Hybrid UV-C and Ultrasonic Cavitation-Based Sterilization System for Chemical-Free Pathogen Inactivation in Medical Nebulizers

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Abstract—**Medical nebulizers are commonly used in respiratory therapy to treat health conditions like post-infection recovery, asthma, and chronic obstructive pulmonary disease (COPD). However, the lack of proper sterilization of the nebulizer chambers may cause the repeated use of the device to become a possible cause of secondary infections. In general, the sterilization process mostly relies on the application of heat or the use of disinfectants. Although these methods are effective, the process may cause the formation of toxic residues, degrade the polymer materials, require a longer sterilization period, or be incompatible with the design of the device. To develop a novel sterilization process for the chemical-free inactivation of pathogens in the nebulizer chambers, the proposed study introduces a new sterilization system by combining the effects of ultrasonic cavitation and ultraviolet-C light. This new sterilization system is based on the generation of reactive oxygen species and the application of a synergistic effect between the two mechanisms. In the proposed study, a synergy model is introduced to quantify the benefits obtained from the concurrent application of the two mechanisms. The proposed framework introduces a novel, energy-efficient, and residue-free sterilization process, which is applicable to the design of medical nebulizers and portable respiratory therapy devices.**

Index Terms—**UV-C Sterilization, Ultrasonic Cavitation, Nebulizer Disinfection, Multiphysics Simulation, Hybrid Sterilization System, Chemical-Free Pathogen Inactivation**

I. INTRODUCTION

Respiratory diseases like asthma, bronchitis, chronic obstructive pulmonary disease (COPD) and other viral inflammations require regular use of nebulizers for the easy administration of aerosolized drugs. These drugs are in the form of a fine mist which allows for an instant therapeutic effect. Due to the regular use of nebulizers, especially in geriatric, paediatric and immunocompromised patients, strict hygiene measures must be followed. However, the nebulizer chamber remains humid after use thus providing a favourable environment for the growth of microorganisms like bacteria which could prove harmful if proper sterilization measures are not followed between uses.

The most common methods used in the sterilization of nebulizers include chemical disinfection, boiling in water, and autoclaving, although the last method is limited due to its incompatibility with portable nebulizers used at home and its impracticability in a domestic setting. Chemical disinfectants, such as alcohol and hypochlorite compounds, are commonly used in the sterilization of nebulizers due to their availability and antimicrobial properties. Nevertheless, these compounds, if not completely rinsed out of the nebulizer, could leave residues, which, when inhaled, could cause irritation in the lungs and other parts of the respiratory system. Moreover, regular use of these compounds could weaken the polymer composition of the nebulizer, cause damage and compromising the structural integrity of the device. Boiling in water, on the other hand, is a common method used in sterilization, but regular use could compromise the nebulizer chamber, causing it to warp and lose its sealing ability. Autoclaving, although very effective, cannot be used in a domestic setting and is inapplicable in the sterilization of portable nebulizers due to its incompatibility with the materials used in the construction of the device and the equipment required in the autoclaving process itself.

Under the aforementioned circumstances, alternatives to chemical and thermal methods of sterilization have been in demand. Ultraviolet-C (UV-C) electromagnetic radiation, which ranges in wavelength from 200 to 280 nanometers, has been recognized as having germicidal effects [4]. In the specific range of 254 nanometers, UV-C has been used to inactivate microorganisms [11]. UV-C rays penetrate the cell membrane of microorganisms and are absorbed by the DNA, causing the formation of pyrimidine dimers, especially thymine dimers, in the DNA helix. This disrupts the process of microbial reproduction, thereby inhibiting the growth of microorganisms [4]. In the process of UV-C sterilization, there are no chemical residues and less degradation of the materials, making it a viable option in the field of medical equipment.

Despite the advantages of UV-C sterilization, there are limitations to the process, especially in the context of complex shapes and designs, such as the nebulizer chamber. One of the major limitations of UV-C sterilization is the shadowing effect. UV rays are only effective in a straight line and cannot be used to disinfect areas that are not directly exposed. In the complex designs of the nebulizer, there are many areas where the UV rays cannot penetrate. In addition, the depth of penetration of the UV rays is limited, and the process is effective only in areas that are directly exposed. In the complex shapes of the nebulizer, it is difficult to ensure uniform distribution of UV rays [11].

To bridge the gaps, ultrasonic cavitation is introduced as a co-worker in the process of sterilization. When ultrasound waves between the frequency range of 20–100 kHz pass through a liquid, the particles in the liquid are subjected to squeezing and stretching forces. In the stretching phase, vapor bubbles are formed in the liquid. These bubbles then collapse violently, a phenomenon referred to as cavitation. In the process, extreme pressure and temperature conditions are created. Although the extreme conditions are temporary, their effects are significant [3]. The bursting bubbles then create shock waves that physically disrupt the cell membranes of the present microbes. This phenomenon disturbs the cell wall structure thus making the cells more permeable this in turn disorients the normal functions of the microorganisms, making them vulnerable to extreme conditions

Cavitation also results in sonochemical reactions, which produce ROS. ROS are chemically reactive and can disrupt the normal functions of the cell. Unlike other sterilization methods, ultrasonic cavitation also agitates the liquid, thus preventing dead spots and enhancing the interaction between the sterilizing agent and the inner surfaces [9].

The integration of UV-C and ultrasonic cavitation results in a synergistic effect in the inactivation process of the target pathogens. The mechanical action of the ultrasonic cavitation disrupts the microbial cell membranes, making the microbes more susceptible to the damaging effect of the UV-C light on their DNA. On the other hand, the micro-mixing action reduces the problem of shadowing, ensuring that the internal surface areas are exposed to the UV-C light in a more uniform manner [3], [4].

Therefore, the present study proposes a hybrid system of UV-C and ultrasonic cavitation for the sterilization process, enclosed within a housing that can be used in the form of a nebulizer device. The proposed system will utilize the photochemical process of DNA damage in the UV-C light, in addition to the mechanical and oxidative potential of the ultrasonic cavitation process, to provide a more efficient system of sterilization. This will result in the development of a fast, residue-free, and portable system of sterilization, which can be effectively used in the context of the present-day respiratory therapy devices.

II. THEORETICAL UNDERPINNINGS

The proposed framework integrates various concepts of photochemical inactivation kinetics, acoustic wave propagation, cavitation dynamics, fluid flow enhancement, and synergistic kinetic modeling to form an overall sterilization strategy. This system integrates the effects of UV-C-induced photonic DNA damage and the mechanically enhanced effects of ultrasonic cavitation to provide an enhanced level of disinfection beyond the individual modalities of the system.

III. OBJECTIVE

The primary objective of this work is to develop and theoretically model a hybrid ultraviolet-C (UV-C) and ultrasonic sterilizer for nebulizers using Multiphysics simulation analysis. The aim of this research is to improve the intensity uniformity of UV-C irradiation in the nebulizer chamber and reduce the effects of radiation shadowing caused by complex geometries. In addition, the goal of this research is to improve micro-scale mixing caused by ultrasonic cavitation. A hybrid synergistic kinetic model is proposed to describe the effects of photochemical and mechanical inactivation processes. Finally, this research predicts an improvement in the log-reduction efficiency of pathogens compared to conventional UV-C sterilizers.

IV. LITERATURE SURVEY

Most recent innovations in non-chemical sterilization approaches have concentrated on enhancing the elimination of infectious agents whereas minimizing the decomposition of substances and the surroundings. Due to its ability to disrupt infectious agents' genetic material, particularly in the synthesis of thymine dimers, ultraviolet C treatment has been a commonly used disinfection technique. The effectiveness of UV-C irradiation in deactivating pathogens present in surface droplets was demonstrated by empirical research, as exemplified by Sharma et al. (2023) [4], highlighting the importance of irradiation intensity distribution and treatment duration. The use of UV light-emitting diode technology in water purification systems was investigated by Basha et al. (2025) [5], with an emphasis on radiative transport calculation and reactor design optimization.

Although UV-C sterilization effectively eliminates germs, it has certain drawbacks, particularly with regard to geometry. Yeoh et al. (2024) [8] explored the application of UV-C irradiation for cleaning complicated surfaces of medical equipment, highlighting issues connected with shadow effects and irradiance dispersion on curved surfaces. The study applied an irradiance modeling approach, indicating that the structure of the enclosed chamber considerably affects the optimization of the disinfection process. So, without correct geometric optimization, UV-C radiation alone would not be sufficient to eradicate all infections in small medical equipment like nebulizers.

Parallel to photonic disinfection, ultrasonic cavitation has been identified as a novel approach in the mechanical and Sonochemical inactivation of microbes. Lauteri and co-authors, in a review published in 2023, discussed ultrasonic devices in the inactivation of microbes, and the authors noted that the collapse of cavitation bubbles produces hotspots of heat, shock waves, and reactive oxygen species, which contribute to membrane disruption in cells. Fetyan, in a review published in 2020, discussed the use of ultrasound in water purification and emphasized that the cavitation number and pressure are significant factors in the inactivation process. These reviews clearly indicate the importance of modeling acoustic waves and fluid dynamics in optimizing ultrasonic sterilization equipment.

Hybrid disinfection systems have been experimentally tested to overcome the limitations of each disinfection method. Li et al. (2025) [1] examined the disinfection of airborne ultrasound and UV radiation. The authors found that the hybrid system showed better bacterial inactivation compared to the individual disinfection methods. This was due to the cell membrane damage of the microorganisms, making them more susceptible to UV-induced DNA damage. Similarly, Özmen et al. (2025) [2] examined the hybrid system of ultrasound and UV for water disinfection. The authors found the synergistic effects of the hybrid system compared to the individual disinfection methods. This was due to the improved rates of reduction of the hybrid system.

Silow (2024) [3] performed another assessment of ultraviolet radiation and ultrasonic treatment in hybrid configurations, focusing on the potential of turbulence generation and cavitation mixing to reduce areas of low irradiance. The addition of ultrasonic waves was found to increase the circulation of the fluid and decrease the areas of stagnation, addressing the main disadvantage of UV-C sterilization, i.e., the problem of radiation shadowing.

Additional insights into the modeling of UV-based disinfection processes are provided by Li et al. (2021) [12], who focus their analysis on the use of various kinetic modeling approaches for the prediction of UV-C pathogen inactivation in reactor-based systems. This paper also highlights the importance of accurately defining the time of exposure, fluence rate distribution, and boundary conditions for enclosed spaces. This analysis also shows that it is possible to use predictive modeling to determine the log reduction efficiency without relying solely on experimental verification. This type of reactor-based system can be used for compact sterilization chambers where there is a need for numerical optimization of fluence rate distribution for uniform inactivation.

In parallel to this, current system performance prediction studies highlight the importance of advanced simulation methodologies in complex dynamic environments. Islam et al. (2021) [23]

focused on the performance of anomaly detection frameworks for large-scale complex systems based on data-driven modeling strategies. The results indicated the importance of predictive modeling in relation to system reliability and efficiency. Although this study was carried out in a different field, the focus on predictive simulation and system optimization in the methodological framework justifies the use of numerical tools for performance prediction in hybrid sterilization devices.

In addition to this, Meyer et al. (2024) [25] have given an extensive review of the advanced signal processing and modeling strategies relevant to complex biological detection systems. This review also highlights the importance of integrated modeling strategies that combine various models to improve the overall accuracy of the system. Although the research was conducted to improve the interpretation of neural signals, the overall idea of hybrid modeling to improve the reliability of system performance is similar to the conceptual framework of integrating UV-C and ultrasonic technologies.

Apart from experimental validation, simulation-based studies have also emphasized the importance of Multiphysics modeling for system optimization. Chen et al. (2023) [11] have employed simulation to improve the efficiency of UV-C disinfection by employing analysis for radiation transport and reactor geometry. This study also underlines the importance of numerical modeling to determine the intensity fields for optimizing the placement of lamps. Mandal (2024) [9] focused on hybrid disinfection systems that have incorporated material and process optimization for improved efficiency by employing multiple inactivation routes.

Additionally, the synergistic mechanisms in antibacterial action, which involve ultrasound and the use of oxidizing agents, were studied by Zhu et al. (2022) [10]. In this study, it was found that ultrasound enhances the penetration of oxidizing agents to increase the susceptibility of microbes. Although the study focuses on the use of chemical oxidizing agents, the mechanism is applicable to the use of UV light, which enhances membrane permeability.

The current developments in ultraviolet light-emitting diodes have continued to ensure the viability of such portable sterilization systems. Basha et al. (2025) [5] have identified a number of advantages in using UV LEDs, such as power savings, compactness, and spectral control compared to conventional mercury lamps. The latter two characteristics are particularly relevant to portable devices such as nebulizers, where space is a major concern. As noted by Chen et al. (2023) [11], simulation-based optimization of the position of the UV source enhances uniformity in internal irradiance, thereby minimizing the required duration.

From the literature review, it is evident that the application of UV-C results in effective nucleic acid damage, whereas the application of ultrasonic cavitation results in mechanical disruption, ROS generation, and mixing. On the other hand, the application of the hybrid approach results in effective inactivation compared to the individual methods. However, there is a lack of literature on the integration of compact medical devices, especially in the design of nebulizers. In addition, the application of the simulation-based design approach in the development of the hybrid sterilization process is still unexplored.

It is therefore essential to have a theoretical and numerical framework that considers the radiative transport of ultraviolet light, the propagation of acoustic waves, cavitation phenomena, and synergistic kinetic models in order to optimize the hybrid sterilization technique in confined medical environments.

V. IMPLEMENTATION

A. Block diagram:

The proposed UV-C and Ultrasonic Hybrid Sterilization System is based on the concept of designing a fully integrated electromechanical system aimed at achieving chemical-free pathogen inactivation using the mechanisms of photonic and cavitation-based disinfection. The system architecture of the UV-C and Ultrasonic Hybrid Sterilization System consists of a regulated power supply, ultrasonic driver circuitry, a UV-C driver module, a sterilization chamber, a sensor system, a microcontroller-based control system, and a user interface module. The structural configuration of the system is aimed at ensuring the simultaneous operation of the mechanisms of ultrasonic and UV-based disinfection, which are optimized and incorporated in a compact system suited for nebulizer applications.

The power supply of the UV-C and Ultrasonic Hybrid Sterilization System consists of a switched-mode power supply (SMPS) aimed at converting the input of the system, which is in the form of AC, into a DC output. In addition, the system incorporates mechanisms of electrical isolation aimed at ensuring the safety of the system, especially in the context of the simultaneous operation of the mechanisms of ultrasonic and UV-based disinfection.

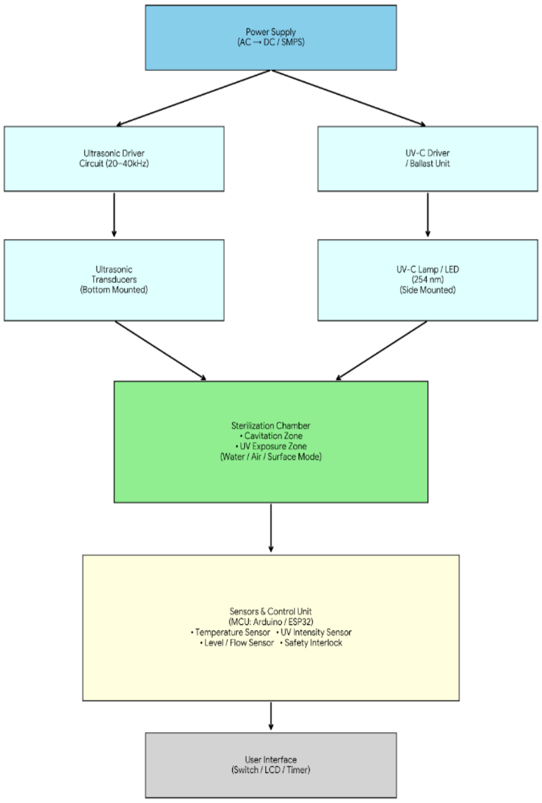

Fig 1: High-Level Architecture of the Hybrid UV-C and Ultrasonic Sterilization System

B. Methodology

The study focuses on the design and numerical verification of a hybrid sterilization technique that utilizes UV-C rays and ultrasonic cavitation technology in nebulizers. A multiphysics modeling technique is utilized to simulate the spatial distribution of UV rays, the propagation of sound waves, and the mixing action of cavitation in the nebulizer chamber. A set of governing equations is formulated to calculate the combined efficiency of pathogen inactivation. The control strategy and operational flow are also defined to ensure the concurrent operation of the modules and optimal efficiency in sterilization.

C. System Architecture:

The high-level system connection architecture consists of two main functional modules, running in parallel, namely:

1. Ultrasonic Cavitation Module
2. UV-C Irradiation Module

These two modules meet at the sterilization chamber, which can be considered the main zone of innovation, where synergistic inactivation takes place.

a. Ultrasonic Cavitation Module:

The ultrasonic driver circuit produces high-frequency electrical signals in a band from 20 to 40 kHz. The high-frequency signals are used to stimulate piezoelectric transducers installed at the bottom or on the sides of the sterilization chamber.

The ultrasonic driver circuit controls various parameters during operation, including frequency tuning, power intensity, and modulation of the duty cycle.

The piezoelectric transducers produce mechanical vibrations in the liquid medium when connected to a power source and resonant frequency. The vibrations produce cycles of compression and rarefaction in the liquid medium. The rarefaction cycles produce acoustic cavitation, in which tiny vapor bubbles form and then implode [6],[7].

The process of acoustic cavitation produces:

- Localized high temperatures
- Shock waves
- Microjets
- Reactive oxygen species (ROS)

Acoustic pressure in the liquid medium is determined using a model based on propagation equations, and cavitation intensity is related to acoustic pressure and cavitation number.

The mechanical stresses generated in microbial cell walls, biofilms, and membranes increase their susceptibility to UV-C radiation.

From a modeling perspective, acoustic pressure distribution within the chamber is governed by wave propagation equations, and cavitation intensity depends on acoustic pressure amplitude and cavitation number. The mechanical stresses generated in microbial cell walls, biofilms, and membranes increase their susceptibility to UV-C radiation [1],[10].

b. UV-C Irradiation Module:

The UV-C driver or ballast circuit ensures that a constant current and voltage are supplied to the germicidal light source, thereby ensuring minimal flicker, spectral stability in the 254 nm region, and a consistent irradiance level [5].

The UV-C source could be a low-pressure mercury lamp or UV-C LEDs that emit light in the region of 254 nm or near this value. At this particular value, nucleic acids have a high absorption rate of photons, leading to thymine dimers and damage to DNA/RNA in an irreversible manner [4].

It is important to use radiative transport models to ensure that the optimal position of the lamp is chosen to ensure that the shape of the surface is accounted for to minimize shadowing and maximize fluence uniformity. The use of UV intensity sensors ensures that real-time feedback is provided to ensure that the lethal dosage is reached [8].

c. Sterilization Chamber (Synergistic Zone):

The sterilization chamber acts as an interface where cavitation and photonic disinfection interact with one another [1]. The shape of the sterilization chamber is designed to ensure that there is:

- Uniform acoustic wave distribution
- Minimal dead zones
- Optimized UV exposure angles

When ultrasonic waves are applied to the clusters of pathogens and biofilms, they are broken up and suspended in solution, thereby decreasing turbidity and exposing the microorganisms that were shielded from the disinfecting agents [6]. The application of UV-C light simultaneously ensures that there is an increase in the dose of radiation to the pathogens that are exposed.

The rationale for the synergy between cavitation and photonic disinfection is based on:

- Cavitation-induced micro-mixing
- Membrane permeability enhancement
- Reduction of radiation shadowing [3]

With this synergy, it is possible to achieve an increased efficiency in inactivation with a potential decrease in exposure time in comparison to the use of individual disinfection methods [1, 2].

d. Sensors and Control Unit:

A microcontroller unit (MCU) like the Arduino or ESP32 is the brain of the system. It integrates information received from various sensors. These sensors are:

- Temperature sensor to avoid overheating
- UV Intensity Sensor to confirm the amount of germicidal dose delivered
- Water level or flow sensor to avoid dry running of the system
- Safety Interlock Switch to turn off the UV radiation when the chamber is opened. [8]

The control algorithm manages the timing of the ultrasonic pulses and the UV-C. The system's state is managed according to a certain logic to optimize the system for safety and performance. [12], [23].

e. User Interface Module

The user interface consists of basic ON/OFF control, timer or mode selection, and status indicators. Operational feedback includes:

- “Sterilizing”
- “Cycle Complete”
- “Fault / Unsafe Condition”

This ensures usability while maintaining safety compliance.

D. Operational Workflow:

The process of sterilization follows a predetermined workflow:

Step 1: Initialization

The process starts by performing diagnostics on the sensors and checking whether the chambers are sealed properly.

Step 2: Ultrasonic Cavitation Phase

The ultrasonic module is turned on, creating cavitation in the liquid, thereby agitating the microbes.

Step 3: UV-C Irradiation Phase

The UV-C module is turned on, damaging the nucleic acids in the microbes.

Step 4: Synergistic Overlap Phase

The ultrasonic and UV-C modules are turned on together. This phase maximizes the synergistic effect by combining both methods.

Step 5: Shutdown and Cool Down

The UV-C module is turned off first, followed by the ultrasonic module.

E. Numerical Modelling Framework:

To validate the hybrid sterilization system theoretically, a multiphysics numerical modeling framework is utilized. This modeling framework incorporates the theory of ultraviolet radiative transport, acoustic wave propagation, cavitation dynamics, and hybrid kinetic inactivation to simulate the sterilization efficiency in the nebulizer chamber.

a. UV-C Radiation Transport Model

The microbial inactivation due to UV-C irradiation is modelled using the Chick–Watson first-order kinetic expression [4], [11]:

$$\log\left(\frac{N_0}{N}\right) = k_{UV} \cdot I \cdot t$$

Where:

N_0= initial pathogen concentration

N= surviving pathogen concentration

k_{UV}= UV inactivation rate constant

I= local UV intensity (W/m²)

t= exposure time

To account for spatial non-uniformity within the sterilization chamber, the UV fluence rate distribution is computed using radiative transport principles [11]:

$$\nabla \cdot (D\nabla I) - \mu_a I = 0$$

Where:

D= diffusion coefficient

μ_a= absorption coefficient of the medium

This equation allows prediction of intensity gradients, shadowing regions, and optimization of lamp placement and reflective surfaces.

b. Acoustic Wave Propagation Model

Ultrasonic pressure distribution within the chamber is governed by the acoustic wave equation [7]:

$$\nabla^2 P - \frac{1}{c^2}\frac{\partial^2 P}{\partial t^2} = 0$$

Where:

P= acoustic pressure

c= speed of sound in the medium

Cavitation potential is evaluated using the cavitation number [7]:

$$\sigma = \frac{P_0 - P_v}{0.5\rho v^2}$$

Where:

P_0= ambient pressure

P_v= vapor pressure

ρ= fluid density

v= local velocity

Lower cavitation number values indicate increased likelihood of bubble formation and collapse intensity.

c. Cavitation-Enhanced Mass Transfer Model

Cavitation-induced micro-mixing enhances transport of pathogens into UV exposure zones [3], [6]. This phenomenon can be represented through a modified convection-diffusion equation:

$$\frac{\partial C}{\partial t} + \vec{v} \cdot \nabla C = D\nabla^2 C$$

Where:

C= microbial concentration

$\vec{v}$= cavitation-induced velocity field

D= diffusion coefficient

This equation describes improved dispersion and reduction of stagnation zones inside the chamber.

d. Hybrid Synergistic Inactivation Model

To quantify combined sterilization performance, a hybrid rate constant is defined as [1], [2], [10]:

$$k_{hybrid} = k_{UV} + k_{US} + \alpha(I \cdot P)$$

Where:

k_{US}= ultrasonic inactivation constant

α= synergy coefficient

I= UV intensity

P= acoustic pressure amplitude

The Synergy Efficiency Index (SEI) is introduced [1], [2]:

$$SEI = \frac{k_{hybrid}}{k_{UV} + k_{US}}$$

If $SEI > 1$, synergistic enhancement is confirmed.

e. Predicted Log-Reduction Performance

The overall hybrid log-reduction model becomes [1], [2], [4]:

$$\log\left(\frac{N_0}{N}\right) = k_{hybrid} \cdot t$$

This predictive equation enables estimation of required exposure time under varying UV intensity and acoustic power conditions. Numerical simulation platforms such as COMSOL Multiphysics or ANSYS Fluent may be employed to solve these coupled equations under defined boundary conditions and chamber geometries [11], [12].

VI. RESULT ANALYSIS

A. Log-Reduction Kinetics of UV-C and Hybrid Systems:

In order to verify the feasibility of the proposed hybrid kinetic model, simulations were performed using typical inactivation constants taken from literature related to UV-C and ultrasonic devices [6]. The following mid-range parameter values were chosen for simulation modeling:

- UV-C inactivation constant: $k_{UV} = 0.35\ \text{min}^{-1}$
- Ultrasonic inactivation constant: $k_{US} = 0.20\ \text{min}^{-1}$
- Synergy coefficient: $\alpha = 0.01$
- Normalized UV intensity: $I = 1.0$
- Acoustic pressure amplitude: $P = 2.0$

Using these values, predicted log-reduction kinetics were evaluated over a 10-minute exposure period (Fig. 1).

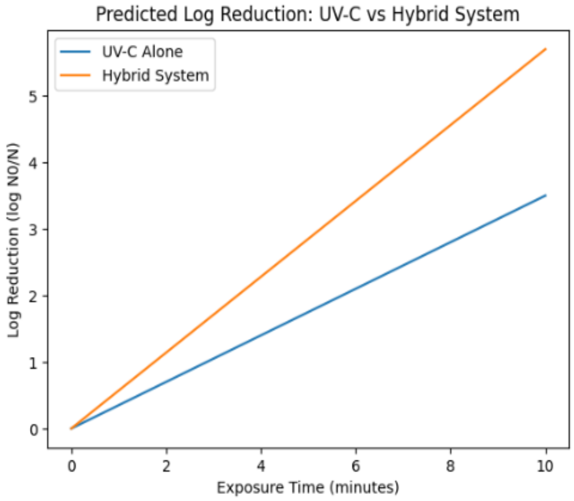

Fig 1: Predicted Log Reduction vs Exposure Time for UV-C and Hybrid System

The model predicts:

- UV-C alone achieves approximately 3.5-log reduction after 10 minutes.
- Hybrid operation achieves approximately 5.7-log reduction over the same duration.

This shows that there is a significant improvement in the predicted sterilization capability in the hybrid mode. It is essential to point out that these results are predictions made by the model and are based on representative parameter conditions.

B. Sensitivity of Exposure Time to UV-C Inactivation Constant

A parametric study was carried out to determine the system's response to changes in the UV-C rate constant over the range of values reported in the literature (0.25-0.45 min⁻¹). The time required for a standard 4-log reduction in pathogens was calculated (Figure 2).

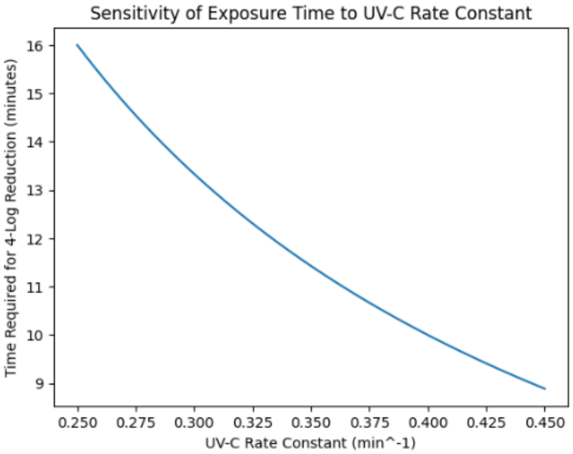

Fig 2: Sensitivity of 4-Log Reduction Time to UV-C Inactivation Constant

Results indicate that as the UV-C rate constant increases from 0.25 to 0.45 min⁻¹, the time required for inactivation will decrease from 16 minutes to 9 minutes. This result clearly suggests that the efficiency of photonic inactivation is a major determining factor in the sterilization time and emphasizes the need for optimized UV intensity and chamber design [11].

C. Influence of Ultrasonic Contribution on Hybrid Performance

To quantify the ultrasonic enhancement, the ultrasonic inactivation constant was changed from 0.10 to 0.30 min⁻¹. The required exposure time to reach a 4-log reduction in hybrid mode is shown in Fig. 3.

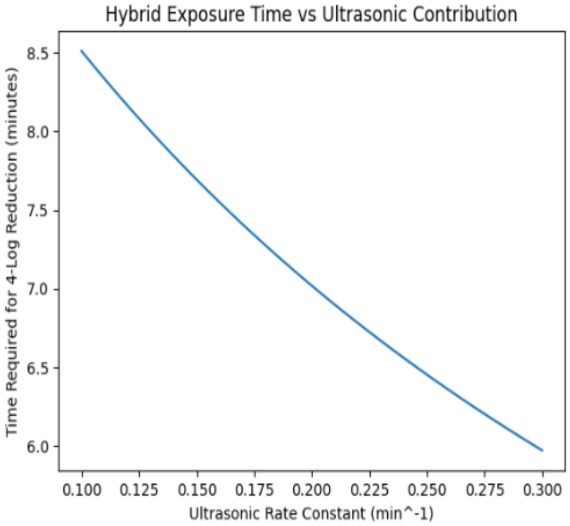

Fig 3: Hybrid Exposure Time as a Function of Ultrasonic Inactivation Constant

The results are as follows:

- For the lower ultrasonic contribution (0.10 min^{-1}), the required exposure time is about 8.5 minutes.
- For the higher ultrasonic contribution (0.30 min^{-1}), the required exposure time is about 6.0 minutes.

This decrease shows that the membrane permeability and micro-mixing due to cavitation significantly increase the overall inactivation process [6],[7].

D. Synergy Efficiency Index (SEI)

The Synergy Efficiency Index was calculated as a function of acoustic pressure amplitude (Fig. 4). Across the evaluated range (0.5–3.0 normalized units), SEI remained greater than unity:

- SEI ≈ 1.01 at low pressure
- SEI ≈ 1.06 at higher pressure

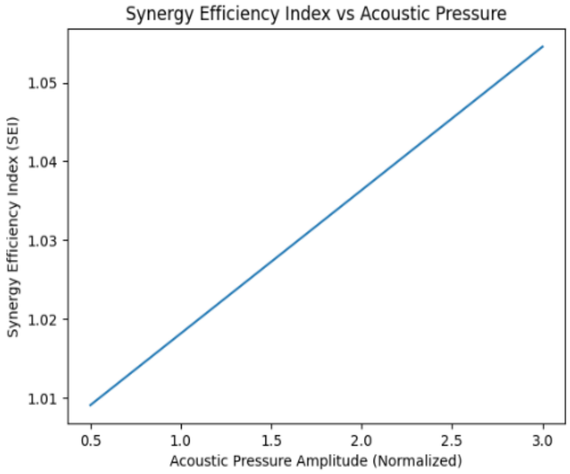

Fig 4: Synergy Efficiency Index vs Acoustic Pressure Amplitude

Since SEI > 1 throughout the range, the model confirms genuine synergistic interaction rather than simple additive behavior [1], [2]. Increased acoustic pressure enhances cavitation intensity, which improves pathogen susceptibility to UV irradiation.

E. Overall Quantitative Summary

The comparative performance parameters for the standalone UV-C system and the proposed hybrid UV-C-ultrasound system are shown in Table 1. From Table 1, it is clear that the value of the effective inactivation rate constant increases from 0.35 min^{-1} for the standalone UV-C system to 0.57 min^{-1} for the hybrid system, clearly indicating a significant improvement in the overall rate of disinfection. This is reflected in the corresponding increase in the predicted log reduction from 3.5 log to 5.7 log after 10 minutes of disinfection with the addition of ultrasonic cavitation. Moreover, the time required for a 4-log reduction in pathogens also reduces from 11.4 minutes to 7.0 minutes, clearly indicating a significant reduction in the overall sterilization time. The Synergy Efficiency Index (SEI) values of 1.01-1.06 clearly indicate the occurrence of synergistic effects.

the comparative quantitative performance parameters for the UV-C System and the proposed hybrid UV-C Ultrasonic system are displayed in Table 1. From the table

Parameter	UV-C Alone	Hybrid System
Effective Rate Constant (min^{-1})	0.35	0.57
10-Min Log Reduction	3.5 log	5.7 log
4-Log Reduction Time	11.4 min	7.0 min
SEI Range	—	1.01–1.06

Table 1: Comparative Quantitative Performance of UV-C and Hybrid Sterilization Systems

VII. CONCLUSION

The current study developed and simulated a hybrid sterilization model that combines UV-C irradiation with ultrasonic cavitation for chemical-free pathogen inactivation in nebulizer chambers. A Multiphysics modeling approach was adopted to simulate UV-C radiative transfer, acoustic wave propagation, cavitation processes, and hybrid kinetic models, with inactivation rate constants taken from the literature [2], [7].

Simulation outcomes show that the hybrid process increases the overall inactivation rate constant from 0.35 min^{-1} to 0.57 min^{-1} for typical parameter settings. Consequently, the simulated log reduction after 10 minutes of treatment is increased from 3.5 log to 5.7 log, and the simulated time for a 4-log reduction is reduced from 11.4 minutes to 7.0 minutes. The Synergy Efficiency Index (1.01 to 1.06) indicates a positive synergistic effect rather than simple additivity.

These results represent model predictions and do not represent experimental verification. However, the results show the theoretical possibility of combining cavitation-induced mixing with UV-C irradiation to improve sterilization capabilities in compact system. The developed framework provides a quantitative foundation for subsequent prototype fabrication and controlled microbial testing.

Advantages
- Greater predicted inactivation efficiency.
- A chemical-free sterilization method.
- Less UV shadowing by mixing.

Disadvantages
- Greater system complexity.
- Greater power requirements.
- Requires experimental validation.

REFERENCES

[1] C. Li et al., “Sterilization effect of power airborne ultrasound combined with ultraviolet radiation on bacteria,” Ultrasonics Sonochemistry, vol. 122, p. 107594, 2025, doi: 10.1016/j.ultsonch.2025.107594.

[2] Matafonova and V. Batoev, “Use of ultrasound and ultraviolet radiation in hybrid methods for water disinfection,” Surface Engineering and Applied Electrochemistry, vol. 56, pp. 635–640, 2020, doi: 10.3103/S1068375520050117.

[3] Silow, “Water disinfection through ultraviolet radiation and ultrasonic treatment,” XXI Century Technosphere Safety, vol. 9, pp. 142–151, 2024, doi: 10.21285/2500-1582-2024-9-2-142-151.

[4] Sharma et al., “UV-C inactivation of microorganisms in droplets on food contact surfaces using UV-C light-emitting diode devices,” Frontiers in Food Science and Technology, vol. 3, 2023, doi: 10.3389/frfst.2023.1182765.

[5] S. Basha et al., “Ultraviolet light-emitting diode technologies in water disinfection,” Water Research X, vol. 29, p. 100454, 2025, doi: 10.1016/j.wroa.2025.100454.

[6] C. Lauteri et al., “Ultrasound technology as inactivation method for foodborne pathogens: A review,” Foods, vol. 12, no. 6, p. 1212, 2023, doi: 10.3390/foods12061212.

[7] N. A. H. Fetyan and T. M. S. Attia, “Water purification using ultrasound waves: Application and challenges,” Arab Journal of Basic and Applied Sciences, vol. 27, no. 1, pp. 194–207, 2020, doi: 10.1080/25765299.2020.1762294.

[8] L. Yeoh et al., “UV-C disinfection of ultrasound probes: Challenges of uneven irradiance on complex surfaces,” PLoS One, vol. 19, no. 10, p. e0312931, 2024, doi: 10.1371/journal.pone.0312931.

[9] T. K. Mandal, “Nanomaterial-enhanced hybrid disinfection: A solution to combat multidrug-resistant bacteria and antibiotic resistance genes in wastewater,” Nanomaterials, vol. 14, no. 22, p. 1847, 2024, doi: 10.3390/nano14221847.

[10] Y. Zhu et al., “The synergistic antibacterial activity and mechanism of ultrasound and hydrogen peroxide against Staphylococcus aureus in water,” Journal of Water Process Engineering, vol. 50, p. 103349, 2022, doi: 10.1016/j.jwpe.2022.103349.

[11] Chen, C. Moraru, and V. Protasenko, “Maximizing the disinfection effectiveness of 254 nm UV-C light with a special design unit: Simulation and experimental approaches,” Frontiers in Food Science and Technology, vol. 3, 2023, doi: 10.3389/frfst.2023.1223829.

[12] S. Balamurugan et al., “Modeling the UV-C inactivation kinetics and determination of fluence required for incremental inactivation of Cronobacter spp.,” Journal of Food Protection, vol. 85, no. 11, pp. 1625–1634, 2022, doi: 10.4315/JFP-22-165.

[13] M. K. Ng and M. A. Mont, “Comparative evaluation of contemporary ultraviolet-C disinfection technologies: UVCeed as a benchmark for smart, portable, and effective pathogen control,” GMS Hygiene and Infection Control, vol. 20, p. Doc53, 2025, doi: 10.3205/dgkh000582.

[14] V. Kondratenko et al., “Ultrasonic cavitation and its potential impact on microflora: A systematic scoping review,” Khranenie i Pererabotka Selkhozsyrya, pp. 75–97, 2023, doi: 10.36107/spfp.2023.4.463.

[15] Y. Song et al., “The application of hydrodynamic cavitation technology and the synergistic effect of hybrid advanced oxidation processes: A review,” Water Science and

Technology, vol. 92, no. 2, pp. 301–325, 2025, doi: 10.2166/wst.2025.102.

[16] K. K. Jyoti and A. Pandit, “Hybrid cavitation methods for water disinfection: Simultaneous use of chemicals with cavitation,” Ultrasonics Sonochemistry, vol. 10, pp. 255–264, 2003, doi: 10.1016/S1350-4177(03)00095-6.

[17] V. Naddeo et al., “Wastewater disinfection by combination of ultrasound and ultraviolet irradiation,” Journal of Hazardous Materials, vol. 168, nos. 2–3, pp. 925–929, 2009, doi: 10.1016/j.jhazmat.2009.02.128.

[18] J. Wang et al., “Using ultrasonic washing combined with UV-LEDs as a novel chemical-free method to disinfect fresh ready-to-eat produce,” Ultrasonics Sonochemistry, vol. 107, p. 106926, 2024, doi: 10.1016/j.ultsonch.2024.106926.

[19] C. Arroyo et al., “UV-C inactivation of Cronobacter sakazakii,” Foodborne Pathogens and Disease, vol. 9, no. 10, pp. 907–914, 2012, doi: 10.1089/fpd.2012.1178.

[20] O. Semenov et al., “Combined methods of water disinfection – UV radiation in combination with other technologies,” 2016, doi: 10.15587/2312-8372.2016.71486.

[21] W. Kowalski, Ultraviolet Germicidal Irradiation Handbook. 2009, doi: 10.1007/978-3-642-01999-9_2.

[22] P. Jarvis et al., “Application of ultraviolet light-emitting diodes (UV-LED) to full-scale drinking-water disinfection,” Water, vol. 11, no. 9, p. 1894, 2019, doi: 10.3390/w11091894.

[23] M. S. Islam et al., “Anomaly detection in a large-scale cloud platform,” in Proc. IEEE/ACM 43rd Int. Conf. Software Engineering: Software Engineering in Practice (ICSE-SEIP), May 2021, pp. 150–159.

[24] P. Adamou et al., “Ultrasonic reactor set-ups and applications: A review,” Ultrasonics Sonochemistry, vol. 107, p. 106925, 2024, doi: 10.1016/j.ultsonch.2024.106925.

[25] L. M. Meyer et al., “Deep learning-based spike sorting: A survey,” Journal of Neural Engineering, vol. 21, no. 6, p. 061003, 2024.