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Research Article

Water Disinfection Via Zinc Oxide (ZnO) Nanowires Chemically Fabricated on A Modified Polyurethane Substrate

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Abstract: Nowadays, water contamination is a big issue due to concerns about health and water scarcity. Unfortunately, most water for human consumption is contaminated with various pathogenic microorganisms that cause water-related diseases. Most traditional chemical and physical disinfectants are energy- and time-intensive and prone to generating harmful disinfection by-products. The recent controversy about waterborne diseases and the safety of commonly used disinfection methods has renewed interest in other forms of disinfection. Low-cost, high-efficiency, and low-energy devices should be developed for potential water disinfection, enabling safe drinking water access. Recently, many researchers have been working on improving the scalability and economics of nanomaterial-based devices to overcome many of the limitations of using traditional anti-microbial agents. Herein, we develop a safe and efficient new nanomaterial decontamination device targeting bacteria in drinking water. Zinc Oxide (ZnO) Nanowires and polyurethane sponges were utilized as affordable and available materials that would lower the cost of the filtration device. The device is based on an electroporation method that applies a low voltage of ~6 V to inactivated bacteria in water. The performance of our device was optimized using different values of voltages, flow rates, microorganism concentrations, and various operation times. By relying on nanotechnology-enabled electroporation principles, this method aims to address the limitations of traditional techniques and offer a feasible solution, especially in areas grappling with contamination issues that lack water treatment infrastructure.

Keywords: Coating; Carbon Nanotubes (CNTs); Nano Sponge; Polyurethane Sponge; Removal Efficiency.

1. Introduction

In recent years, the contamination of drinking water with various pathogenic microorganisms has escalated into a global concern [1]–[4]. Waterborne pathogens are the primary cause of significant outbreaks of enteric illnesses, encompassing gastroenteritis, dysentery, diarrhea, and viral hepatitis [5]–[8]. To combat this issue, various chemical and physical agents have been extensively employed to eradicate these waterborne diseases effectively.

A principal approach to eliminating pathogenic microorganisms is through chemical disinfection processes [9]–[11]. These processes utilize various chemical agents such as chlorine and chlorine-containing compounds to rid water of microorganisms. Due to its proven ability to kill a broad spectrum of microbes, chlorine is the most commonly used disinfectant. Additionally, other disinfecting agents such as fluorine, ozone, iodine, and heavy metal ions (including silver), among others, are utilized in various combinations and concentrations to achieve optimal effectiveness in removing pathogenic microorganisms [12]–[14].

Despite chlorination's widespread use and efficacy in water treatment, it is accompanied by a significant drawback: the formation of disinfection by-products (DBPs). These DBPs, which result from the reaction between chlorine and organic matter in water, have raised concerns due to their potential health effects. Indeed, studies have shown that certain types of DBPs have carcinogenic properties, with links to cancer observed in laboratory animals, particularly affecting organs such as

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the liver, kidneys, and large intestine [15], [16]. Consequently, there is a pressing need to reevaluate conventional chlorination practices and explore alternative disinfection methods that can mitigate the formation of harmful DBPs while maintaining water safety.

In response to this imperative, interest has grown in applying physical disinfection methods as viable alternatives. These methods, which include ultraviolet (UV) radiation, electric discharges in water (such as electrochemical disinfection), and others, operate by leveraging various physical fields and forces to achieve microbial inactivation [17]–[19]. UV radiation, for instance, disrupts the DNA of microorganisms, rendering them unable to reproduce. Similarly, electric discharges generate reactive species that can effectively neutralize pathogens. While these physical methods offer promise, they are not without limitations. For instance, they may be less effective in waters with high concentrations of soluble organic materials, suspended particles, or intense coloration, limiting their applicability in certain contexts [15], [20].

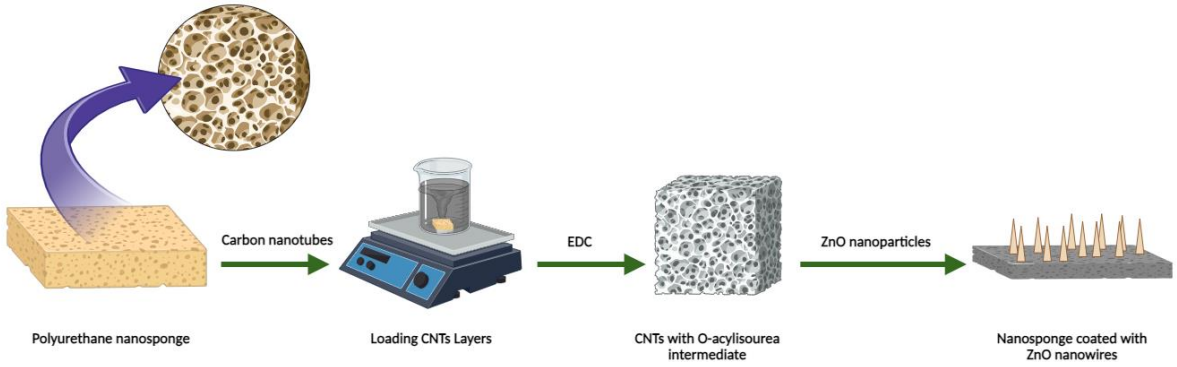

Figure 1. Multi-step Process for Manufacturing Nanocomposite Sponges Coated with Zinc Oxide (ZnO) Nanowires.

In light of these limitations, there is an urgent need to develop innovative disinfection methods that are both efficient and adaptable to various water conditions. Practical, affordable, rapid, and low-energy methods protect drinking water from disease-causing pathogens, especially in developing countries with limited resources [21], [22]. These new methods must provide clean and safe water without producing harmful by-products or requiring extensive infrastructure.

Researchers are exploring various novel technologies and approaches to address these challenges. One promising area is advanced oxidation processes (AOPs), which combine UV light with hydrogen peroxide or ozone to produce highly reactive hydroxyl radicals that can effectively break down organic contaminants and kill pathogens. Another area of interest is the development of photocatalytic materials, such as titanium dioxide, which can harness sunlight to drive disinfection reactions. Additionally, ongoing research is into nanomaterials and electrochemical processes that can offer high efficiency and scalability for water treatment applications.

2. Literature Review

2.1. Nanotechnology Innovations: Electroporation

In recent years, nanotechnologies have offered unprecedented technological solutions to remove harmful materials from water [23]–[26]. Recently, separation membranes with pore sizes at the nanoscale (nanomembranes) have been used for the removal of organic as well as inorganic contaminants [27], [28]. Due to their large specific surface, structure, and surface properties, nanomaterials are recognized as promising anti-microbial agents. Examples include silver nanoparticles (Ag NPs), chitosan, and carbon nanotubes (CNTs) [28]–[32]. The challenge of achieving affordable, low-energy, and high-efficiency disinfection without producing carcinogenic by-products calls for new technologies for efficient disinfection and microbial control. The electroporation method, widely used today in molecular biology, shows excellent potential for disinfecting water [33]. Electroporation can be characterized as a dramatic increase in membrane permeability induced by externally applied short and intense electric pulses [34]–[36]. There is evidence that prolonged exposure of the cell membrane of microorganisms to a strong electric field causes inactivation of microorganisms due to increasing the permeability of the outer envelope, which leads to leakage of intracellular components [37], [38]. Because of this, several very recent studies have successfully demonstrated that electroporation may be used as an alternative method for water disinfection. In recent years, novel flow devices have been designed to enable fast water disinfection using one-dimensional nanomaterials (1D-NE) [39]. Disinfection of water using electroporation can be performed by

applying a low voltage from 0 V to 20 V to inactivate bacteria and viruses. In these devices, conductive one-dimensional nanomaterials (1D-NE) of different types of anti-microbial agents are grown on various kinds of surfaces [39], [40]. The sharp nanoscale features concentrate the electric field strength, creating localized zones of intensified electroporation effects [39]–[43] (Figure 2). As water flows through these high-field regions, microbial cell membranes are permeabilized, causing leakage of intracellular contents and deactivation.

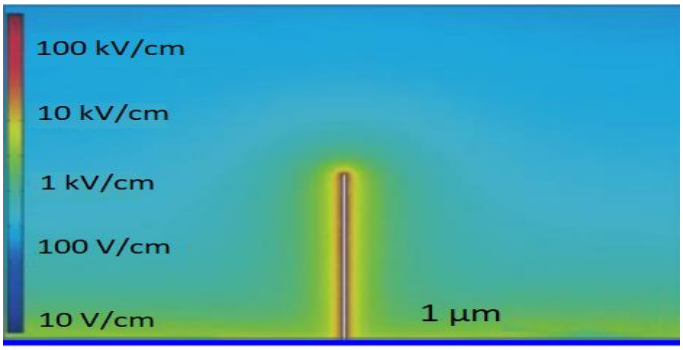

Figure 2. The Electric Field Distribution at The Vicinity of Nanowire (NW) [44].

However, several questions remain about the consistency of inactivation effects across different microbes and water chemistries [40], [45]–[47]. There is also a limited understanding of the impacts on water quality and the potential formation of disinfection by-products [48]. Further research is critically needed to address these knowledge gaps and fully realize the promise of electroporated nanotechnology solutions for sustainable, widely implementable water disinfection. This study has innovated a new nanomaterial decontamination device with high disinfection efficiency. To improve the stability of the filtration devices, the zinc oxide nanowires have been chemically fabricated on a modified polyurethane substrate. We expect chemical methods will increase our filtration device's stability and enhance the nanomaterials' conductivity. The device's efficiency for inactivating microorganisms has been evaluated using various values of external voltages, water flow rates, microorganism concentrations, and operation times. Nanomaterials have received considerable attention due to their unique physicochemical characteristics, including optical properties, catalytic activity, magnetic properties, and antibacterial properties (Table 1).

Table 1. Related Research

Authors	Objective of research	Method	Outcome of research	Limitations of research
Haoyu Wang. et. al. (2021) [49]	Water sterilization	Branched CuO-Co3O4 nanowires coated with carbon on Cu foam.	The bactericidal effect is at a flow rate of 1000 mL min and a voltage of 10V.	It has no long-term stability (it lost its disinfection abilities after continuous operation).
Zheng-Yang et. al. (2022) [50]	Water Disinfection.	Electro chlorination with nanowire-enhanced electroporation.	Complete bacteria removal at the flow rate of 2.4 × 104 L/ (m2 h) and a voltage of 2.0 V.	Low efficiency under high water flux due.
Ying zheng et. al. (2023) [51]	The optimization of electroporation electrodes.	The correlation between the morphology of the nanoarray of ZnO and the efficiency of electroporation disinfection.	ZnO nano-pyramid exhibited the best electroporation disinfection efficiency.	The electroporation disinfection efficiency against the positive bacteria was 84.4%.
Pushpendra et. al. (2022) [52]	Study a hand-powered, portable disinfection system.	LEEFT water disinfectant system powered by EMG.	5-log (E. coli) and 4-log (S. aureus).	Nanowires detached, and Cu was released during the bacteria inactivation experiment.
Ecem et al. (2020) [53]	Removal of E. coli bacteria from water.	Fabricating AgNW-GF filter.	Achieved 2 log removal for 103 CFU/ml E. coli concentration.	Ag releases significantly increase with an increase in the concentration of E. coli-contaminated water.
Zheng-Yang et. al. (2021) [54]	Disinfection of air-transmitted bacteria and viruses.	Resonance-vibration-driven (RV) air disinfection methods.	>99.99% microbial inactivation within 0.025s in airflow (2 m/s).	The antibacterial efficiency is poor in the no-charge-model system.

Authors	Objective of research	Method	Outcome of research	Limitations of research
Zheng-Yang et. al. (2017) [55]	Food, water, and medical waste treatment.	Carbon-nanotube sponges.	There was no detection of live bacteria in the effluent using 2V for 5 seconds.	After a long term (60 min) of use, the bacteria tended to attach to the tip structure, leading to a failure of the disinfection process.

2.2. A Basic Mathematical Equation of Electroporation

Estimate the magnitude of the electrical field at point (y), which is located at a distance (x) from the center of a spherical conductor that is held at potential V (Figure 3). The electrical field at the surface of the spherical conductor is created by a charge Q placed in the center of the sphere.

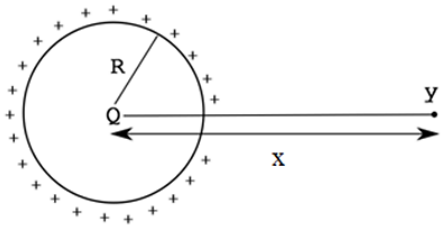

Figure 3. The Electric Field at Point Y is at Distance X From the Center of the Charged Conductor.

$$|E| = k \cdot | Q |/x^2 \quad (1)$$

Where E is the electric field, k is the electric constant, and Q is the creating electric field. Since the electric potential V is equal to:

$$V = k \cdot Q/x \quad (2)$$

The equivalent charge at point Q should be:

$$Q = V \cdot x/k \quad (3)$$

By substituting eq. (3) in eq. (1) we will get:

$$|E| = |V|/x \quad (4)$$

The electrical potential does not change inside of a spherical conductor because the electric field inside the conductor is equal to zero (E = 0), so the electric potential on the surface is equal to the electric potential inside the sphere:

$$V_{Inside} = V_{Outside} = \frac{kQ}{R} \quad (5)$$

Figure 4 shows electric potential (V) dependence on the distance (x) at different positions: inside, at the surface, and outside of a spherical conductor.

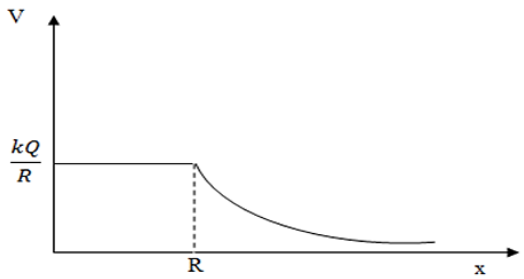

Figure 4. The Electric Potential (V) versus the Distance (x).

Therefore, just at the surface of the spherical conductor, the magnitude of the electrical field is:

$$|E| = \frac{|V|}{R} \quad (6)$$

This explains why the electrical field is amplified at convex regions of the equipotential surface with high curvature. Since the potential difference (ΔV) across the cell membrane that has membrane thickness, d, is equal to:

$$\Delta V = E \cdot d \quad (7)$$

The electrical field necessary for creating potential difference equal to 1V for cell membrane thickness ≈ 10-8 m is:

$$E = \frac{\Delta V}{d} = 10^8 \ V/m \quad (8)$$

To create the desired field in the vicinity of nanowires with a radius of curvature of 20 nm, the applied voltage should be:

$$V = R \cdot E = 20 \cdot 10^{-9} \cdot 10^8 = 10\,V \quad (9)$$

Since the electric potential is higher near the nanowires, the bacteria and viruses are more electroporated in this area, and their cell membranes are ruptured. Damage of cell membranes and leakage of intracellular components causes inactivation and death of microorganisms [45], [56].

Figure 5 shows the electroporation process using one-dimension nanomaterials (1D-NE).

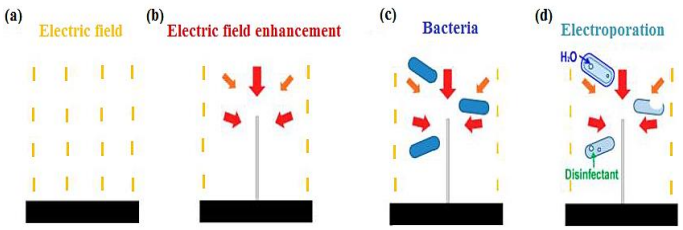

Figure 5. Schematic shows microorganisms being electroporated at the vicinities of nanowires material [56].

3. Material and Methods

3.1. Preparation of Acid Treated CNTs

The experimental process involved a meticulously orchestrated sequence to prepare acid-treated Carbon Nanotubes (CNTs), which was pivotal in facilitating the binding of ZnO nanowires. Initially, Multi-Walled Carbon Nanotubes (MWCNTs) underwent purification with diameters ranging from approximately 15 to 25 nanometers and lengths spanning 10 to 20 micrometers. This purification process involved subjecting the MWCNTs to a 530°C air burn for 30 minutes to eliminate impurities and enhance their quality.

Subsequently, the purified CNTs were subjected to oxidation at ambient room temperature, utilizing a 3:1 mixture of concentrated sulfuric acid (H2SO4) and nitric acid (HNO3). This oxidation step was instrumental in introducing carboxyl groups (-COOH) onto the surface of the nanotubes, thereby enhancing their reactivity and functionalization potential. The resulting mixture underwent treatment in an ultrasonic bath for an hour to disperse any aggregated nanotubes, ensuring homogeneity within the solution. The mixture was then suspended and refluxed in 40 milliliters of concentrated hydrochloric acid (HCl) for 2 hours. Subsequently, the solution was meticulously neutralized using sodium hydroxide (NaOH), followed by filtration and thorough washing with deionized water until achieving a pH of 5.5, thereby removing any residual acids or by-products.

In the final stages of the process, the filter paper containing the acid-treated CNTs was immersed in deionized water and subjected to ultrasonic treatment to redissolve the CNTs, ensuring their dispersal and uniform distribution within the solution. This comprehensive procedure, as detailed in references [48], [57], [58], yielded acid-treated CNTs primed for effective integration with ZnO nanowires, facilitating their application in the experimental setup.

3.2. Preparation of Zinc Oxide (ZnO)

The synthesis of Zinc Oxide (ZnO) involved a methodical series of procedures capitalizing on its semiconductor properties and anti-microbial characteristics. ZnO, a semiconductor metal oxide exhibiting a band gap of 3.37 eV at standard room temperature, has garnered attention in recent scholarly investigations for its capacity to enhance electron transport through dense arrays of ZnO nanowires, thereby establishing direct conduction pathways within the substrate [59], [60].

This study employed ZnO nanowires and the synthetic protocol commenced with the dissolution of 5.5 grams of zinc acetate in 100 milliliters of ethanol. Subsequently, this solution underwent gradual introduction into 200 milliliters of a 1 mg/ml polyethyleneimine (PEI) solution under continuous stirring (pH of 9). PEI has been demonstrated to effectively facilitate the binding of metal ions or nanoparticles to the surface of carbon nanotubes. The mixture was heated at 150°C under vigorous stirring for 1 hour, forming amine-terminated ZnO nanoparticles with a positive charge [58].

3.3. Decoration of Polyurethane Sponge with Carbon Nanotubes (CNTs) and Zinc Oxide (ZnO) Nanowires

Enhancing the polyurethane sponge with Carbon Nanotubes (CNTs) and Zinc Oxide Nanowires (ZnONWs) unfolded through a systematic sequence, each step meticulously designed for optimal integration. It commenced with thoroughly cleansing the 1cm × 2cm polyurethane sponge, meticulously treated with acetone, isopropanol, and deionized water to eliminate impurities and particles, ensuring a pristine surface for subsequent modifications. The successive application of an acid-treated CNT suspension was equally precise, involving the coating of the sponge using a spin coater for three cycles at 2000 rpm, followed by controlled heating at 70-80 °C to ensure robust adhesion of the CNTs to the sponge substrate. This step was crucial for establishing a durable and effective CNT matrix on the sponge surface.

Creating a structurally sound and functional device necessitated a cross-linker, EDC (1-Ethyl-3-(3-dimethylaminopropyl carbodiimide hydrochloride)). EDC facilitated reactions between the carboxylic groups on CNTs and the amine groups on modified ZnO nanoparticles, forming crucial amide bonds. Following a meticulous two-hour immersion in a 0.5 M EDC solution and subsequent washing steps, Zinc Oxide nano crystallites were seeded onto the acid-treated CNTs substrate.

The subsequent coating with a modified ZnO nanoparticle solution, coupled with heating at 100°C and a growth process at 92°C, ensured the controlled

development of ZnO nanowires on the CNT substrate, enhancing the device's anti-microbial properties and electron transport capabilities. A comprehensive cleaning regimen involving isopropyl alcohol, acetone, and deionized water was employed to prepare the decorated sponge for integration into the final filtration system. This included establishing connections to conductive wires and ensuring seamless integration and functionality for its intended applications [57], [61].

3.4. Bacteria Samples Preparation

The investigation into the disinfection efficacy of the nano sponge filtration system necessitated a rigorous preparation of bacterial samples to assess its performance comprehensively. Specifically, Gram-negative Escherichia coli and Gram-positive Bacillus subtilis were selected as target microorganisms due to their relevance in various environmental and healthcare settings.

The cultivation of the bacteria commenced with separate overnight cultures in Tryptic Soy Broth (TSB), meticulously maintained at a controlled temperature of 37°C to promote optimal growth conditions. Following incubation, the microbial cultures underwent harvesting via centrifugation at 900 grams, thereby facilitating the concentration of bacterial cells. After centrifugation, the cells underwent a meticulous washing process involving two cycles of sterile water rinsing to eliminate residual culture media or extraneous impurities.

Following the purification steps, the bacterial cells were suspended in water to achieve a standardized concentration of approximately ~107 colony-forming units (CFU) per milliliter. To uphold uniformity and ensure controlled experimental conditions, 100 milliliters of each bacterial suspension were meticulously prepared and stored at ambient room temperature as control samples. These control specimens provided a crucial baseline for comparative analysis when evaluating the nano sponge filtration device's disinfection performance. The meticulously prepared bacterial suspensions functioned as the test samples, enabling the thorough evaluation of the filtration system's efficacy in disinfecting and eliminating microbial contaminants from the aqueous matrix [5].

3.5. Construction of a Device

The assembly of the experimental setup involved the meticulous construction of a filtration device tailored to assess the antibacterial efficacy of the incorporated ZnO nanowires. Two specially modified nano sponges, designed in parallel, were intricately interconnected utilizing conductive wires. These interlinked nano sponges were delicately positioned within a funnel connected to a filtering flask. The seamless connection between the filtering flask and a pump was established via a rubber tube, as illustrated in Figure 6 of the experimental setup.

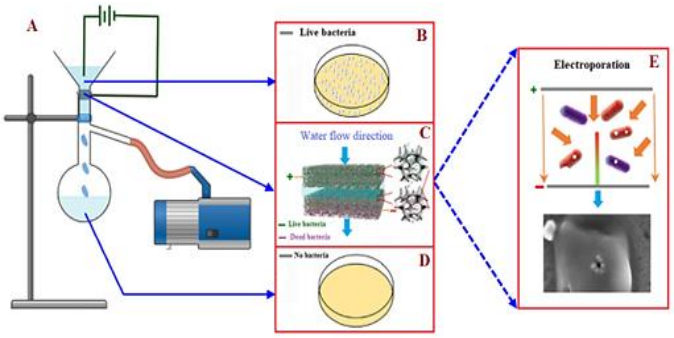

Figure 6. (A) Inserting Nano sponge Inside the Cross-Section; (B) 1 ml of Bacteria Solution Was Incubated Overnight in Agar Plate; (C) The Disinfection Device During the Operation; (D) 1 ml Of Filtered Bacteria Solution Was Incubated Overnight in Agar Plate; (E) Microorganisms Being Electroporated at The Vicinities of Nanowires Material.

Two electrodes were activated to initiate the experimental procedure, powering the system's electrical components. Simultaneously, the pump was set into motion to facilitate the controlled flow of the water sample through the modified nano sponge filter. As the water traversed the filter, its interaction with the embedded ZnO nanowires was meticulously monitored to evaluate the system's antibacterial efficiency. This setup provided a robust platform for assessing the disinfection capabilities of the ZnO nanowires within the context of water filtration.

4. Results

4.1. Test Device Performance Using Different Voltages

To evaluate the improvement in the efficiency of the device, a polyurethane nano sponge with a pore size ~of 500 µm was utilized to get a fast flow rate, avoid fouling, and ensure a high probability of microbial electroporation. First, the device is connected to the peristaltic pump to control the water flow rate. The flow rate was kept at 5 mL/min. To investigate the performance of the device, 100 ml of the control and two model-contaminated water samples (~107CFU/mL) were passed through the nano sponge filtration device at various external voltages ranging from 0 V to 12 V using a DC power supply. The concentration of the live bacteria in the effluent water collected samples were tested using the spread plate method, and the microbial log-inactivation efficiency (E) of the device was estimated using the equation (10) [54], [55].

$$Removal\ efficiency\ (\%) = -\log\left(\frac{C}{C_\circ}\right) \quad (10)$$

where $C\ and\ C_{\circ}$ represents the microorganisms' concentration CFU/mL of the live bacteria before and after the disinfection process, respectively. The effluents were collected, and the disinfection efficiency of the device was evaluated (Figure 7).

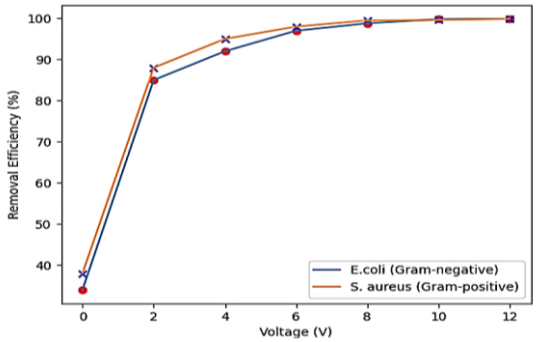

Figure 7. The Percentage of Removal Efficiency of The Nano Sponge Filtration Device vs. Applied Voltages.

4.2. Test Device Productivity at Different Flow Rates

A modified polyurethane sponge with variable flow rates was employed to assess the productivity of our device. After determining the optimal voltage for heightened removal efficiency, established in (A), an applied voltage of 6 volts was selected. Two model-contaminated water samples, each containing approximately ~107 colony-forming units per milliliter (CFU/mL), were passed through the device at varying flow rates ranging from 0 to 25 milliliters per minute (ml/min) utilizing a peristaltic pump. The effluent from the device was meticulously collected in an autoclaved container to maintain sterility.

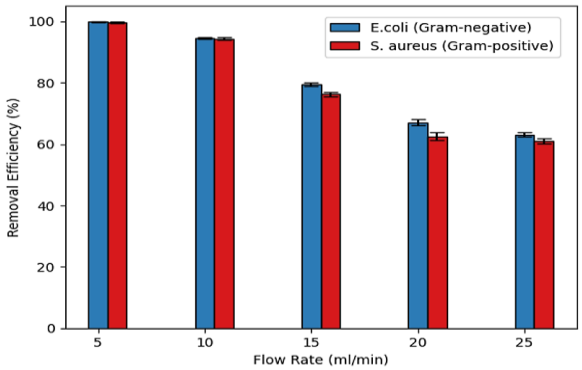

Figure 8. The Percentage of Disinfection Efficiency of The Nano Sponge Filtration Device vs. Different Flow Rates.

Subsequently, the number of surviving bacteria in the effluent was quantified using the spread plate method, determining the CFU/mL for each sample. The log-inactivation efficiency (E) was computed employing equation (10). The collected effluents underwent comprehensive analysis to evaluate the disinfection efficiency of the device across different flow rates (Figure 8). This systematic evaluation allowed for the characterization of the device's performance under varied flow conditions, providing valuable insights into its efficacy in microbial disinfection.

4.3. Test Device Antibacterial Activity at Different Microorganism Concentrations

Following the successful completion of sections 4.1 and 4.2, wherein optimal results were achieved with specific parameters of applied voltage (6V) and a flow rate of 5 mL/min, further investigations were undertaken. These subsequent experiments involved varying the concentrations of microorganisms to assess the antibacterial performance of the filter.

Microorganism-seeded water samples were meticulously prepared, containing a range of approximately 10^3 to 10^9 colony-forming units per milliliter (CFU/mL) of either Escherichia coli or Bacillus subtilis microorganisms. These prepared samples were subsequently pumped through the microbial electroporation device, allowing for the evaluation of their disinfection efficiency under diverse microbial concentrations.

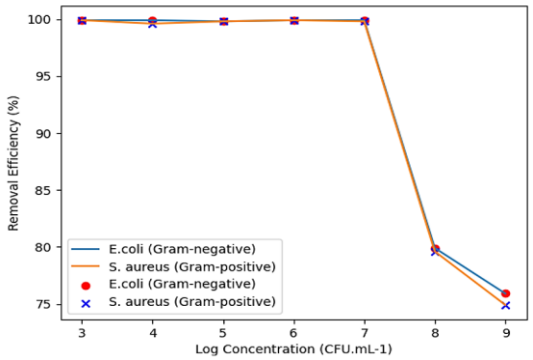

Figure 9. The Percentage of Disinfection Efficiency of The Nano Sponge Filtration Device with Different Microorganism Concentrations.

Effluents from these experiments were collected at different concentrations, and the disinfection efficiency of the device was meticulously evaluated, as delineated in Figure 9. This comprehensive analysis enabled the characterization of the device's efficacy across various microbial concentrations, providing valuable insights into its antibacterial performance under varied environmental conditions.

4.4. Test Device Stability

The stability of our device has been rigorously assessed through periodic evaluations. To ascertain the antibacterial performance stability of the device, microorganism-

seeded water samples containing approximately 10^3-10^9 colony-forming units per milliliter (CFU/mL) of Escherichia coli microorganisms were meticulously prepared. These samples were then systematically pumped through the microbial electroporation device, maintaining a constant applied voltage of 6V and a 5 mL/min flow rate.

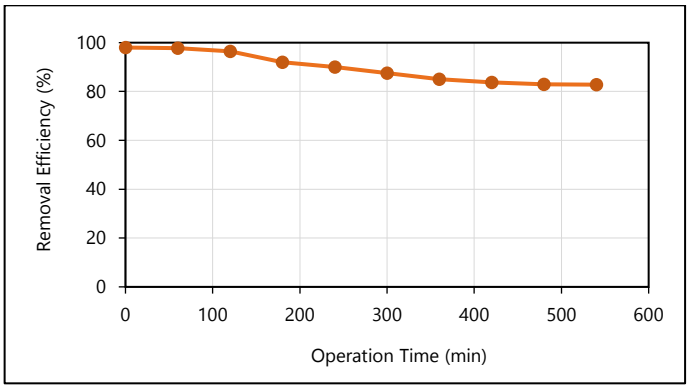

Figure 10. The Percentage of Disinfection Efficiency of The Nano Sponge Filtration Device at Different Operation Time.

Effluents from the device were collected at regular intervals over a specified period, each time into autoclaved containers to uphold sterility. The disinfection efficiency of the device was meticulously evaluated over time, with the collected data depicted graphically in Figure 10. This systematic investigation allowed for the comprehensive assessment of the device's ability to maintain consistent antibacterial performance over extended durations, providing crucial insights into its long-term stability and efficacy in microbial disinfection applications.

5. Discussion

To investigate the output performance of the electroporation disinfection device, water samples seeded with two models of pathogens, E. coli of Gram-negative species and Bacillus subtilis of Gram-positive species, were used. The disinfection performance of the device was first tested in the absence and presence of external voltages ranging from 2 to 12 V. During testing. A peristaltic pump maintained the bacterial concentrations and the flow rate through the device at 5 mL/min. The two models of microbes, with concentrations of approximately ~10^7 CFU/mL, flowed through the disinfection device, and the number of surviving microorganisms in the effluent was counted using the spread plate method.

Without an applied voltage, the electroporation-disinfecting device demonstrated lower inactivation rates of 38% for E. coli and 35% for Bacillus subtilis. This inactivation is attributed to the physical contact between the bacteria and the electrodes. However, when an external voltage was applied, the inactivation efficiency significantly increased, showcasing the effectiveness of the electroporation process in enhancing bacterial inactivation. This underscores the importance of electrical parameters in optimizing the performance of the disinfection device. The device's ability to effectively inactivate microorganisms at various voltage levels highlights its potential for application in water treatment systems.

The filter's disinfection performance was further evaluated under various flow rates, with a bacterial concentration of ~10^7 CFU/mL and an applied voltage of 6V. The results showed that increasing the flow rates led to a noticeable decrease in the removal efficiency, from 99.7% and 99.4% to 63% and 61% for E. coli and Bacillus subtilis, respectively (Figure 7). This observation suggests that lower flow rates allow more time for bacteria to contact the electrodes, resulting in better disinfection. Additionally, the device's performance was assessed at different microorganism concentrations. At ~10^7 CFU/mL, the removal efficiency was 99%, but it dropped to 75% at ~10^8 CFU/mL (Figure 8). This decline indicates that the device's efficiency is compromised at higher microbial concentrations, possibly due to the saturation of active sites on the electrodes.

Testing the stability of the nanowire filter over an extended period is crucial for optimizing performance for real-world applications. In a long-term test using synthetic water with ~10^7 CFU/mL of E. coli at a flow rate of 5 mL/min and 6V, the filter maintained a high removal efficiency of 80% after 9 hours, demonstrating remarkable stability. This stability is attributed to the chemical cross-linking and enhanced conductivity of the zinc oxide nanowires, which ensure consistent performance over time. The slight decline in efficiency is likely due to the release of active surface sites and some zinc oxide nanowires, which might reduce the number of active sites available for bacterial inactivation.

The anti-microbial properties of nanomaterials, such as silver particles and zinc oxide nanowires, have been extensively studied. Yoon et al. [62] demonstrated the anti-microbial effect of silver particles on bacterial contamination of activated carbon fibers, indicating significant antibacterial activity due to the presence of silver nanoparticles. Similarly, Dastjerdi and Montazer [63] reviewed the application of inorganic nano-structured materials in textiles, emphasizing their anti-microbial properties, including optical, catalytic, magnetic, and antibacterial characteristics. Additionally, Lalley et al. [64] investigated the bactericidal effect of silver-impregnated activated carbon, confirming the effectiveness of silver in enhancing antibacterial activity in water treatment applications.

6. Conclusion

In this research, we present the development of a novel nanowire-based disinfection device aimed at addressing two critical challenges: low flow rate and stability, which have historically hindered the application of nanowire-based technologies in water treatment. We have successfully reduced manufacturing costs and enhanced the device's flow rate by utilizing polyurethane sponges as the structural backbone. A chemical growth method was implemented to improve the stability and conductivity of the nanomaterials employed, ensuring robust integration of nanowires onto the sponge substrate and enhancing overall durability and performance. Comprehensive evaluations will involve testing the device's bactericidal efficacy, operational performance, productivity, and longevity under various conditions. By systematically optimizing these parameters, we aim to achieve superior disinfection efficiency, providing an effective, low-cost water purification solution that leverages nanomaterials' unique properties to address the pressing need for safe drinking water.

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