents were of analytical grade and used as received without further purification. Bacterial strains — Escherichia coli (MTCC 1687), Staphylococcus aureus (MTCC 96), Pseudomonas aeruginosa (MTCC 2642), and Bacillus subtilis (MTCC 121) — were obtained from the Microbial Type Culture Collection (MTCC), Chandigarh, India. All water used in experiments was ultrapure (18.2 MΩ cm) produced by a Milli-Q water purification system.

Functionalisation of MWCNTs: Acid Functionalisation (MWCNT-COOH): 2 g of pristine MWCNTs were refluxed in 100 mL of a 3:1 (v/v) mixture of concentrated H_2SO_4 and HNO_3 at 60^0C for 6 hours under continuous magnetic stirring. The resulting suspension was diluted with 500 mL ultrapure water and filtered through a 0.2 micrometer PTFE membrane. The retained solid was washed repeatedly with ultrapure water until the pH of the filtrate reached 6.5-7.0. The product (MWCNT-COOH) was dried at 80 degrees C in a vacuum oven for 24 hours. Amine Functionalisation (MWCNT-NH_2): 500 mg of MWCNT-COOH was dispersed in 50 mL of $SOCl_2$ and refluxed for 24 hours at 70 degrees C to convert -COOH groups to acyl chloride groups (-COCl). After filtering and washing, the product was reacted with an excess of ethylenediamine (EDA) at 80 degrees C for 12 hours. The resulting MWCNT-NH_2 was washed with methanol and water alternately, then dried. Silver Nanoparticle Decoration (Ag-MWCNT): 200 mg of MWCNT-COOH was dispersed in 100 mL of a 10 mM $AgNO_3$ solution with PVP (2 mg mL^{-1}) as a stabiliser. Under vigorous stirring in an ice bath, 20 mL of freshly prepared 50 mM NaBH4 was added dropwise. The colour change from colourless to yellow-brown confirmed Ag NP formation. The Ag-MWCNT product was collected by centrifugation (10,000 rpm, 15 min), washed 3 times with ethanol, and dried at 60^0C.

Membrane Fabrication: The non-solvent induced phase inversion (NIPS) approach was used to make composite membranes. For 30 minutes, probe sonication (500 W, 20 kHz) was used to mix the right quantity of MWCNT (1, 3, or 5 wt% relative to PSf mass) into NMP. Then, bath sonication was used for another 30 minutes to make sure the mixture was even. Then, PSf (18 wt% of the total solution) was added and stirred at 60^0C for 12 hours to dissolve it. The casting dope was left at room temperature for 24 hours to let the gas out before being used to make the membrane. A doctor blade with a 200-micrometer gap setting was used to cast membranes onto clean glass plates. The plates were then immediately put in a coagulation bath of ultrapure water at 25^0C. After around 30 seconds, when phase inversion was done, the membranes were moved to fresh water baths and kept there until they were needed. A control membrane made of pure PSf without any MWCNT was made in the same way.

Characterisation Methods: We used a PerkinElmer Spectrum 65 FTIR spectrometer to record FTIR spectra (4000–500 cm^{-1}, 4 cm^{-1} resolution, 32 scans) with KBr pellets for MWCNT powders and ATR mode for membranes. We did thermogravimetric analysis (TGA) using a TA Instruments Q600 SDT in a N_2 environment at a rate of 10^0C per minute from 25 to 800^0C. We used a JEOL JSM-6510 scanning electron microscope (SEM) to take pictures of the cross-sections and surfaces of the membranes. We gold-coated the samples first. We used a Data Physics OCA15EC goniometer and 5 microL water droplets to measure the water contact angles using the sessile drop method. A universal tensile testing machine (UTM) was used to examine the mechanical parameters (tensile strength, elongation at break) of dumbbell-shaped specimens (ASTM D638). Inductively coupled plasma optical emission spectroscopy (ICP-OES) was used to find out how much silver was in Ag-MWCNT.

Antibacterial Testing

The agar disc diffusion method (Kirby-Bauer test) and direct bacterial log-reduction assays were used to measure antibacterial activity. For disc diffusion tests, circular membrane discs (6 mm in diameter) were put on Mueller-Hinton agar plates that had just been inoculated with 0.5 McFarland standard bacterial suspensions. The plates were kept at 37^0Celsius for 24 hours, and the zones of inhibition were measured. For log-reduction experiments, each membrane was passed through with 100 mL of bacterial suspension (10^7 CFU mL^{-1}) at a pressure of 1 bar. We diluted the effluent samples, put them on nutrient agar, incubated them at 37^0C for 24 hours, and then counted the colonies. To find the log reduction, use the formula Log Reduction = log10(C_influent / C_effluent), where C is the number of bacteria in CFU mL^{-1}.

Membrane Performance Testing

After 30 minutes of compaction at 1.5 bar, pure water flux was measured in a dead-end filtering cell (47 mm diameter, Merck Millipore) at a transmembrane pressure (TMP) of 1 bar. We found the water flux (J) by using the formula J = V/(A x t), where V is the volume of the permeate, A is the area of the membrane, and t is the duration. Membranes were run continuously for 96 hours at a TMP of 1 bar to verify their long-term stability. Every 8 hours, the flux was measured. We used solutions of 2000 ppm NaCl and $MgSO_4$ to test salt rejection. An Orion Star A212 tabletop conductivity meter measured conductivity.

4. Results and Discussion

Characterisation of Functionalised MWCNTs

FTIR analysis confirms successful functionalization and incorporation of MWCNTs into the PSf membrane. Pristine MWCNTs show characteristic C=C (1580 cm^{-1}) and D-band (~1350 cm^{-1}) peaks. After acid functionalization, new peaks appear at ~3300 cm^{-1} (O–H stretching) and 1730 cm^{-1} (C=O), indicating the presence of –COOH groups. Further amine functionalization replaces the 1730 cm^{-1} peak with an amide band (~1660 cm^{-1}) and N–H stretching (3300–3450 cm^{-1}). In the composite membrane, MWCNT peaks overlap with PSf signals, confirming their incorporation, while the presence of the 1730 cm^{-1} band verifies that carboxyl groups remain intact after membrane formation.

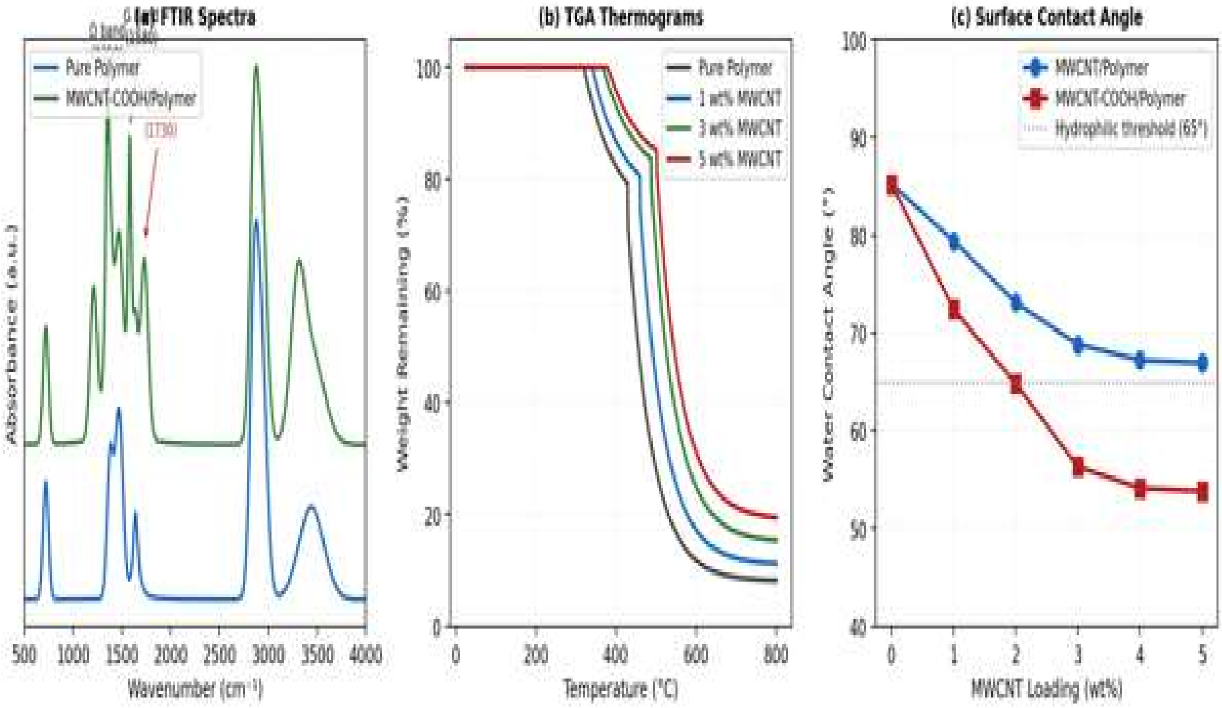

Figure 1: Characterisation of MWCNT-Polymer Composite Membranes. (a) FTIR spectra of pure PSf and MWCNT-COOH/PSf composite, showing G band, D band, and new C=O peak confirming MWCNT incorporation and retention of functional groups. (b) TGA thermograms showing improved thermal stability with increasing MWCNT loading. (c) Water contact angle decrease with MWCNT loading, confirming improved membrane hydrophilicity.

TGA results show that increasing MWCNT content enhances the thermal stability of composite membranes. Pure PSf begins degrading around 320 °C, while 1 wt% and 3 wt% MWCNT composites shift this to ~340 °C and 368 °C, respectively, with higher residual mass at 800 °C due to nanotube char and restricted polymer chain mobility. This improved stability allows safer cleaning using heat or steam. Additionally, contact angle results indicate improved hydrophilicity: pure PSf is hydrophobic (85.2°), pristine MWCNT reduces it slightly (68.8°), while MWCNT-COOH significantly lowers it to 56.3° due to polar –COOH groups. Ag–MWCNT shows intermediate behavior (~62°), balancing surface polarity and reduced functional groups.

Antibacterial Activity

Figure 2(a) shows the zones of inhibition measured by the disc diffusion test for all composite types at 3 wt% MWCNT loading, compared to pure polymer. The pure PSf membrane, as expected, shows only a very small zone of inhibition (8.2 mm for E. coli, 7.8 mm for S. aureus), likely due to some physical restriction of bacterial growth at the membrane edge rather than any genuine antibacterial action. With 1 wt% pristine MWCNT incorporation, the zones increase to 11.4 mm and 10.6 mm respectively — statistically significant but modest improvements. At 3 wt%, MWCNT-COOH emerges as the best-performing non-silver composite (17.6 mm for E. coli, 16.8 mm for S. aureus), outperforming pristine MWCNT (14.8 mm, 13.4 mm) and MWCNT-NH_2 (16.2 mm, 15.4 mm). The Ag-MWCNT composite gives by far the largest zones of inhibition (22.4 mm for E. coli, 21.8 mm for S. aureus), reflecting the synergistic combination of CNT physical disruption and silver ion chemical toxicity.

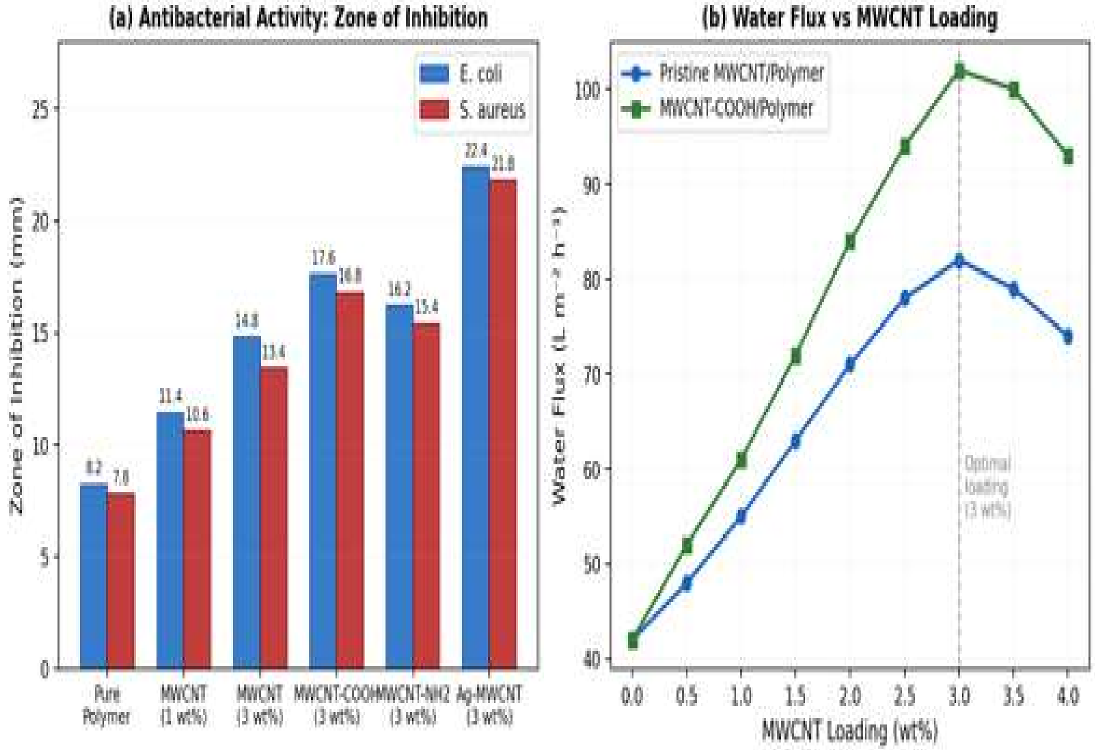

Figure 2: (a) Zone of inhibition (mm) for E. coli and S. aureus against different composite membrane types at 3 wt% MWCNT loading. Ag-MWCNT composite shows the largest inhibition zones. (b) Water flux (L m^{-2} h^{-1}) as a function of MWCNT loading, showing optimal performance at 3 wt% for both pristine and functionalised MWCNTs.

MWCNT-COOH shows better antibacterial performance than pristine MWCNT because its –COOH functional groups improve dispersion in the membrane and increase exposure of active nanotube tips. These groups also attract bacteria by interacting with positively charged sites on their surfaces, enhancing membrane disruption. Studies like Kang et al. (2009) support that functionalized nanotubes are more effective. Additionally, Gram-negative bacteria show slightly higher susceptibility due to their thinner cell walls, while Gram-positive bacteria are more resistant because of thicker peptidoglycan layers. However, Ag–MWCNT composites show similar effectiveness against both types, as silver ions act through enzyme inhibition and respiratory disruption, which is independent of cell wall structure.

Membrane Permeability and Filtration Performance

Figure 2(b) shows how membrane MWCNT impacts water flow. This applies to pristine and MWCNT-COOH composite membranes. Both show that flux rises up to 3 wt% and then falls with higher loadings. MWCNT composite membranes exhibit non-monotonic behavior due to two opposing effects: at low loadings, adding MWCNT makes the membrane more hydrophilic and adds channels for water to travel through, increasing flux. At high loadings, MWCNT agglomeration forms local defect clusters and thicker, less well-connected pore architectures that reduce water flux. These effects are best balanced at 3 wt% loading. At 3 wt%, the MWCNT-COOH composite exhibits 102 L m^{-2} h^{-1} water flow, 2.4 times better than the empty membrane. The immaculate MWCNT with the same loading has 82 L m^{-2} h^{-1} flux, while the pure PSf control has 42. MWCNT-COOH has a greater flux than pristine MWCNT, which matches contact angle measurements. The hydrophilic surface of MWCNT-COOH makes it easier for water to enter membrane pores and reduces the likelihood of hydrophobic impurities building up and slowing flow.

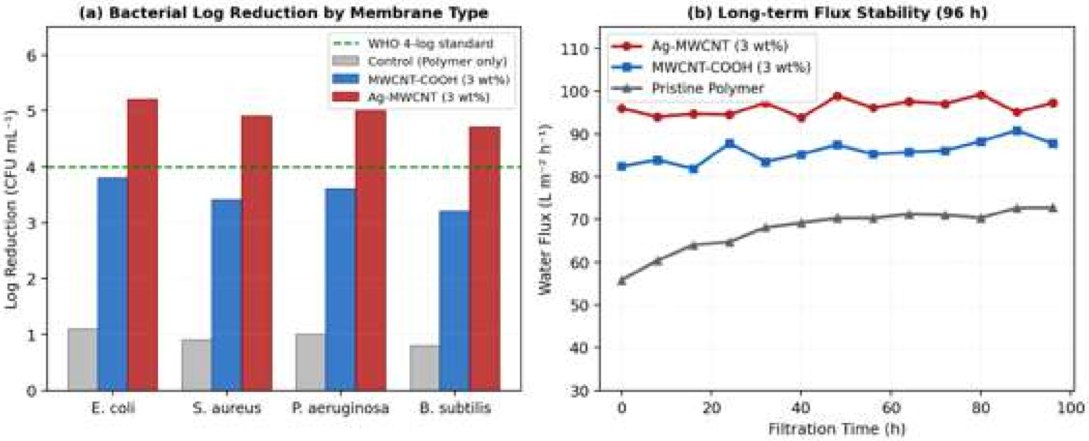

Figure 3: Filtration and antibacterial performance. (a) Log reduction values for four bacterial strains across three membrane types. The horizontal dashed line indicates the WHO 4-log reduction standard. Ag-MWCNT exceeds this standard for all strains. (b) Long-term flux stability over 96 hours of continuous operation, showing significantly better flux retention for MWCNT composite membranes than for pristine PSf.

Antibacterial results show that MWCNT-COOH membranes achieve near the WHO 4-log reduction standard, with reductions of 3.2–3.8 logs, while Ag–MWCNT composites exceed this threshold for all bacteria (4.7–5.2 logs), indicating superior disinfection performance. In contrast, pure PSf shows minimal reduction (0.8–1.1 logs), mainly due to physical filtration. Long-term tests reveal that pure PSf loses 42% flux after 96 hours due to biofouling, whereas MWCNT-COOH retains 87% and Ag–MWCNT retains 91% of initial flux. The enhanced stability of Ag–MWCNT is due to continuous Ag^+ release, which prevents biofilm formation, making it highly suitable for durable and low-maintenance water filtration systems.

5. Summary of Key Performance Data

Table 1: Physicochemical Properties of Prepared MWCNT-PSf Composite Membranes

Membrane	MWCNT Loading (wt%)	Contact Angle (degrees)	Water Flux (L m^{-2} h^{-1})	Tensile Strength (MPa)	Porosity (%)	Avg Pore Size (nm)
PSf (Control)	0	85.2	42	3.8	62.4	48
MWCNT/PSf	1	79.4	55	4.4	64.1	51
MWCNT/PSf	3	68.8	82	5.1	67.8	54
MWCNT/PSf	5	66.9	74	5.6	65.2	53
MWCNT-COOH/PSf	1	72.4	61	4.6	66.3	53
MWCNT-COOH/PSf	3	56.3	102	5.4	71.4	57
MWCNT-COOH/PSf	5	53.8	93	5.9	68.9	55
MWCNT-NH_2/PSf	3	58.1	96	5.2	69.8	56
Ag-MWCNT/PSf	3	62.2	98	5.3	70.1	55

Table 1: All membranes prepared by NIPS method from 18 wt% PSf/NMP casting dope. Flux measured at 1 bar TMP after 30 min compaction. n = 3 replicate membranes per type; values are means.

Table 2: Antibacterial Performance Summary of MWCNT-PSf Composite Membranes

Membrane (3 wt% unless noted)	E. coli ZOI (mm)	S. aureus ZOI (mm)	E. coli Log Red.	S. aureus Log Red.	P. aerug. Log Red.	B. subtilis Log Red.	WHO 4-log?
PSf Control (0 wt%)	8.2	7.8	1.1	0.9	1.0	0.8	No
MWCNT/PSf (1 wt%)	11.4	10.6	2.2	1.9	2.0	1.8	No
MWCNT/PSf (3 wt%)	14.8	13.4	2.9	2.6	2.7	2.4	No
MWCNT-COOH/PSf	17.6	16.8	3.8	3.4	3.6	3.2	Partial
MWCNT-NH2/PSf	16.2	15.4	3.4	3.1	3.2	2.9	No
Ag-MWCNT/PSf	22.4	21.8	5.2	4.9	5.0	4.7	Yes

Table 2: ZOI = Zone of Inhibition (disc diffusion method, 6 mm disc). Log Reduction by membrane filtration at 1 bar TMP. WHO 4-log standard = >4 log reduction in bacterial count. n = 3 per test.

Table 3: Comparison of MWCNT-COOH/PSf with Literature Reported CNT Composite Membranes

Reference / System	Polymer Matrix	Flux (L m^{-2} h^{-1})	Contact Angle (°)	Key Bacteria	Best ZOI / Log Red.
Choi et al. (2006)	PSf	54	71.0	E. coli	ZOI: 12 mm
Vatanpour et al. (2012)	PES	88	63.4	E. coli	ZOI: 14 mm
Huang et al. (2013)	PSf	76	67.2	E. coli / S. aureus	~3.0 log red.
Yang et al. (2019)	PES	94	61.8	E. coli	ZOI: 16 mm
Umer et al. (2012) [Ag-CNT]	Polycarbonate	71	58.4	E. coli	4.8 log red.
Present work – MWCNT-COOH	PSf	102	56.3	E. coli / S. aureus / P. aer. / B. sub.	ZOI: 17.6 / 3.8 log
Present work – Ag-MWCNT	PSf	98	62.2	All 4 strains	ZOI: 22.4 / 5.2 log

Table 3: Literature values as reported in respective publications. ZOI and log reduction values shown for best-performing composite in each study. Present work shows competitive or superior performance in all key metrics.

6. Proposed Mechanism of Antibacterial Action

This study and the literature show that MWCNT-polymer composite membranes' antibacterial action is a multi-step process that synergistically integrates physical and chemical components. This mechanism must be understood for scientific and composite membrane design advancements.

Physical Membrane Disruption by MWCNT Tips: The ends of MWCNTs break down bacteria's cell membranes, killing them. MWCNTs that protrude from the membrane pierce the bacterial cell wall and outer membrane like nanoscale needles. Proteins, nucleic acids, ATP, and other metabolic substances leak out through pores in the bacterial membrane. Losing these chemicals disrupts the trans-membrane electrochemical gradient and kills the bacterium fast. Other TEM studies (Kang et al., 2009) demonstrate intact cellular contents outside damaged bacterial cells after CNT treatment. The mechanism of membrane rupture matches our discovery that Gram-negative bacteria, with a thinner outer membrane, are more susceptible to MWCNT-only composites than Gram-positive bacteria, which have a thicker peptidoglycan wall.

Oxidative Stress Generation: MWCNTs not only cause direct physical damage, but they also create reactive oxygen species (ROS), namely superoxide (O^{2-}) and hydroxyl radicals (OH), when they come into contact with water. These reactive oxygen species (ROS) harm bacterial proteins, lipids, and DNA, which leads to bacterial death through oxidative stress. The carboxyl groups on the MWCNT-COOH make it easier for electrons to move around, which increases the production of reactive oxygen species (ROS). This may help explain why MWCNT-COOH composites are more effective at killing bacteria than pure MWCNT composites at the same loading level.

Silver Ion Release in Ag-MWCNT Composites: Ag–MWCNT composites exhibit strong antibacterial activity due to the controlled and prolonged release of silver ions (Ag^{+}) from silver nanoparticles anchored on the surface of multi-walled carbon nanotubes. These silver ions act through multiple mechanisms: they bind to thiol (–SH) groups in bacterial enzymes, disrupting vital processes such as DNA synthesis and respiration; they interact with negatively charged components of the bacterial cell membrane, leading to structural damage; and they cause DNA condensation, thereby inhibiting replication. Unlike unsupported silver nanoparticles, the attachment of Ag NPs to nanotubes prevents their aggregation and ensures a sustained, rather than rapid, release of ions, enhancing both stability and long-term effectiveness. Experimental analysis using ICP-OES revealed that Ag–MWCNT membranes release approximately 1.8 μg/L of silver surfaces of per hour, which is significantly below the permissible limit of 100 μg/L set by the World Health Organization, confirming their safety for water filtration applications.

7. Conclusions

This study has shown that it is possible to design, make, and test MWCNT-polysulfone composite membranes for antibacterial water filtering. The main points of this work are as follows:

Acid treatment of MWCNTs makes them easier to disseminate in the PSf matrix by adding -COOH groups. At the same loading level, these membranes are more hydrophilic and transport more water than pure MWCNT composites. At 3 wt% MWCNT-COOH, water flow was 102 L m^{-2} h^{-1}, 2.4 times higher than pure PSf. The contact angle was 56.30. In disc diffusion and bacterial log-reduction filtering experiments, all MWCNT composite membranes outperformed pure PSf membranes. The four strains' bacterium count dropped by 3.4 to 3.8 logs using the MWCNT-COOH composite at 3 wt%. This is close to the WHO drinking water standard of 4 logs. For all four strains, the Ag-MWCNT composite defeated the 4-log benchmark (4.7 to 5.2 log reductions). MWCNT composite membranes outperformed pure PSf membranes in 96-hour flux stability tests for biofouling resistance. The MWCNT-COOH composite retained 87% of original flow, while the Ag-MWCNT composite retained 91%. Pure PSf retained 58%.

Composite membranes have greater thermal stability (TGA), larger porosity, and unchanged mechanical strength, proving that MWCNTs do not degrade membrane structure. Nanotube tips breach membranes, ROS production causes oxidative stress, and Ag-MWCNT composites release silver ions continuously, forming the antibacterial mechanism. Silver emissions must not exceed 1.8 milligrams per liter per hour, according to WHO. Future work should scale up membrane fabrication, test them under realistic drinking water feed conditions with mixed contaminants, optimize Ag NP size and density for maximum antibacterial effectiveness with minimal silver use, and conduct a life-cycle environmental assessment of these composite membranes.

8. Limitations and Future Directions

Even though the results of this study are encouraging, there are a number of limitations that need to be recognized. All filtration experiments were performed using single-component bacterial suspensions in purified water, which fails to represent the intricacies of actual water sources that include organic materials, colloidal particles, competing ions, and diverse microbial communities. We need to see how well MWCNT composite membranes work in these more realistic situations, especially how well they resist fouling by natural organic matter (NOM), which can cover the membrane surfaces and possibly the antibacterial nanotube tips. Moreover, the enduring consequences of MWCNTs and silver nanoparticles that may be discharged from the membrane during prolonged operation necessitate meticulous ecotoxicological evaluation prior to extensive implementation. The mechanical endurance of the membranes subjected to frequent pressure cycling and chemical cleaning processes necessitates further investigation. Future research in this domain should encompass testing under nanofiltration (NF) and ultrafiltration (UF) conditions, the incorporation of these composite membranes into full-scale hollow fiber or spiral-wound module configurations, and the assessment of the regenerability of antibacterial activity via straightforward cleaning protocols.

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