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Exploring Emerging Water Disinfection Technologies: A focus on Hydrodynamic Cavitation

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Abstract

Availability of clean drinking water is an ongoing global demand. Contaminated water sources, inappropriate waste disposal, and inadequate hygiene procedures exacerbate it. These elements support the growth of pathogenic microbes like bacteria, viruses, and parasites, which cause a variety of diseases that are transmitted by water. Disinfection plays a vital role in water treatment processes by eliminating these pathogens and ensuring public health safety. Commonly used methods like Chlorination, Ozonation, and Ultraviolet (UV) treatment are well known for their effectiveness in disinfection. However, chemical disinfection methods have drawbacks, including the potential formation of carcinogenic residues. The efficacy of disinfection techniques varies based on factors such as water quality conditions and the resistance of microorganisms to treatment. Consequently, there is increasing interest in alternative disinfection approaches that reduce reliance on chemical agents. The potential of hydrodynamic cavitation as a cutting-edge method for water disinfection is examined in this review paper. Hydrodynamic cavitation shows significance in reducing levels of microorganisms such as Total Coliforms and E. coli. A method for successfully eliminating pathogens from water is provided by the physical and chemical effects produced by cavitation bubbles. Furthermore, the review examines critical variables such as pressure, temperature, pH levels, and the design of cavitation devices, all of which significantly impact disinfection efficiency. Developing sustainable and efficient water treatment systems requires an understanding of and optimization of these parameters. By advancing alternative disinfection technologies like hydrodynamic cavitation, researchers aim to address current challenges in water sanitation effectively. These innovations not only improve water quality and public health but also mitigate environmental impacts associated with traditional chemical disinfection methods.

Keywords: Disinfection, hydrodynamic cavitation, *E. coli*, total coliforms, wastewater treatment

INTRODUCTION

All living organisms, including humans, rely on water for survival, making adequate water supply essential for human well-being. However, ensuring access to safe drinking water continues to pose a major challenge in today's world. The quality of drinking water is paramount, yet it has progressively deteriorated due to industrial pollution, agricultural activities, and the increasing volume of domestic waste resulting from population growth. Contamination from faecal matter, inadequate waste disposal, and poor hygiene practices all play a role in spreading pathogenic microorganisms [1] like viruses, bacteria, and parasites. These microorganisms are responsible for various waterborne diseases, posing significant health risks including malnutrition, reduced resistance to infections, and impaired physical and

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cognitive development. Water microbes and their corresponding water borne disease is mentioned in Table 1. Thus, while water is vital for life, it can also be a source of illnesses that lead to suffering, chronic disabilities, and even death. Enhancing the quality of drinking water involves both pollution control and the implementation of effective water treatment methods. Traditional techniques such as Chlorination [2,3], Ozonation [4], and Ultraviolet treatment are widely accepted for their effectiveness. However, chemical disinfection methods have drawbacks, such as the creation of potentially harmful by-products. The efficacy of disinfection methods depends on factors like solution conditions and the resistance of microorganisms. As a result, there is a growing need for alternative disinfection approaches that reduce dependence on chemical agents. Disinfection, specifically targeting microorganism destruction, stands out as a critical step in ensuring the safety of drinking water and preserving human health.

Table 1. Water microbes and corresponding borne diseases [1].

Microbial Agents	Class	Disease
Clostridium botulinum	gram positive bacteria rod shape	botulism
Campylobacter jejuni	gram negative bacteria curved helical shape	food poisoning
Vibro cholerea	gram negative bacteria common shape	cholera
Escheriachia coli	gram negative bacteria rod shape	diarrhea
Shigella dysenteriae	gram negative bacteria rod shape	dysenteria/shigellosis
Entamobea histolytica	anaerobic parasitic protozoan, cyst	amebiasis
Hepatovirus	virus	hepatitis
Astrovirus	astroviridae	gastroenteritis
Giardia lambila	flagellated protozoan parasite	giardiasis

HYDRODYNAMIC CAVITATION (HC)

Hydrodynamic cavitation [5] involves the process of vaporization, generation and subsequent implosion of bubbles. When local pressure drops to some point below saturated vapour pressure and recovers or rises above vapour pressure, due to sudden decrease and increase in local pressure cavitation occurs. If the recovery pressure does not exceed the vapour pressure, it indicates flashing has occurred. In pipe systems, cavitation commonly arises from either increased kinetic energy or elevated pipe elevation.

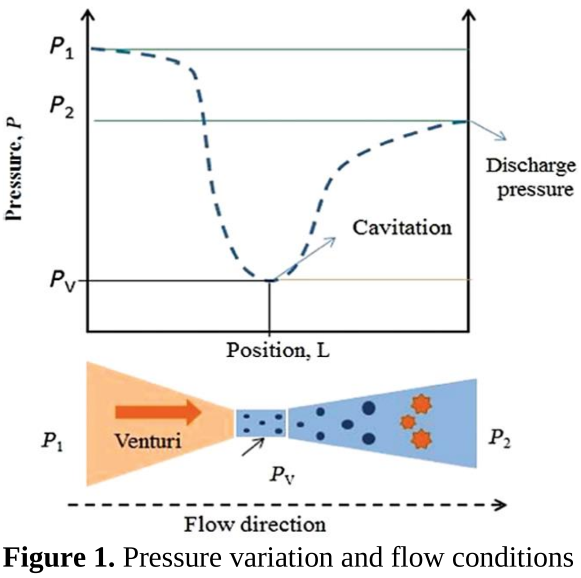

Figure 1. Pressure variation and flow conditions in cavitating device (Venturi) [5].

Hydrodynamic cavitation is produced by forcing liquid through narrow constrictions within a conduit. As the liquid passes through these constrictions, its kinetic energy increases while its pressure decreases. Through efficient throttling, the pressure drops below the liquid's vapour pressure at the vena contracta, leading to the formation of vapour cavities as the liquid flashes into vapour. Subsequently, as the liquid jet expands, the velocity decreases and the pressure recover in the downstream section of the cavitating device resulting in the collapse of cavities. A typical pressure profile of a venturi-based device [5] is shown in Figure 1.

In the downstream section, boundary layer separation occurs, and some amount of energy is released in the form of permanent pressure drop. The magnitude of the pressure drop greatly influences the intensity of cavitation and turbulence in the downstream section. Thus, it is necessary to control the operating and the geometrical parameters of the devices to get the required cavitation intensity. The dimensionless cavitation number (CV) represents the hydraulic characteristics of a cavitation device.

It characterizes the condition of cavitation inside the cavitation device [6]. It is represented by Eq. (1):

$$C_v = \frac{P_2 - P_v}{0.5\ \rho v^2} \text{--} \qquad (1)$$

Where,
C_v = Cavitation Number
P_2 = Downstream recovery pressure
P_v = Saturated vapour pressure
Þ = Density of fluid
V= mean velocity of fluid

Hydrodynamic Cavitation Reactors

The devices employed in hydrodynamic cavitation reactors encompass a diverse range of mechanisms, each designed to induce and manipulate cavitation bubbles within a fluid medium. Liquid whistle reactors [7], for instance, utilize specially engineered nozzles or flow constrictions to induce cavitation by rapidly decreasing fluid pressure. These reactors leverage the principle of pressure differentials to initiate cavitation bubble formation, thereby creating localized regions of intense energy

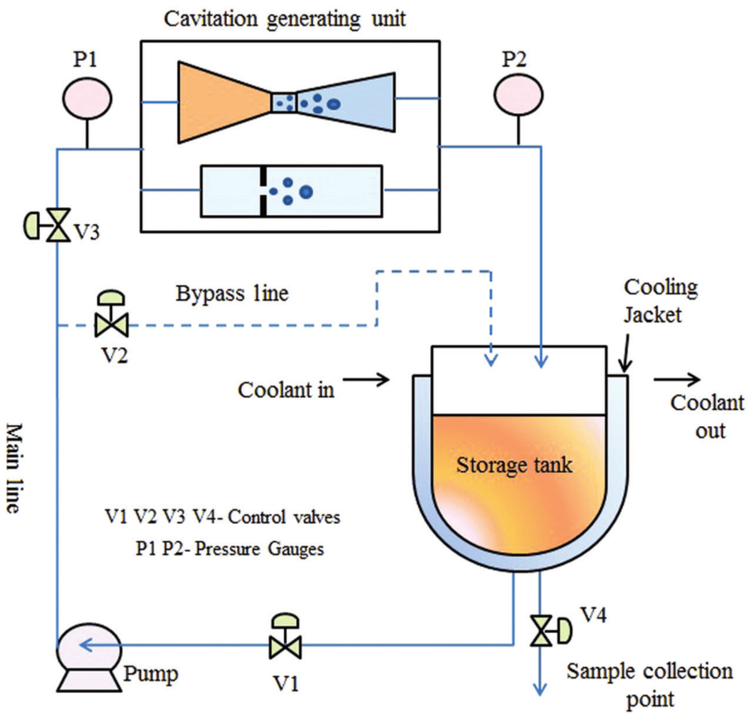

Figure 2. Hydrodynamic Cavitation Schematic set up [5].

release upon collapse. Similarly, blade benders operate on a mechanical basis, employing rotating blades or impellers to generate high shear forces and turbulence within the fluid. This turbulent flow environment promotes cavitation bubble nucleation, facilitating various physical and chemical processes. Additionally, flow-constricting devices such as venturi nozzles and orifice plates [7] play a crucial role in hydrodynamic cavitation reactors by manipulating fluid flow to create pressure differentials conducive to cavitation bubble formation. Schematic diagram of Venturi nozzle and orifice plate cavitor is shown in Figure 2. By strategically controlling fluid velocity and pressure gradients, these devices effectively induce cavitation, enabling a wide range of applications spanning chemical processing, environmental remediation, and industrial manufacturing. Together, these devices constitute the foundational elements of hydrodynamic cavitation reactors, offering a versatile platform for harnessing cavitation's potential across numerous engineering disciplines.

MECHANISMS OF DISINFECTION BY HYDRODYNAMIC CAVITATION

Sudden pressure and velocity variation cause dynamic cavity oscillations, and as the cavity collapses, certain physical and chemical effects occur in its vicinity leading to the desired transformations. Also, the type of cavity collapse controls the desired transformation. Pandit [8] highlighted two conditions of cavity collapse: symmetric and asymmetric. The cavity may remain spherical till the point of collapse or nonspherical because of the presence of interface at the boundary wall or other particle/bubble surface near the oscillating cavity. The formation of reactive free radicals and the thermal pyrolysis of organic molecules are favourable under spherical collapse, i.e. symmetric collapse, which are essential for chemical transformations. Monspherical collapse, or asymmetric collapse, involves the rapid collapse of cavitation bubbles in liquid. This collapse generates high-velocity liquid jets and intense turbulence in localized areas. These conditions are advantageous for various physical transformations and processes within the liquid, enhancing mixing, chemical reactions, and other phenomena. Although both symmetric collapse and asymmetric collapse receive the same energy from pressure fluctuations, energy is delivered in different forms, i.e. either in the form of intense turbulence or in the form of extreme condition of pressure and temperature. The symmetric collapse is beneficial for applications involving chemical changes especially for the oxidation reactions. The chemical transformations are primarily induced by the formation of reactive free radicals of the substrate molecules and secondarily through thermal breakdown of larger molecules into the smaller molecules under the conditions of local hot spot. An illustrative example involves the creation of highly reactive hydroxyl radicals (˙OH) due to the dissociation of water molecules in cavitation. These radicals possess strong oxidation capabilities, enabling them to oxidize large organic molecules effectively. Chemical transformations occur through two primary mechanisms: firstly, molecules trapped within collapsing cavities undergo thermal decomposition as the cavities collapse; secondly, the resulting free radicals react with targeted molecules at the liquid-cavity interface and within the bulk liquid, thereby initiating oxidation processes.

WATER DISINFECTION BY HC AT DIVERSE OPERATING PARAMETERS AND FLOW CONFIGURATIONS

Disinfecting water is vital to guarantee its safety and suitability for drinking. One notable method gaining prominence for its effectiveness in eradicating pathogens is hydrochloride (HC) treatment. However, the efficiency of HC disinfection is influenced by several operating parameters, including temperature, pressure, and concentration, treatment time, PH as well as variations in flow geometry within the disinfection system. Recognizing the influence of these factors is crucial for optimizing water treatment procedures and improving the overall efficiency of disinfection methods. In this study, we investigate how different operating conditions and flow configurations affect the efficiency of water disinfection using HC, aiming to provide insights for improving water treatment systems and ensuring the delivery of safe drinking water to communities.

Jyoti and Pandit [8] investigated microbial effectiveness of cavitating reactors for bore well water disinfection. They compared hydrodynamic and acoustic cavitation with high-speed and high-pressure homogenization. Results showed higher pump discharge pressure improved disinfection efficiency. A hybrid approach combining hydrodynamic cavitation, acoustic cavitation, and hydrogen peroxide achieved 97% disinfection efficacy, suggesting potential for water treatment applications.

Balasundaram [6] et al. examined the impact of hydrodynamic cavitation on E. coli cells, particularly focusing on the release of periplasmic and cytoplasmic proteins resulting from cell wall damage. They investigated a wide range of cavitation numbers (Cv) spanning from 0.09 to 0.92, with the most significant protein release observed at Cv = 0.13. Additionally, they explored various cell concentrations ranging from 0.1% to 5.0%, identifying that the highest level of E. coli cell disruption occurred at a concentration of 0.5%.

Balasundaram and Harrison [9] studied the effect of orifice geometry and number on selective release of periplasmic proteins. Circular holes showed higher acid phosphatase release. Increased flow rates led to greater release after 1000 passes. The best configuration had more circular holes at maximum flow rate. Data on initial concentration and bacterial survival rate were not included.

Sawant [10] et al. examined the impact of a single orifice plate on zooplankton disinfection in seawater. Through experiments with a test loop comprising a centrifugal pump, valve, and orifice plate, they found that maximum disinfection (82%) occurred with the orifice plate and fully open valve at a cavitation number (σv) of 14.68.

Arrojo [11] et al. compared disinfection efficiency of orifice plates and Venturi tubes, varying hole numbers, discharge pressure, and initial E. coli concentration. They found highest efficiency with smallest orifice plate for 10^7 CFU/ml. Orifice plates required higher pressure for equivalent cavitation events, resulting in more violent collapses. Orifice plate efficiency decreased with higher initial concentrations, unlike Venturi tubes. Cavitation numbers were unspecified.

Wang et al. [12] tested hydrodynamic cavitation (HC) alone and combined with sodium hypochlorite and chlorine dioxide for bore well water disinfection. They found increased efficiency with hybrid systems. Higher inlet pressure and more holes of smaller diameter improved disinfection. Experiments used low bacteria concentrations (2500-3000 CFU/ml), with HC combined with chlorine dioxide achieving maximum 95% efficacy. Confidence intervals for concentration measurements were not provided.

Badve MP and Pandit AB [13] investigated hydrodynamic cavitation's utility for disinfecting seawater [12]. They assessed various cavitating devices and found slit geometry consumed 40% less energy than cylindrical geometry for similar disinfection levels. Combining hydrodynamic cavitation with conventional treatments like chlorination and thermal treatment significantly enhanced disinfection rates. Reaction rates nearly doubled with 5 ppm hypochlorite in combination with cavitation compared to hypochlorite alone, and disinfection rates increased 2.5 times at 50°C with cavitation compared to thermal treatment alone.

Zhimeng Liu [14] et al. studied the removal of organic pollutants and microorganisms using hydrodynamic cavitation. They found that the removal rates were affected by reaction time and operating temperature, with increased rates observed by extending reaction time or raising temperature. Removal rates for colority, COD, and petroleum pollutants were 80.0%, 72.13%, and 70.00%, respectively. Moreover, the removal rate of Escherichia coli exceeded 99.99%.

Vivek V Ranade [15] et al. compared vortex diode and single-hole orifice plate cavitating devices for water disinfection against Escherichia coli and Staphylococcus aureus. Vortex diode achieved nearly complete elimination of E. coli with lower pressure drop, while orifice plate required higher pressure for effective removal of gram-positive bacteria.

Vivek V Ranade [16] et al. applied hydrodynamic cavitation for water disinfection and proposed practical prototype development. They examined disinfection efficiency against Escherichia coli and Staphylococcus aureus, analysing factors such as pressure, temperature, pH, and microbial concentration for orifice and vortex flow cavitation devices. Vortex diode required notably lower pressures, around 50% less than orifice for equivalent disinfection. Notably, hydrodynamic cavitation demonstrated effectiveness at ambient conditions and high bacterial concentrations. Additionally, they investigated disinfection potential of natural oils, observing significant enhancement in cavitation rate with oils like eucalyptus and clove oil, leading to substantial disinfection rate improvements and potential cost reduction.

The summary of disruption of microbes present in water use of hydrodynamic cavitation by varying geometries and optimum process conditions are mentioned in following Table 2.

Table 2. Overview of studies on disruption of microbes in water using HC at different geometries and optimum conditions

S.N.	**Reference**	**Source and the characterization of Raw water**	**specification of experimental set-up and cavitation devices**	**Design of Experiments (DOE)and range of operating parameters**	**optimum process conditions and performance parameters**	**Reaction Kinematics**
1	Jyoti and Pandit (2003)	Bacteria population Bore wall water (CFU/ml) HPC=6500-7000 T.coliforms (per 100 ml) =150-200 F.coliforms (per 100 ml) =80-100 F strptococci (per 100 ml) =180-200	Multiple-hole orifice plate: 33 (nos)× 1 mm(dia) Flow area=25.92 mm2 Volume of Bore wall water = 75 L Centrifugal Pump = 5.5 KW (Cv=0.19)	Pressure: 1.72 ,3.2, 5.17 bar H2O2 = 5 mg/l to 150 mg/l (Hydrogen Peroxide Oxidizing Element) AC/US flow cell 40 = kHz Reaction time = 15 min & 60 min	% Disinfection rate of Total coliform (E.Coli) after 60 min HC at 5.17 bar = 85% HC (5.17 bar) + 5 mg/l H2O2 = 90% HC (1.72 bar) + AC (40 kHz) = 96% HC (1.72 bar) + AC + 5 mg/l H2O2 = 97%	First order
2	Sawant et al. (2008)	zooplankton from seawater	Different configurations of orifice: 25% open area, 50% open area, 75% open area Volume of Seawater =1000 L Centrifugal Pump = 7.5 HP Pipe Diameter =26 mm (Cv = 14.68)	Pressure: 3.2,3.3, 3.8 bar No of passes: Single and Double	<u>% killing of zooplankton for different passes</u> Orifice = 75% open area Inlet Pressure P1 = 3.2 bar 82% killing for single pass (Reaction time 12.75 min) 95% killing for doule pass (Reaction time 25 min)	Not Used
3	Arrojo et al. (2008)	Inactivation of Escherichia Coli from saline solution Initial concentration = 10^7 CFU/ml	Multiple-orifice plates: 1 × 5 mm, 6 × 2 mm, 25 × 1 mm Flow rate= 4m3/h volume of tank = 60 L	Discharge Pr: 1,1.5 and 2 bar Initial concentration: 10^3,10^4,10^5 CFU/ml Reaction time: 5,15,30,60,120 min	<u>% of Disinfection efficiency for 120 min</u> 1) 100% disinfection For Orifice Plate (2	Not Used

			SS Centrifugal Pump = 9.0 KW Different venturis: V1 = 40 mm2, V2 = 20 mm2, V1 = 10 mm2,		bar, 10^3 CFU/ml) &the rate of inactivation of E. coli is 0.0075 min^{-1} 2) 100% disinfection For Venturi (1 bar, 10^3 CFU/ml) &the rate of inactivation of E. coli is 0.018 min−1	
4	Balasundaram et al.(2006)	Cell Disruption of Brewers' Yeast	Different configuration of orifice plate: 25x2 mm 1x12 mm 1x15 mm 1x17 mm 1x19 mm 1x22 mm Volume of tank=20 L Centrifugal multistage pressure Pump = 15.0 KW + 2 pole Pipe ID = 26.7 mm	Parameteric study on cell disruption 1) Cv= Range of 0.9 to 0.99 at 1% W/V 2) Concentration = Range 0.1% to 5 %W/V for Optimum CV	Optimum Parametrs for Maximum cell disruption for OP: 25 x 2 mm 1)Cv=0.13 2) Cell concentration of yeast= 0.5 %W/V	Not Used
5	Balasundaram and Harrison (2011	Release of Periplasm and total soluble protein from *E. coli* during cell disruption	Orifice of different shapes and sizes: Circular = 40(nos.) × 2 mm Square = 32 x (2 × 2) mm Rectangular = 16x (2 × 4) mm Circular = 25x2 mm Circular = 5 × 5 mm Circular = 1 × 14 mm Volume of tank=20 L Centrifugal multistage pressure Pump = 15.0 KW + 2 pole Pipe ID = 26.7 mm	Optimum Orifice geometry for constant flow area=128 mm2 cavitation numer= 0.14-0.19	% release of periplasm from E coli Circular OP= 40 × 2 mm > 90% for circular orifice (40 × 2 mm) than other geometries 50% of total soluble protein release in all orifice plates	Not Used
6	Zhimeng Liu et al. (2016)	Pollutant and Microorganism (*E. coli*) Removal from Water Initial colority= 50 PCU COD = 95.7 mg/L at 25°C	Multi hole circular orifice plate: 49 x 1 mm Plate thickness 4.0 mm Total area of OP: 38.47 mm2 Water tank capacity: 50 L Flow rate Q= 2	Inlet pressure =2.5 bar Reaction time = 0 to 3 hrs Temp of Petroleum =25 to 50 C	80% colority removal rate for 3 hrs 72 % COD removal rate for 3 hrs 70% petroleum removal rate for 3 hrs 65% Petroleum	Not Used

			m3/h Reciprocating pump = 1.1 kw		Removal at 50 C > 99.99% *E. coli* removal rate for 2 hrs	
7	Wang et al. (2015)	Bore well water (*E. coli*) bacterial IC :2500–3000 CFU/ml TOC: 4.25-4.75 mg/l	Multi hole Orifice plate: 33 x 2 mm 33 x 1 mm 20 x 2 mm 17 x 3 mm Diameter of each plate = 40 mm Holding tank Volume= 70 Liters Centrifugal pump (2900 rpm, 5 kW) copper pipe (length 30 m, diameter 10 mm)	pressure= 3.5, 4.0 and 4.5 bar Temp =25 to 50 C Feed water = 20 L ClO2 = 0.5 and 1.0 mg/l Naocl= 2.0 mg/l	% of Disinfection rate at 60 min for OP:33 x 2 mm HC (33 x 2 mm OP) at 4.5 bar = 67.30% HC (4.5 bar) + ClO2 (1.0 mg/l) > 95%	First order
8	Badve MP and Pandit AB (2015)	Disinfection of sea water	slit venturi: 3.7 W x 0.92 H (mm) alpha=2.71 /mm circular venturi Dia of hole= 2 mm alpha = 2.00/mm cross sectional area= 3.04 mm2 Volume of sea water = 4 lit Reciprocating pump: 1.1 KW	pH = 4,5,8,10 Temp= 30,40,50,60 NaoCl= 1, 3, 5 PPM	% disinfection in 15 Minutes for slit venturi (1) Effect of PH ---- HC +PH 10 = 56% (Alkine Ph is more significant than acidic PH in HC) (2) Effect of Temp ----HC + 60 C = 100% (Thermal treatment with HC is more significant) (3) Effect of Naocl HC +Naocl (5 ppm) = 100%	Not Used
9	Vivek V Ranade et al. (2019)	Disinfection of water (*E. coli*) Initial concentration = 10^3 CFU/ml	Vortex Chamber (66 mm diameter) circular hole Orifice Plate (1 x 3 mm) Flow rate = 1 m3/h Centrifugal Pump= 2.2 Kw and 2900 rpm Volume of holding Tank = 60 L	Parametric study Pressure drop 1) Venturi = 0.5 ,1.0 and 2.0 bar 2) Orifice = 2.0, 5.0, 10.0 bar	% disinfection in 60 Minutes 1) 99 % for 0.5 bar in vortex diode 2) 99 % for 10 bar in Orifice Plate 3) 97% for 2.0 in bar orifice plate	First order
10	Vivek V Ranade et al. (2019)	Disinfection of water (E coli) Initial concentration = 10^3 CFU/ml	Vortex Chamber (66 mm diameter) Centrifugal Pump= 2.2 Kw and 2900 rpm Volume of holding Tank = 60 L	Parametric study 1) pressure Drop (0.5,1.0,2.0 bar) 2) temperature (28, 40,50 C) 3) pH of water (4, 7, 10 pH) 4) microbial inoculum 5) Natural oils:	% Disinfection of water for 15 min 1) HC + 1 bar = 43% 2) HC + 4 PH = 71% 3) HC + 50 C = 70% 4) HC + Nilgiri	First order

				Castor oil, Cinnamon oil (Dalchini oil), Eucalyptus oil (Nilgiri Oil) Clove oil	Oil (0.1% v/V) = 74 % HC + Clove Oil (0.1% v/V) = 63 % HC + Castor Oil (0.1% v/V) = 36 % HC + Dalchini Oil (0.1% v/V) = 30% 5) AC = 3.18% 6) HC + AC + Clove oil (0.1% v/V) = 51%	

CONCLUSION

Collectively, these studies illustrate that hydrodynamic cavitation holds promise as a highly effective method for disinfecting water. Various approaches, including hybrid systems and different cavitation devices, have shown promising results in removing microbial contaminants such as Escherichia coli and Staphylococcus aureus from water sources. Factors such as pressure, temperature, and reactor geometry play significant roles in enhancing disinfection efficiency. Additionally, the use of natural oils in conjunction with hydrodynamic cavitation shows promise for further improving disinfection rates and reducing operational costs. Overall, these findings underscore the viability of hydrodynamic cavitation as a practical and efficient method for water treatment applications, offering potential solutions for addressing waterborne microbial contamination.

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