SWASTIIK Technology for Drinking Water Treatment- "Enhancing Water Disinfection Efficacy using Fennel Oil and Hydrodynamic Cavitation"

Sanyogita N. Berde[1,2], Divya Dixit[1], Shilpa S. Chapadgaonkar[2], Vinay M. Bhandari[1*]

[1]Chemical Engineering and Process Development Division
CSIR-National Chemical Laboratory, Pune-411008, India
[2]Department of Biosciences and Technology
Dr. Vishwanath Karad MIT World Peace University, Pune-411038

[*]E-mail: **vm.bhandari@ncl.res.in**

Received: 17. 6.2024, Revised: 24.7.2024, Accepted: 25.7.2024

Abstract

Providing safe drinking water is of paramount importance for sustaining life. New technology, Safe Water and Sustainable Technology Initiative from Indian Knowledgebase (SWASTIIK), combining hydrodynamic cavitation and natural oils having antimicrobial properties, was evaluated for effective water disinfection using fennel seed oil for the first time. For model organism, *E. coli.*, while acoustic cavitation (0.2% fennel oil) gave 100% disinfection in 10 minutes, for vortex diode cavitation device, the disinfection in 2 minutes was 70% and 99.6% at 0.5 and 1 bar ΔP respectively. Process improvement with aeration yields 100% disinfection in just 1 minute. The cost, 0.25 Rs/m^3, confirmed cost-effectiveness. The hybrid approach showed highest per-pass disinfection and high cavitational yield of 236 CFU/mL/J. The oil after the treatment can be easily separated and recycled. The removal of oil was achieved using adsorption by activated carbon to restore the original taste and smell of the drinking water.

Keywords Cavitation; Disinfection; Natural oil; Process; Water treatment

Introduction

Water is essential for life on Earth, vital to many biological processes and necessary for the survival and proper operation of all living things. Its role as a transport medium enables the efficient distribution of nutrients, gases, and waste products throughout organisms[1,2]. The scarcity of potable water is the primary cause of many ailments and disorders. A fundamental human right recognised by the United Nations is the right to access clean drinking water. However, millions of people throughout the world still do not have access to clean drinking water despite substantial advances achieved over the previous few decades. The World Health Organisation (WHO) estimates that as of 2020, around 2.2 billion people do not have access to safe drinking water. This includes 785 million people who are forced to rely on surface water sources that are frequently polluted[3]. Contaminated water can cause diarrheal diseases, which are responsible for an estimated 485,000 deaths each year, mostly among children under the age of five. In addition, unsafe water can lead to the spread of other waterborne diseases such as cholera, typhoid fever, and hepatitis A.[4]. The most commonly encountered coliform to signify faecal contamination is *E. coli*, which is virtually exclusively present in both animal and human faeces. Different *Escherichia coli* (*E. coli*) strains use virulence factors that have an impact on a wide range of cellular functions to cause a variety of extraintestinal and intestinal diseases[5]. Microorganisms like bacteria or pathogens can persist, multiply, and propagate in water sources, which poses serious health issues[6,7].

In view of the adverse effects of harmful bacteria, it is essential that appropriate methodologies be adopted for their effective removal/ elimination. Chemical disinfection methodologies involve employing chlorine-based substances (e.g. sodium hypochlorite, chlorine gas or chlorine dioxide), ozone, ultraviolet (UV) radiation, hydrogen peroxide, etc. The generation of hazardous disinfection by-products (DBPs), many of which are carcinogenic e.g. trihalomethanes and haloacetic acids, and their harmful impact on health is the main concern. Additionally, with time, some germs may become resistant to or modify chemical disinfectants, decreasing effectiveness[8]. The danger of exposure to DBP is typically thought to be outweighed by the risk of waterborne infections brought on by microorganisms[9]. Researchers are studying new water disinfection techniques due to health concerns and the rise of chlorination-resistant pathogens[10]. The physical methods such as UV have limitations in terms of efficiency, scale-up or cost[11,12]. Advanced Oxidation Processes can remove many contaminants from water and wastewater. However, some by-products generated during these processes may be more toxic than the original contaminants[13].

Cavitation based methods have the potential to provide possible alternative to chlorination. Types of cavitation can be classified based on the mechanism that generates the cavities. These mechanisms include optic cavitation, acoustic cavitation, particle cavitation, and hydrodynamic cavitation. The cavitation mechanism, largely contributes to physico-chemical transformations via cavities generation, growth, and collapse (implosion); the implosion results in extreme temperature (10000K) and pressure (~1000-5000 atm) conditions, thereby split water thereby generating hydroxyl radicles that drive oxidation/ oxidative damage[14]. Thus, intensive shock waves, extreme temperature and pressure conditions and oxidative damages mainly impact the effectiveness of any cavitation process, consequently on the selection of the process type/ device type. In the field of water disinfection, cavitational reactors have been proposed as an innovative method for improving the microbiological quality of drinking water[14-19]. Furthermore, cavitational reactors have also been explored for the treatment of industrial wastewater, where they have shown potential for achieving high levels of degradation of organic pollutants[20-21]. Adapting to stricter pollution control norms, it is necessary to study advanced cavitation processes to efficiently and economically treat complex and persistent pollutants in wastewater[22]. The acoustic and hydrodynamic cavitation appear to be the most promising approaches. Hydrodynamic cavitation is more efficient, easy to operate, easy to scale-up and is commonly used in industrial applications such as wastewater treatment, where it can be used to destroy organic contaminants[23]. However, its potential in the water treatment is still not fully explored.

Recently, vortex flow-based cavitation reactors were reported for water disinfection[24]. The new device was able to destroy microorganisms to a greater extent than traditional techniques. Mane and co-workers for the first time reported a new hybrid hydrodynamic process combining the traditional knowledge of Ayurveda- using natural oils, and with substantially less pressure drop compared to conventional devices like orifice[18,19,25]. Different natural oils like eucalyptus oil, and clove oil were evaluated in combination with hydrodynamic cavitation for increased cavitation rates and the effectiveness. All the types of harmful bacteria were shown to be completely eliminated such as gram-negative, gram-positive and also antimicrobial-resistant bacteria (AMR) and difficult to treat, opportunistic pathogens[19]. The new technology was named as SWASTIIK- Safe Water and Sustainable Technology Initiative from Indian Knowledgebase. The process was further improved by Dixit et al. using different newer natural oils such as Ajwain, thyme, oregano, peppermint, harsingar, cinnamon leaf, and black pepper oil etc. and for different formats and molecular docking studies[26].

The new technology, SWASTIIK, has potential to offer the most promising alternative to the existing chemical methods simultaneously eliminating the disadvantages of harmful DBP formations apart from being simple and cost effective. It is, however, imperative to evaluate best possible alternatives in Ayurvedic natural oils that not only intensify the process for instant disinfection, but also possibly help in generating quality drinking water without taste problems or odour or even for possible health benefits. Studies have provided valuable insights into the efficacy, safety, and potential health benefits of essential oil compounds in water treatment, suggesting their application in SWASTIIK technology for disinfection purposes[27].

It is therefore the objective of this study to further extend the scope and horizon of the methodology by newer investigations on natural oils and process validation for complete elimination of *E. coli*, a Gram-negative, facultative anaerobic bacterium. Use of Fennel oil was considered for the study in this regard for investigating acoustic cavitation and hydrodynamic cavitation using vortex diode, since Fennel oil has trans-anethole (80.8%) and estragole (9.6%), which are known to have antibacterial characteristics[28,29]. The essential oil obtained from fennel seeds has potent antibacterial properties and could be used as a natural alternative to synthetic antibacterial agents and its use in SWASTIIK can be potentially more attractive.

Material and methods

Materials

Bacterial strain of *Escherichia coli* (ATCC-8739) was obtained from NCIM- National Collection of Industrial Microorganism at CSIR- National Chemical Laboratory, Pune, Bharat. Nutrient Broth (Himedia Nutrient HiVeg broth) was used as the cultures growth medium and Nutrient agar (Himedia) was used to plate the culture and get total bacterial count of the *E. coli* present in the sample. A 100% pure therapeutic grade natural fennel oil, derived from the seeds of *Foeniculum vulgare Mill*, was obtained from local sources. The oil was acquired in its pure form and was used without any further processing or alterations, ensuring its original chemical composition and properties remained intact.

Measurement of disinfection activity

The bacterial strain was inoculated in 100 mL Nutrient Broth (Himedia Nutrient HiVeg broth) which was further incubated at 37℃ overnight at 200 rpm in an incubator-shaker. As it is more challenging to eradicate bacterial colonies that grow robustly as opposed to saturation or death phase, robust growth phase was established by incubating bacteria overnight. To achieve a final concentration of 10^4-10^5 CFU/mL, the known bacterial culture concentration was prepared using distilled water for acoustic and hydrodynamic cavitation studies.

The system's viable bacterial population was determined using the plate count method. At regular intervals starting from 1 minute, samples were collected from the cavitation experiments and 100µL was then plated onto a sterile petri plate containing Nutrient agar medium. The colonies were measured by Eq. 1, colony forming units per millilitre (CFU/ml) after the plates were incubated at 37°C for 24 hours.

$$\frac{CFU}{ml} = \frac{N\text{umber of colonies on N.Agar plate}}{\text{volume plated (mL)}} x dilution\ factor \qquad (1)$$

The difference in the starting and final concentrations was used to compute the percentage disinfection.

Acoustic Cavitation

A UCP-20 Sonication Unit was employed to induce acoustic cavitation using a frequency of 40 kHz and a power level of 500 W. Four flasks, each containing 200 mL contaminated water samples with known levels of microorganisms were studied for a duration of 15 minutes. The effect of concentration of fennel oil was studied for 0% (no oil), 0.05%, 0.1%, and 0.2%. The samples were collected at specific time intervals during the operation.

Hydrodynamic Cavitation

A vortex flow-based hydrodynamic cavitation was employed using a vortex diode as a cavitating device (MOC- Aluminium, chamber diameter of 66 mm and capacity of 1 m^3/h). The experimental set-up consists of a high-pressure multistage centrifugal pump, a 50 L volume water storage tank, cavitating devices, temperature control using a JULABO Chilling system (Model FL 1701), and pressure and flow controls/indicators. The details of the set-up are well reported in the previous studies[18].

A typical volume of 20 litres of contaminated water, with a known concentration of *E. coli* bacteria was added to the tank. The water was pumped through vortex diode using specified pressure and specified experimental conditions. Three different pressure drop levels: 0.5 bar, 1 bar, and 1.5 bar were evaluated for the pressure effect. Similarly, the concentration of fennel oil was varied at three different levels: 0.05%, 0.1%, and 0.2% (v/V). The samples were collected at predetermined time intervals and analysed for extent of disinfection under different conditions. Process intensification was studied using aeration at an optimized pressure drop of 1 bar for two different conditions: without the addition of fennel oil and with the addition of 0.1% fennel oil.

Elimination of taste and smell

The taste and odour removal studies were carried out using adsorption technique and NORIT as an adsorbent. A packed column was assembled, starting with a layer of glass wool at the bottom, followed by activated norit carbon above it. The treated water samples were collected at different time intervals.

Results and discussion

The efficacy of the different methodologies can be best evaluated using *Escherichia coli (E. coli),* a standard model organism, frequently used as an indicator organism in microbiology studies as it indicates faecal pollution / related health problems corresponding to its presence in water[30-32]. The disinfection was studied using both, acoustic and hydrodynamic cavitation methods; with and without addition of the fennel oil at different operating conditions and using process intensification with aeration in hydrodynamic cavitation. The results are discussed below.

Acoustic Cavitation

The results on disinfection using fennel oil and acoustic cavitation are shown in Fig 1. It is evident that the concentration of the fennel oil has significant effect of the extent of disinfection and disinfection efficiency increase with the increase in the concentration of fennel oil.

Compared to only ~20% disinfection using only acoustic cavitation, a complete disinfection, 100% removal, was achieved using 0.2% fennel oil solution within 10 minutes (Fig 1. (b)). The results of Fig. 1 depicting complete elimination of the harmful bacteria are important in highlighting the efficacy of fennel oil in disinfection by the process of acoustic cavitation, especially for a smaller scale of operation. The huge enhancement in the rate constant values and also enhanced synergy in the combination of acoustic cavitation and the fennel oil (Table-1) also confirms the utility of using fennel oil in this regard.

Hydrodynamic Cavitation- Effect of Pressure

The pressure drop across the cavitating device is one of the most important parameters in any hydrodynamic cavitation process from energy utilization point of view. There are many different designs in cavitating devices, the simplest being orifice with a single hole and is based on using linear flow and obstruction in the path for sudden pressure drop. A vortex flow based device employs swirling/ vortex for generating the sudden pressure drop, requiring a specific design of the chamber for the specified flow[33]. Vortex diodes as reactors and effluent treatment devices. A vortex diode used in the present study requires significantly lower pressure drop compared to orifice and also was found to be more efficient with only pressure drop of 0.48 bar as point of cavitation inception[20]. The experiments were carried out using the pressure drop of 0.5, 1.0 and 1.5 bar to ensure the process in the cavitating regime.

The results of pressure variation, without addition of natural oil, are shown in Fig 2. Lower pressure drop of 0.5 bar yields a disinfection of 65%, while a slightly lower value of 61% was achieved at a pressure drop of 1.5 bar in 60 mins. Interestingly, at a pressure drop of 1 bar, a high efficiency, 82% disinfection was observed. Thus, the optimum pressure drop conditions can be seen as 1.0 bar pressure drop, under the conditions of no oil addition.

Hybrid Hydrodynamic Cavitation- Effect of Fennel Oil

The results of hybrid cavitation process using fennel oil and acoustic cavitation were excellent giving 100% disinfection in 10 minutes for 0.2% oil addition. Thus, it would be prudent to evaluate efficacy of hydrodynamic cavitation in this regard as significant improvement can be expected. By using the pressure drop conditions of ΔP 0.5 bar and 1.0 bar, three different concentrations of fennel oil were investigated: 0.05%, 0.1%, and 0.2%. The results are shown in Figs. 3 and 4.

As expected, due to the intense conditions of hydrodynamic cavitation, the disinfection is achieved in remarkably short time intervals and oil addition provides tremendous impetus. A concentration of 0.2% fennel oil resulted in > 99.6% removal of the target microorganisms within just 1 minute of operation compared to ~10 minutes in acoustic cavitation. The concentration of 0.1% fennel oil showed 70% reduction in microbial load within 1min implying that critical concentration of the natural oil is essential for achieving 100% disinfection and also that appropriate hybrid combination is essential. The results also highlight the importance of the methodology since many earlier investigators failed to accomplish 100% disinfection using any of the cavitation format-acoustic or hydrodynamic, using any of the cavitating device with the efficiency comparable to this work. Further, the rapid disinfection underlines the effectiveness of fennel oil as a powerful antimicrobial agent.

The progress of disinfection shows an interesting trend with respect to both pressures drop and for oil concentration. A disinfection of 82% within 60 minutes at a pressure drop of 1 bar can be altered to ~90% by the addition of fennel oil (0.05%) in just 10 minutes. With 0.1% oil, the disinfection is 92% in10 min and with 0.2% oil, > 99% in just 2 minutes. These results clearly show that the fennel oil, especially at higher doses, significantly enhances the disinfection process. The results (Fig. 4) indicate 1 bar pressure drop and 0.2% oil concentration to be most effective in achieving 100% disinfection.

Hydrodynamic Cavitation- Effect of Fennel Oil- Process Intensification

As mentioned earlier, aeration is one of the simplest forms of process intensifications which can contribute to increasing number and quality of the cavities consequently enhancing the performance of the hydrodynamic cavitation process. In the present study, a simple air pump was used to bubble air by inserting tube in the storage tank containing water. An optimized pressure drop of 1 bar was used to compare the results. The results of process intensification in the form of aeration are shown in Fig 5.

It is interesting to note the progression in achieving the enhancement in disinfection: The aeration has marginal impact in the initial progress though both HC and HC+aeration yield 80 % disinfection in 60 minutes, but no oil addition, clearly and this gets further enhanced to 100% disinfection for the combination of HC + aeration + fennel oil (0.1%), at the same ΔP of 1 bar, highlighting the aeration impact in the hybrid process (SWASTIIK). Most importantly, the time required for the complete disinfection is just 1 min compared to the 60 minutes of HC that too with limited 80% disinfection. Thus, from the results of Fig. 5, it is evident that a complete elimination of harmful bacteria, *E. coli,* can be accomplished instantly using mild operating conditions (ΔP 1 bar, HC+aeration+0.1% fennel oil).

Per-Pass Disinfection

The enhancement in the rates of disinfection can be quantified for different process formats using the rate model- per pass disinfection[18,25]. The per-pass disinfection factor physically describes the disinfection behaviour in hydrodynamic cavitation systems and provides useful information on the extent of disinfection per cycle, number of passes for achieving the desired effect and therefore also on the effectiveness of the process apart from cost of the process. The following rate equations were used:

The effective disinfection rate constant (k), measured in s^{-1}, is determined in the following manner in the conventional model:

$$k = \ln\left(\frac{C_0/C}{t}\right) \tag{2}$$

In this case, C_0 and C stand for the initial and current concentrations of bacteria, both expressed in CFU/mL, at any given time t.

The effective rate constant (k), also expressed as s^{-1}, in the per-pass disinfection model of hydrodynamic cavitation is defined as follows:

$$k = \frac{\varphi n}{t} = \frac{\varphi}{\tau} \tag{3}$$

where, n is the number of passes, and φ the per-pass disinfection factor, which quantifies the importance of any cavitating device.

The per-pass disinfection factor (φ) can be calculated as:

$$\varphi = -\ln\left(\frac{C/C_0}{n}\right) \tag{4}$$

An important factor used in cost estimates is the number of passes (n), since a lower value of n directly relates to a lower cost of the disinfection procedure. The following equation can be used to calculate the number of passes.

$$n = \frac{Qt}{V} \qquad (5)$$

Where, Q is the flow rate, t is time, and V is the volume treated. By using this model, it is possible to determine the per-pass disinfection factor and the effective rate constant, which facilitate correct comprehension and analysis of the disinfection process. The results of using the model are presented in Table-1 and in Fig. 6.

The order of magnitude enhancements in the use of natural oil and the hybrid cavitation process is clearly evident from the results. At ΔP 1 bar, concentrations of 0.05%, 0.1%, and 0.2% of fennel oil requires 6 passes each. It should be noted that the effective oil concentrations in this SWASTIIK process depends on the nature of the oil and also on the nature of the intensification, if any.

The combination of aeration, 0.1% fennel oil, and ΔP 1 bar results in the greatest improvement. The number of passes in this situation drops considerably to 0.6, showing practically instant disinfection within single pass.

Plausible Mechanism for Disinfection

The mechanism of SWASTIIK process has been well discussed in the recent times. However, specific action of natural oils having antimicrobial activity depends on the inherent constituents, often many, that participate in damaging the cell structure along with cavitation attributes. The high efficiency using fennel oil, therefore, can be attributed to the content of oil which includes phenols, terpenes, bioactive compounds such as anethole, fenchone, and limonene and other antibacterial compounds. These damage/destroy microbial cell membranes, leading to cell destabilisation and eventual death[34,35]. The lipophilic compounds in fennel oil can interact with the lipid bilayer of the cell membrane, leading to its destabilization and subsequent leakage of cellular contents. Some components of fennel oil, such as anethole, have been shown to inhibit specific bacterial enzymes. This inhibition can interfere with essential metabolic pathways or processes within *E. coli* cells, ultimately leading to cell death. The oil also contains compounds that can generate reactive oxygen species (ROS) when exposed to bacterial cells. ROS can cause oxidative damage to cellular components, including DNA, proteins, and lipids, thereby impairing vital cellular functions and leading to cell death. Fennel oil also prevents the growth of different microbes by interfering with their enzyme and metabolic systems. Additionally, the antioxidants in fennel oil cause germs to experience oxidative stress, which damages vital biological components and causes inactivation. However, in order to maximise the efficacy of fennel oil as a disinfectant, it is crucial to take into account variables like concentration, exposure period, and the nature of specific bacteria targeted[36-37].

The effects of the oil and cavitation can be seen in Figs. 7 and 8. Through intense shock waves, shear forces, and high temperatures and pressures generated during bubble collapse, hydrodynamic cavitation can physically disrupt the cell membranes of *E. coli*, leading to cell death. The localized hotspots and high-pressure regions are generated during the implosion can induce thermal and mechanical stresses on the *E. coli* cells, potentially damaging their cellular components and disrupting vital cellular processes. Hydrodynamic cavitation produces reactive species, such as hydroxyl radicals (·OH), which have strong oxidizing properties and contribute in oxidising the biomolecules within E. coli cells leading to cellular damage and inactivation.

Removal of Taste and Smell pertaining to the Natural oils

The addition of oil imparts odour and taste, many a times not pleasant, and therefore not desirable for the drinking water purpose. The oil-water separation is easy and can be accomplished by a number of techniques, the layer separation being the simplest one. In this work, we have used adsorption technique similar to that used in the household water purification systems. The water was passed through the bed of adsorbent- Norit activated carbon to remove the flavour and smell of fennel oil. The treated water after the adsorption step was found to normal drinking water without any taste of oil or odour.

Energy and Cost Calculation

The cavitation yield per volume treated (CFU/mL/J) can be obtained by Eq. 7

$$\frac{cavitational\ yield}{volume\ treated} = \frac{(c_0 - c)}{(\Delta P \times Q \times t)} \tag{7}$$

The cavitational yield represents the efficiency of the different processes and the order of magnitude higher values for the combination of HC+aeration+Fennel oil validates the efficacy of the suggested process over the conventional one (Fig 9). To calculate the cost of treatment per cubic meter of water using the equation provided, the values for the number of passes (n), pressure drop (ΔP), power consumption (P), and pump efficiency (η) are needed. Given that the flow rate (Q) for a vortex diode measured at a pressure drop of ΔP = 1 bar is 710 LPH (litres per hour) and the volume treated is 20 L (litres), the number of passes, n can be obtained.

The cost of treatment can be calculated by Eq. 8

$$\frac{cost\ of\ treatment}{m^3\ of\ water} = \frac{n\Delta PP_E}{36\eta} \tag{8}$$

Considering the cost of electricity (P_E) at 10 Rs/kWh and a pump efficiency (η) of 0.66, the cost of treatment per cubic meter of water can be calculated. At 0.2% fennel oil and without aeration, corresponding to 100% removal of bacteria in 2 minutes, the cost of treatment was just 0.498 Rs/m^3, with high cavitational yield of 117.4 CFU/mL/J, compared to 2.5 Rs/m^3 for 0.1% oil. The cost is drastically reduced by 10 times with process intensification using aeration for HC + aeration + oil, resulting in 0.25 Rs/m^3. In general, the cost of the chlorination process is the lowest among all the methods (~0.32 Rs/m^3), while the costs for physical and physicochemical methods range from 80 to 650 Rs/m^3 [26]. The overall operating cost of the present disinfection process is expected to be comparable to or even lower than that of chlorination without having any disinfection by-products. Additionally, the oil can be recycled and used again, making the cost of fennel oil negligible. These values indicate that a particular treatment combination needs to be explored for achieving instant disinfection. The cost of 0.25 Rs/m^3, and the yield of 236.4 CFU/mL/J signifies a high effectiveness in reducing the microbial load for the drinking water treatment and the techno-economic viability of the process.

Conclusions

The present study introduces a novel application of fennel seed oil in the hybrid cavitation process-SWASTIIK, offering promising consequences for water disinfection. The main findings of this innovative green hybrid cavitation technology are as follows:

1. Acoustic Cavitation: Complete disinfection of *E. coli* was achieved within 10 minutes using a 0.2% fennel oil solution.
2. Hydrodynamic Cavitation using vortex diode yields close to 100% disinfection within 2 minutes for 0.2% oil concentration and for 0.5 bar pressure drop. Increasing the pressure drop to 1 bar, reduces the oil dose.
3. Process Intensification by aeration and for pressure drop of 1 bar and 0.1% fennel oil concentration yielded complete disinfection (100%) within 1 minute.

4. The process using fennel seed oil in the hybrid cavitation process, at a concentration of 0.1%, resulted in significantly lower costs (0.25 Rs/m^3).

Overall, the study demonstrated the potential of SWASTIIK process of hybrid hydrodynamic cavitation using fennel seed oil for rapid and efficient disinfection of *E. coli*, highlighting its potential for large-scale applications.

Statements and Declarations-

Funding Sources- Acknowledgement
The author-VMB wishes to acknowledge the financial support from Water Innovation Center-Technology, Research and Education **(WICTRE) (DST/TM/WTI/WIC/2K17/100(G)),** of Department of Science and technology, Ministry of Science and Technology, India and also financial support from Council of Scientific and Industrial Research (CSIR), Government of India (**MLP102326**). Divya Dixit would like to acknowledge fellowship of Department of Science and technology, Ministry of Science and Technology India.

Figures:

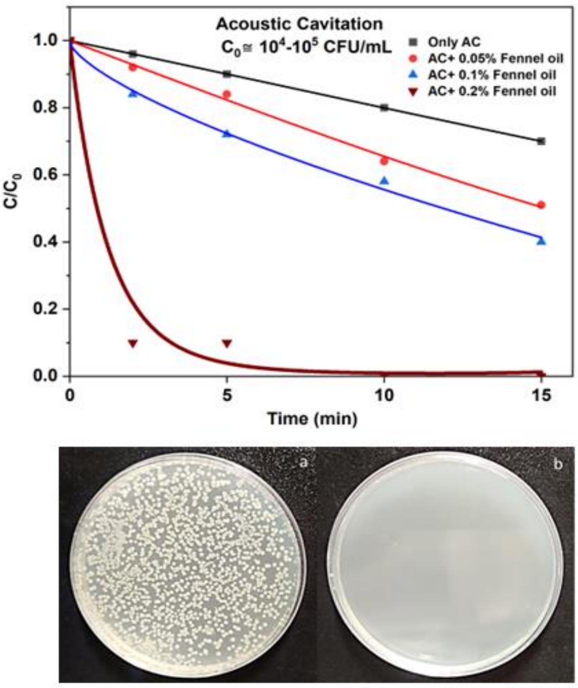

Fig. 1: Effect of fennel oil in acoustic cavitation, (a) 0 min (b) 10 min (0.2% fennel oil)

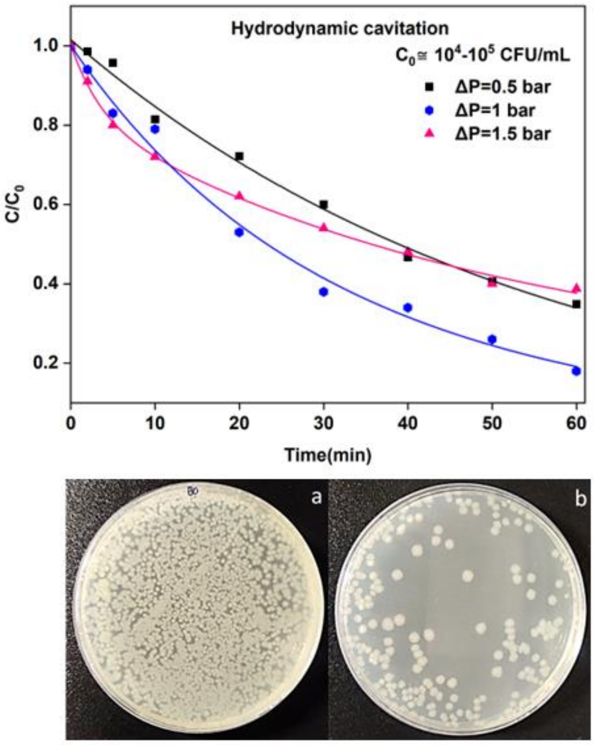

Fig. 2: Effect of pressure on disinfection using hydrodynamic cavitation (a) 0 min (b) 60 min (∆P 1 bar)

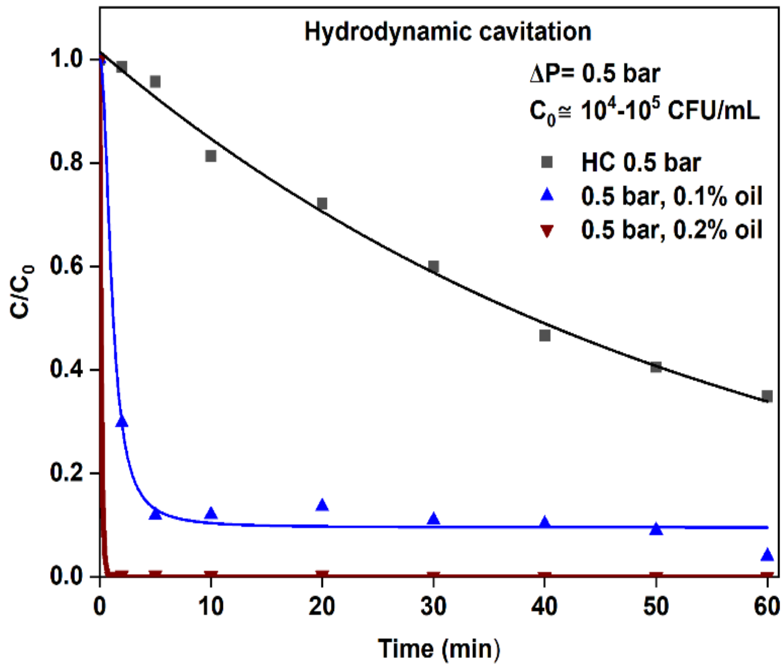

Fig. 3: Effect of varied fennel oil concentration at ΔP 0.5 bar

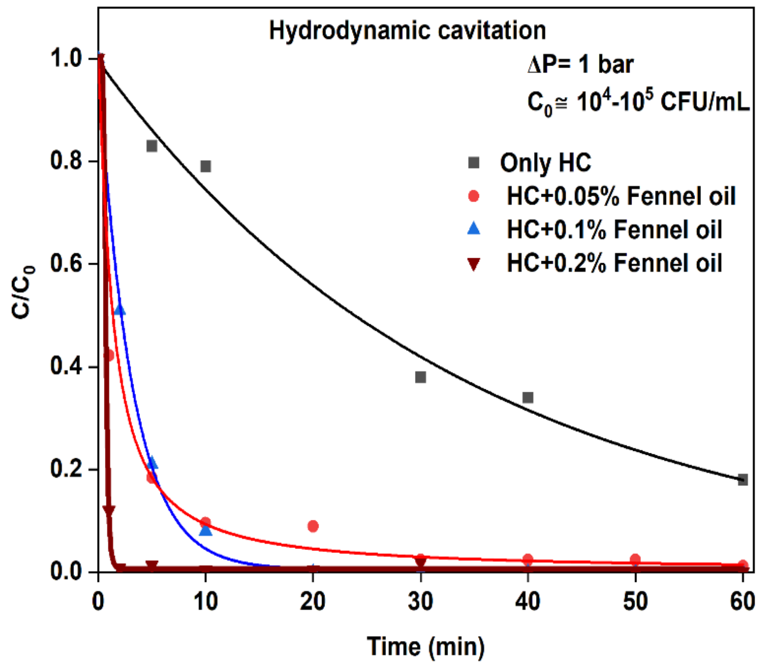

Fig. 4: Effect of fennel oil concentration at ΔP 1 bar

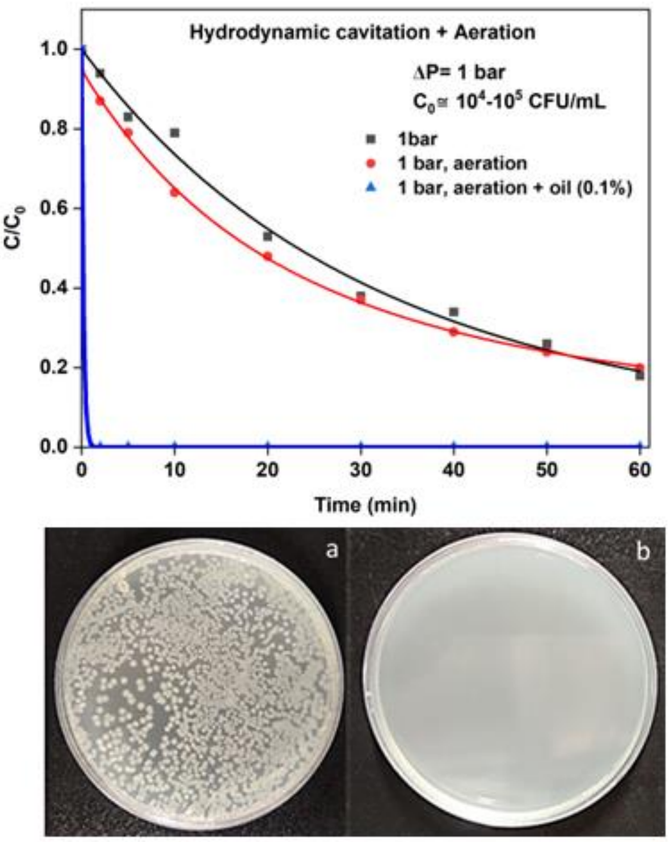

Fig. 5: Effect of aeration in hybrid methodology, (a) 0 min (b) 1 min (∆P 1 bar, 0.1% fennel oil)

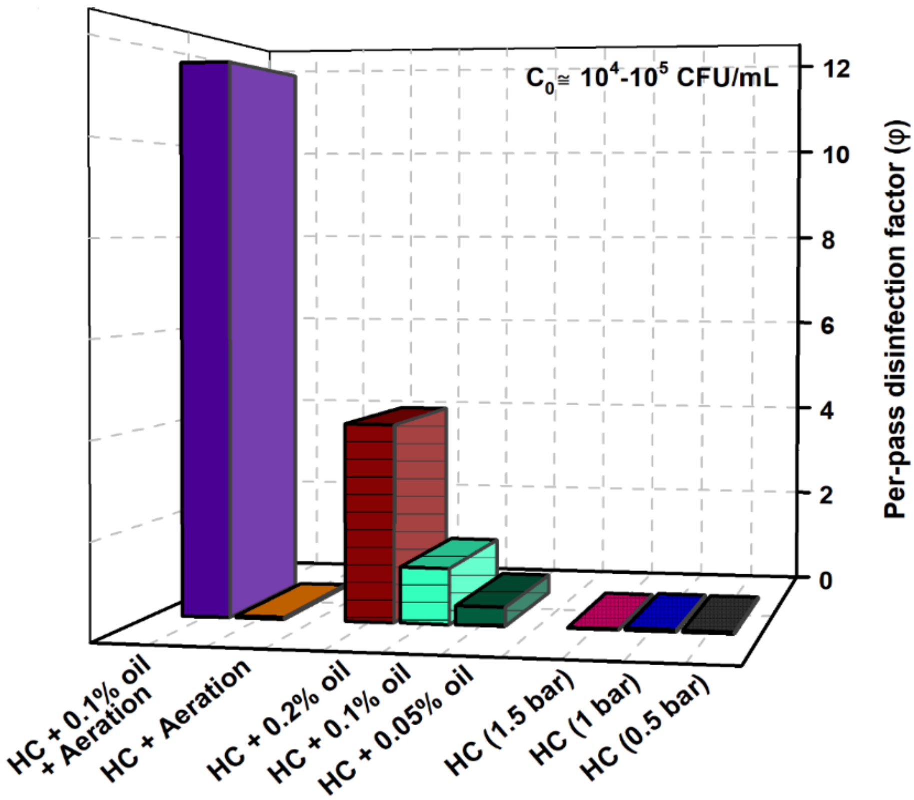

Fig. 6: Per-pass Disinfection

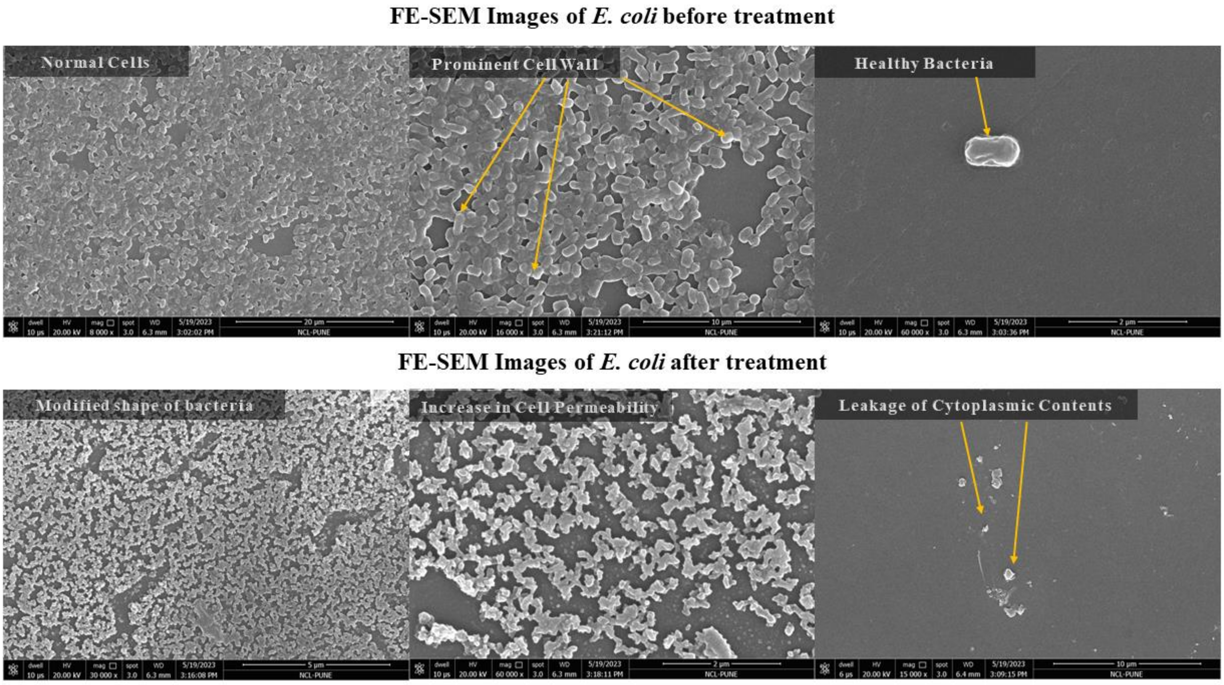

Fig 7: FE-SEM images of the effect of fennel oil on *E. coli*.

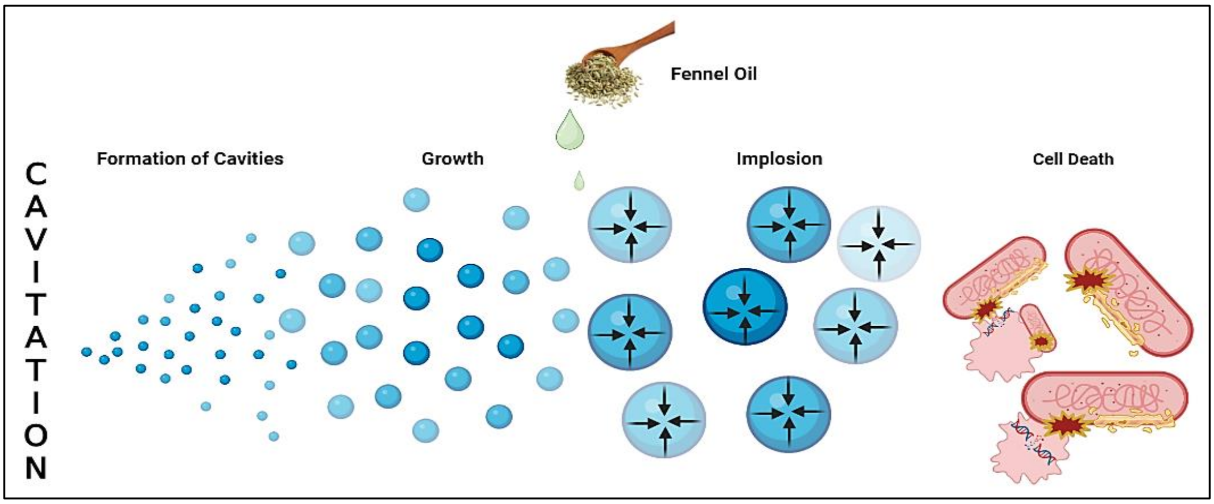

Fig 8: The effect of hydrodynamic cavitation and fennel oil on *E. coli*.

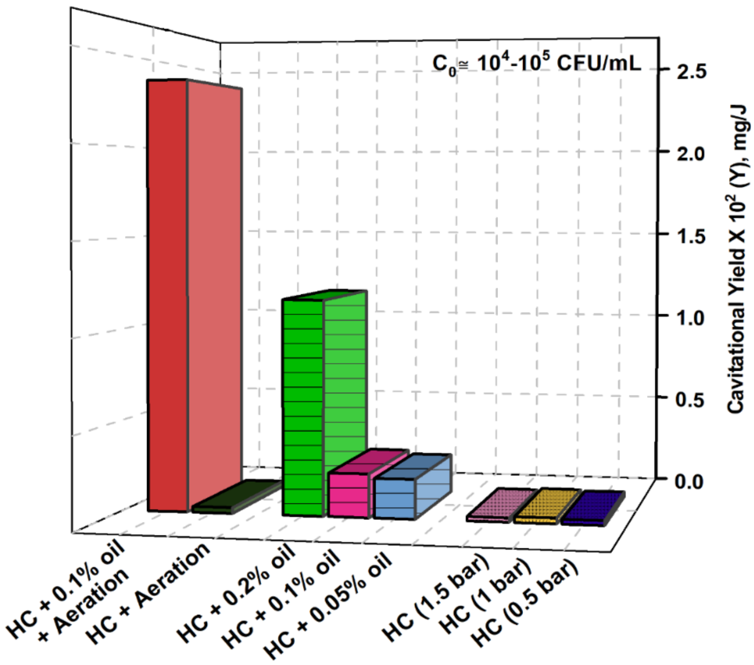

Fig. 9: Cavitational Yield

Table:

Table 1: Comparison of different processes

Processes	**Disinfection (%)**	**Treatment Time (min)**	**k x 10^4 (min^{-1})**	**Synergistic Index**
Only AC	30	15	2.4	-
AC + 0.05% fennel oil	49	15	4.5	1.472
AC + 0.1% fennel oil	60	15	6.1	1.583
AC + 0.2% fennel oil	100	15	69.1	14.73
HC (ΔP 0.5 bar)				
Only HC (ΔP 0.5 bar)	59	60	1.8	-
HC + 0.1% fennel oil	91	60	5.0	1.541
HC + 0.2% fennel oil	100	2	664.5	128.5
HC (ΔP 1 bar)				
Only HC (ΔP 1 bar)	82	60	2.8	-
HC + 0.05% fennel oil	100	60	23.5	6.666
HC + 0.1% fennel oil	100	20	69.1	15.92
HC + 0.2% fennel oil	100	2	244.0	47.20
COMBINED PROCESS				
HC (ΔP 1 bar) + aeration	80	60	2.7	0.114
HC (ΔP 1 bar) + aeration+ 0.1% fennel oil	100	1	690.8	159.2

References

1. L. Armstrong, and E. Johnson, Nutrients 10, 1928, 2018.
2. M. Chaplin, Biochem Mol Biol Educ. 29, 54, 2001.
3. L. Yemi, New Report on Inequalities in Access to Water, Sanitation and Hygiene Also Reveals More than Half of the World Does Not Have Access to Safe Sanitation Services. 2019.
4. L. Hooper, N. Martin, A. Abdelhamid, and G. Davey Smith, Cochrane Database Syst Rev, 2015.
5. J.B. Kaper, J.P. Nataro, and H.L.T. Mobley, Nat Rev Microbiol, 2, 123, 2004.
6. V. Tyagi, A. Chopra, Kazmi A.A., and A. Kumar, Iranian J Environ Health Sci Eng, 3, 205, 2006.
7. S.T. Odonkor, and J.K. Ampofo, Microbiol Res, 4, 2, 2013.
8. D. Ghernaout, A.S. Alghamdi, and B. Ghernaout, Applied Engineering, 3, 13, 2019.
9. M. Lindmark, K. Cherukumilli, Y.S. Crider, P. Marcenac, M. Lozier, L. Voth-Gaeddert, D.S. Lantagne, J.R. Mihelcic, Q.M. Zhang, C. Just, and A.J. Pickering, Environ Sci Technol, 56, 9164, 2022.
10. M. Garvey, J. Hayes, E. Clifford, and N. Rowan, Water Environ. J., 29, 27, 2015.
11. B.A. Younis, L. Mahoney, and N. Palomo, Water, 10, 1275, 2018.
12. K. Song, M. Mohseni, and F. Taghipour, Water Res, 94, 341, 2016.
13. S. S. Raj, Pooja Thanekar, Kshama Balapure, and V. M. Bhandari, J. ISAS, 2, 23, 2024.
14. K.K. Jyoti, and A.B. Pandit, Biochem. Eng. J., 7, 201, 2001.
15. K.K. Jyoti, and A.B. Pandit, Ultrason Sonochem, 10, 255, 2003.
16. K.K. Jyoti, and A.B. Pandit, Biochem. Eng. J., 18, 9, 2004.
17. P. Thanekar, and P. Gogate, Fluids, 3, 98, 2018.
18. M.B. Mane, V.M. Bhandari, and V. V. Ranade, J. Water Proc. engineering, 43, 2021.
19. M.B. Mane, V.M. Bhandari, K. Balapure, and V. V. Ranade, Ultrason Sonochem, 69, 2020.
20. N.B. Suryawanshi, V.M. Bhandari, L.G. Sorokhaibam, and V. V. Ranade, Sci Rep, 6, 2016.
21. P.G. Suryawanshi, V.M. Bhandari, L.G. Sorokhaibam, J.P. Ruparelia, and V. V. Ranade, Environ. Prog. Sustain. Energy, 37, 295, 2018.
22. K. Sharma, M. Chethana, V. Bhandari, L.G. Sorokhaibam, V. Ranade, and D. Killedar, J. ISAS, 1, 49, 2023.

23. V. V. Ranade, and V.M. Bhandari, Industrial Wastewater Treatment, Recycling and Reuse, Elsevier, 06975, 2014.
24. P. Jain, V.M. Bhandari, K. Balapure, J. Jena, V. V. Ranade, and D.J. Killedar, J. Environ. Manag., 242, 210, 2019.
25. M.B. Mane, V.M. Bhandari, K. Balapure, and V. V. Ranade, Ultrason Sonochem, 61, 105272, 2020.
26. D. Dixit, V.M. Bhandari, M.B. Mane, and K. Balapure, Biochem. Eng. J., 187, 108631, 2022.
27. K. Balapure, and V. Bhandari, J. ISAS, 2, 18, 2024.
28. W.R. Diao, Q.P. Hu, H. Zhang, and J.G. Xu, Food Control, 35, 109, 2014.
29. A.A. Shahat, A.Y. Ibrahim, S.F. Hendawy, E.A. Omer, F.M. Hammouda, F.H. Abdel-Rahman, and M.A. Saleh, Molecules, 16, 1366, 2011.
30. C.D. Köhler, and U. Dobrindt, Int J. Med. Microbiol, 301, 642, 2011.
31. P. Pokharel, S. Dhakal, and C.M. Dozois, Microorganisms 11, 344, 2023.
32. A. Leimbach, J. Hacker, and U. Dobrindt, Curr. Top. Microbiol. Immunol., 358, 3, 2013.
33. V. V. Ranade, A.A. Kulkarni, and V.M. Bhandari, WO 2013054362, US9422952B2, 2013.
34. F. Anwar, M. Ali, A.I. Hussain, and M. Shahid, Flavour Fragr. J., 24, 170, 2009.
35. W.R. Diao, Q.P. Hu, H. Zhang, and J.G. Xu, Food Control, 35, 109, 2014.
36. A. Mutlu-Ingok, G. Catalkaya, E. Capanoglu, and F. Karbancioglu-Guler, Food Front 2, 508, 2021.
37. R. Amorati, M.C. Foti, and L. Valgimigli, J. Agric. Food Chem., 61, 10835, 2013.