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Novel hydrodynamic cavitation system for microorganism reduction in urban wastewater discharged over Fonce river

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ABSTRACT

The objective of this research article is to present the results of the evaluation of a pilot unit for microorganism reduction in urban wastewater using the hydrodynamic cavitation (HC) principle, which was developed by the San Gil University Foundation (UNISANGIL). Three hydrodynamic cavitation reactors (HCRs), named CAV-A, CAV-2A, and CAV-2V, were tested in the designed disinfection system. The experiments evaluated each reactor in terms of the logarithmic reduction (LR) and the percentage reduction (Pr) for four microbiological parameters: fecal coliforms, total coliforms, aerobic mesophilic and molds and yeasts, during the treatment of urban wastewater discharged into a natural point of the Fonce River in San Gil, Santander, Colombia. Three tests were performed on each reactor in a system with a flow rate of 10L/s and a tank of 1800L. The results for the reactor of the best performance (Venturi type, CAV-V) were, on average for each parameter, 0.68±0.31, 0.69±0.15, 1.57±1.09 and 0.9±0.09 for LR, and 74±13.83, 78±7.87, 89±9.68, and 87±2.57, for Pr. This work is a pioneer in developing microorganism reduction in wastewater of an actual discharge over a river without a previous primary and secondary treatment. Experiments demonstrate the viability of applying HC as an alternative physic element for the tertiary treatment of urban wastewater, especially in continuous flow scenarios prior to discharge. The findings of this study have the potential to significantly influence the methodology for wastewater treatment in urban areas. Future investigation is warranted to validate the system's efficacy when combined with other disinfection methods.

Keywords: hydrodynamic cavitation, urban wastewater, microorganism reduction.

INTRODUCTION

The accelerated increase in the world population has generated a greater demand for safe drinking water for the development of human and industrial activities, with a consequent impact on ecosystems due to the discharge of wastewater without prior treatment (Lebiocka, 2020; Y. Chen et al., 2023). Currently, 441 billion cubic meters of domestic or urban wastewater and wastewater from production processes are generated worldwide. It is estimated that in 2050 this figure will reach 571 billion of cubic meters (United Nations Environment Program, 2023). These factors, together with the effect of climate change, represent a challenge for the conservation of water sources, as well as for the reuse and exploitation of wastewater for different uses such as agriculture, industry, and human consumption (Egerer et al., 2023; Kabata et al., 2024). It is expected that by 2030, worldwide, the potential of wastewater collected and treated will reach 75%, and that reuse will increase as new treatment techniques are developed (Qadir et al., 2020).

Domestic wastewater is treated in wastewater treatment plants (WWTPs). These facilities receive the effluent and utilize physical, chemical, and/or biological processes to reduce the pollutant load. This load typically comprises organic matter, nutrients (such as nitrogen and phosphorus), suspended solids, pathogenic microorganisms, and chemical compounds, including detergents, heavy metals, and pharmaceutical products (G. Yadav et al., 2021). The treatments are divided into primary, secondary, and tertiary stages. The primary and secondary stages focus on removing loads of biochemical oxygen demand (BOD_5), Chemical oxygen demand (COD), and suspended solids loads. In the tertiary stages, the main objective is disinfection or the reduction of the microbiological load (Macedo et al., 2022; Eduardo et al., 2023). However, even after tertiary treatment, microbiological loads may persist in the treated water and are subsequently discharged into the receiving water bodies (Zamorska & Kielb-Sotkiewicz, 2023).

Disinfection or inactivation of the microbiological load is achieved using chemical or physical methods and is performed prior to the discharge or reuse of treated water (Collivignarelli et al., 2018; Verwold et al., 2021). Disinfection generates a positive impact on the environment and the well-being of the population since it prevents the transmission of diseases produced by pathogens and microorganisms present in water, such as *E. coli*, improving public health and reducing associated medical costs (Zhou et al., 2016; Elsaidy et al., 2022; Vizioli & Montagner, 2023) Chlorination is the most widely used chemical method for disinfection in drinking water potabilization and wastewater treatment (Z. Li et al., 2021). However, in recent years, adverse effects on human health and the environment have been found (Xue et al., 2023), since, during the process, chloramines react with organic matter present in wastewater, and trihalomethanes (THMs) are generated, which are highly harmful and carcinogenic (Dong et al., 2021).

For this reason, the development of new technologies for disinfection that are efficient and economical and do not have an impact on human health and the environment has been promoted (Hazra et al., 2024). Hydrodynamic cavitation, HC, is one of them.

Cavitation is defined as bubble formation in a liquid due to its pressure variations. In hydrodynamic cavitation, these pressure variations could be generated by the travel of the liquid at high velocities through pipes, where abrupt pressure drops can occur (P. B. Patil et al., 2021). This occurs in various reactors specifically designed with geometries that favor cavitation, such as Venturi tubes, orifices, vortex diodes, or rotary designs, among others (Sarvothaman et al., 2024; Zheng et al., 2022).

HC has a wide range of applications in environmental treatment. One application is the treatment of water contaminated with printing inks. Zampeta et al., (2022) reported a significant reduction in coagulant use (by 33%) and treatment costs (up to 20%), representing a promising step toward reducing the environmental impact of contaminated water. HC is also used to enhance methane production in wastewater treatment plants (Zupanc et al., 2023), by pretreating the active sludge using a rotary cavitation reactor. Furthermore, HC has substantial applications in the treatment of water contaminated with agricultural pesticides (Raut-Jadhav et al., 2016; B. Li et al., 2021). Kumari et al., (2025), reported, for example, a pesticide concentration reduction between 99% and 99.99% in a five liters (5L) sample when HC was combined with photocatalytic oxidation. The treatment of water contaminated with pharmaceuticals is another key area, as demonstrated by (Bagal & Gogate, 2014), whose work reported a 76% reduction in total organic carbon in samples contaminated with diclofenac sodium when combining HC with TiO_2 water treatment. Other research in this area includes studies on the degradation of tetracycline (Wang et al., 2017), and ciprofloxacin (M. Chen et al., 2023).

But, undoubtedly, one of the most relevant applications of HC is the reduction of pathogenic microorganisms in contaminated water. HC is a physical method that can be implemented on a large scale and minimizes the need for added chemicals (Dular et al., 2016). This microbial reduction is possible because the violent collapse of cavitation bubbles inside the reactor generates extreme conditions, including localized temperatures up to 15.000 K and pressures between 100 and 5000 atm (Hong et al., 2022). These conditions damage the microorganisms in the fluid, causing cell membrane rupture and DNA damage, thereby eliminating or inactivating the pathogens (Sun et al., 2020).

Gogate, (2007) presented one of the first studies on the feasibility of using cavitation for wastewater disinfection. Based on an exhaustive literature review, this work concludes that while the estimated cost is slightly higher than chemical treatments, the benefit of being a treatment without harmful effects makes it viable. Furthermore, the study infers that HC is more beneficial than ultrasound cavitation for industrial environments. Separately, Agarkoti et al., (2021), reviews the potential of cavitation for water disinfection, detailing mechanical design aspects, operating conditions, and environmental application. This review also highlights the logistical and economic superiority of HC for treating actual wastewater effluents and its effectiveness when combined with advanced oxidation processes like hydrogen peroxide and Fenton's reagent.

The high potential of hydrodynamic cavitation (HC) for microbial load reduction has driven a surge in recent scientific literature too. Experiments by (Sun et al., 2022), showed microorganism reduction with logarithmic reduction (LR) values between 1.1 and 3.3 in food substances like unpasteurized milk or sugarcane juice. Other studies have specifically focused on water disinfection using devices like orifice plate reactors and similar designs (Bhukya et al., 2021). Research focused on achieving high reduction rates often involves recirculation systems, demonstrating significant efficacy. Salve et al., (2019), reported a 100% reduction of *E. coli* using an orifice plate reactor after 120 minutes of recirculation. Y. Chen & Martynenko, (2016) achieved 100% reduction of *E. coli*, *B. subtilis*, *B. halodurans*, and *P. putida* using a system called the Cavitating Jet after 3, 5, 6, and 4 passes, respectively. Gregersen et al., (2020) employing two HC reactor types, achieved 5 logs for *E. coli* and Klebsiella after 60 minutes, 3 logs for *P. aeruginosa* after 90 minutes, and 6 logs for *P. syringae* in 20 minutes of recirculation. While many studies report high efficacy, some show lower results under certain conditions. For instance, Arya et al., (2023) recorded a coliform reduction of up to 30% using a cavitation valve in a 15-minute recirculation system with a maximum concentration of 4580 CFU/100 ml.

Despite these positive results, in the literature consulted, no works experimented with the effects of cavitation on the reduction of microorganisms in scenarios outside the laboratory nor in water directly discharged into a river, in addition to the effect on four microbiological parameters. This circumstance motivated the execution of the present investigation, whose objective was the development of nine experiments of microbiological load reduction in urban wastewater directly discharged into a water source, testing three hydrodynamic cavitation reactors (HCR) designed by the University Foundation of San Gil, UNISANGIL, with three different geometries, from now on called CAV-A, CAV-2A, and CAV-V.

The research, unique in the approach of an alternative physical system for the reduction of microorganisms in a direct flow of wastewater over a river, determined the logarithmic reduction LR and the percentage of reduction Pr, of four important microbiological parameters: fecal coliforms (*E. coli*), total coliforms, aerobic mesophilic and molds and yeasts. The reactors were installed in a pilot wastewater disinfection unit, strategically located in one of the 11 urban water discharges into the crucial Fonce river in the municipality of San Gil, Santander – Colombia. This unit is situated on the premises of a hydroelectric plant operated by the Santander Electricity Company, ESSA. The Fonce River is vital for the economic development of the 10 municipalities that are located in its watershed and depend on it for ecological goods and services, and for the development of adventure sports. The potential impact of this research on public health and ecological sustainability is significant, with nearly 70,000 inhabitants that could benefit directly and indirectly from it.

MATERIALS AND METHODS

Wastewater sample

For the experimental analysis, wastewater samples were collected from an urban discharge with an average flow rate of 10 L/s, randomly between November 8, 2023, and March 4, 2024, at different times in the morning, with average ambient temperatures of 26 °C, during periods of no rainfall, to avoid the effect of mixing of rainwater and wastewater. The randomness of the sampling times was intended to determine the response of the reactors in a natural operating environment, in which the contaminant microbiological load also varies randomly. During the experiments, the people in charge of collecting the samples had the corresponding protection and biosafety elements due to the risk generated by this type of waste. In each test, wastewater samples were collected before and after passing through the hydrodynamic cavitation system. The samples were refrigerated from discharge until delivered to the UNISANGIL laboratories. Likewise, an initial physicochemical characterization of the waters of the selected discharge was carried out, as shown in Table 1. The physicochemical parameters of the wastewater samples were measured following the Standard Methods for the Examination of Water and Wastewater, which are internationally recognized collections of water quality analysis procedures. Specifically, the SM 4500 method was used for pH, SM2550B for temperature, SM2130B for turbidity, SM2510B for conductivity, SM2320B for total alkalinity, SM5210B for BOD_5, SM5220B for COD, SM2540D for total solids, SM2540F for settleable solids, SM2540C for total suspended solids, and SM2540C for dissolved solids. Each parameter was measured five times.

Table 1. Physical and chemical parameters of urban wastewater San Gil – Colombia at a discharge over Fonce river

Parameter	Value
Hydrogen potential (PH)	7.7 ± 0.116
Temperature (°C)	25.4 ± 2.413
Turbidity (NTU)	222 ± 63.073
Conductivity (μS/cm)	685 ± 92.026
Total alkalinity (mg $CaCO_3$/L)	139 ± 49.681
BOD_5 (mg O_2/L)	277 ± 49.681
COD (mg O_2/L),	646 ± 40.016
Total solids (mg/L)	602 ± 164.761
Settleable solids (ml/ L)	0.3 ± 1.590
Total suspended solids (mg/L)	144.83 ± 72.043
Dissolved solids (mg/L)	381.03 ± 112.554

Configuration of the HC system

The hydrodynamic cavitation pilot unit used for the development of the experiments consisted of a circuit composed of a metallic container, a metallic support structure, a sample reception tank with a capacity of 1.800 L with a built-in sedimentation system, a manual slide gate valve, and a solenoid valve, a 10 HP high-pressure centrifugal pump of 69 meters of water column and a flow rate of 12 L/s, a cavitation reactor, two pressure sensors of 5000 PSI (accuracy of 1%), arranged to measure and display the pressure at the inlet and outlet of each reactor, and an automation system consisting of a Siemens SIMATIC S7-1200 programmable logic controller (PLC) and a SIMATIC Ktp700 touch screen. The construction of the water circulation assembly used high-pressure polyvinyl chloride (PVC) with a diameter of 1.5 inches. The three cavitation models were designed with computational fluid dynamics (CFD) tools based on the technical characteristics of the pump mentioned above. They were interchanged to experiment with the disinfection effect of each reactor. Each reactor was installed in the pilot unit to perform operational tests and measure the effect of HC on wastewater microorganisms. A review of the use of CFD for the design of hydrodynamic cavitation reactors for wastewater treatment can be found in (Hong et al., 2022). Figure 1 shows the CAV-A reactor, Figure 2 the CAV-2A reactor, and Figure 3 the CAV-V reactor. The three reactors were designed under the same operating parameters but with different geometries to generate cavitation. CAV-A and CAV-2A have a fin-shaped geometry, while CAV-V has a Venturi-type geometry. The CAV-A reactor is in the process of patenting (CO 2022007330). The reactors are constructed of stainless-steel SAE 304 with Teflon seals, a high-strength material, to prevent premature wear. Figure 4 shows the system schematic.

Table 2 shows the inlet and outlet pressures of the treated water, the flow rate handled in each of the three experiments carried out with each

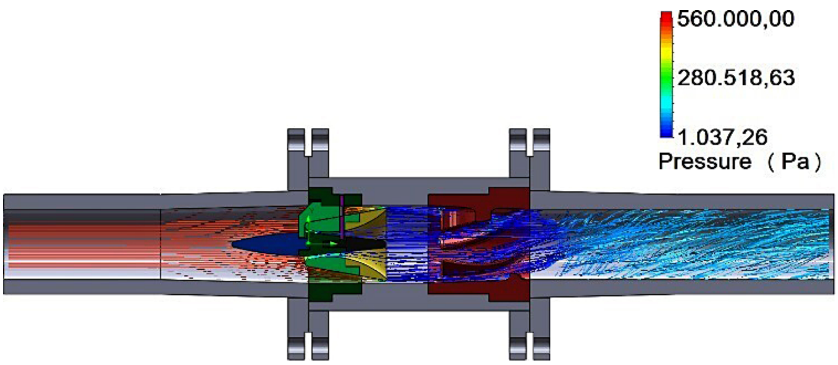

Figure 1. CAV-A cavitation reactor – cross section

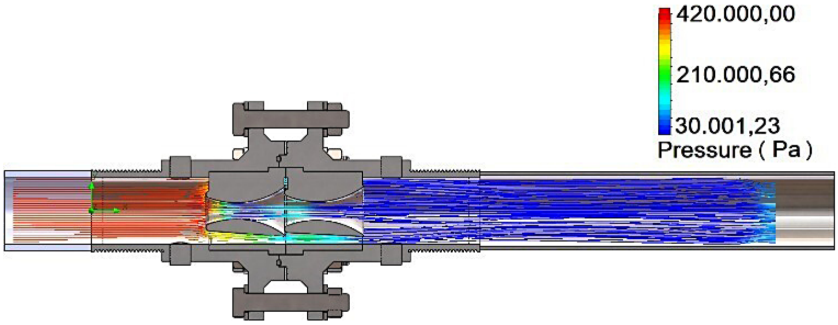

Figure 2. Cavitation reactor CAV-2A – cross section

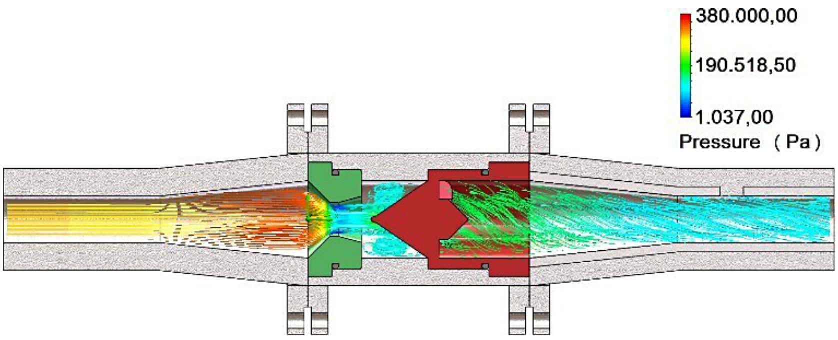

Figure 3. Cavitation reactor CAV-V – cross section

Table 2. Operating conditions of the three reactors

Parameters	TEST 1	TEST 2	TEST 3
CAV-A σ_v = 0.409			
Inlet pressure (psi)	99	86	85
Outlet pressure (psi)	3	9	2.1
Operating flow rate (L/s)	5.84	9.64	9.82
CAV-2A σ_v = 0.450			
Inlet pressure (psi)	57	77	34
Outlet pressure (psi)	34	28	12
Operating flow rate (L/s)	13.95	11.4	23.98
CAV-V σ_v = 0.201			
Inlet pressure (psi)	75	46	26
Outlet pressure (psi)	11.6	6.6	4.2
Operating flow rate (L/s)	11.29	12.5	12.5

reactor, and the value of the cavitation number calculated (), calculated from the reactor outlet pressure measured with the pressure sensor, the vapor pressure, and the velocity in the restriction, calculated from the fluid inlet velocity and the area ratio in the reactor restriction. The inlet pressure corresponds to the value recorded on the sensor displayed when the wastewater enters the cavitation reactor. The outlet pressure, on the other hand, corresponds to the pressure of the wastewater after its treatment in the reactor.

Note that the pressure deltas (difference between inlet pressure and outlet pressure) and the operating flow rates are variants since the system was tested in a direct discharge into the Fonce River, in which the physical conditions of the water flow and the pollutant load, including the microbiological load, are also changing.

Experimental procedure

The pilot disinfection unit was put into continuous operation to validate the performance of the cavitation reactors. To achieve this, a PVC bypass line was adapted to the wastewater discharge, allowing it to feed the storage and sedimentation tank. Before entering the tank, the flow rate passes through a screen that retains large materials that could cause obstructions during the process. The wastewater flowing into the disinfection system is, therefore, free of suspended solids that could obstruct the reactors.

The automation system allows the pilot unit to operate autonomously. Every time the receiving tank reaches its maximum level, the electro pump activates, remaining in operation until the tank is empty. Once this occurs, the pump automatically turns off and the solenoid valve closes, restarting the cycle when the tank fills again. This process repeats continuously. To prevent overload and wear of the electro pump, two were installed to work alternately. The changeover between the pumps is performed automatically. Additionally, two bypass lines were installed in the hydraulic circuit to take water samples: one before the electro pump and the other after the reactor, as mentioned previously.

Three tests were carried out with each of the hydrodynamic cavitation models. In each experiment, once the water temporarily collected in the tank was circulated through the cavitation reactor, it was released to continue its course to the river. The system installed in all tests was the same, except for the reactor change.

Once collected, the samples for analysis were transported to the laboratory in compliance with the protocol established by the Colombian Institute of Hydrology, Meteorology and Environmental Studies, IDEAM, to begin the procedure for measuring microbiological parameters.

Analytical methods

Inactivation of microorganisms

The microbiological parameters analyzed were fecal coliforms, total coliforms, aerobic mesophilic, and molds and yeasts, which are the most common in wastewater discharges and are regulated by environmental regulations. Upon completion of each disinfection experiment, the samples entered the microbiology laboratory. They were analyzed under the membrane filtration method described by norm EPA 1604 of the Environmental Protection Agency of the United States (EPA, 2002) and the "Standard Methods" (Public & Association, 1992; Baird et al., 2017). Results regarding colony-forming units per 100 milliliters (CFU/100ml) were reported. All analyses were performed in triplicate to determine the concentration of the different microbial groups (*E. coli*, Total Coliforms, Mesophilic Aerobes, and Molds and Yeasts). Three serial dilutions were performed using factor 1/1000, and boxes with optimum growth for counting (<300 ufc) were chosen to determine the microbial concentration.

Therefore, the scope of the present investigation reached the evaluation of microorganisms whose identification at certain levels manifests the potential presence of taxonomically or physiologically related pathogens. It is beyond the scope of the research to evaluate each microorganism separately and in a specific medium that can be considered pathogenic. In the literature consulted, results are mainly reported for fecal coliforms, specifically *E. coli*. This work extended the examination to total coliforms, aerobic mesophilic, and molds and yeasts. Outside the study's

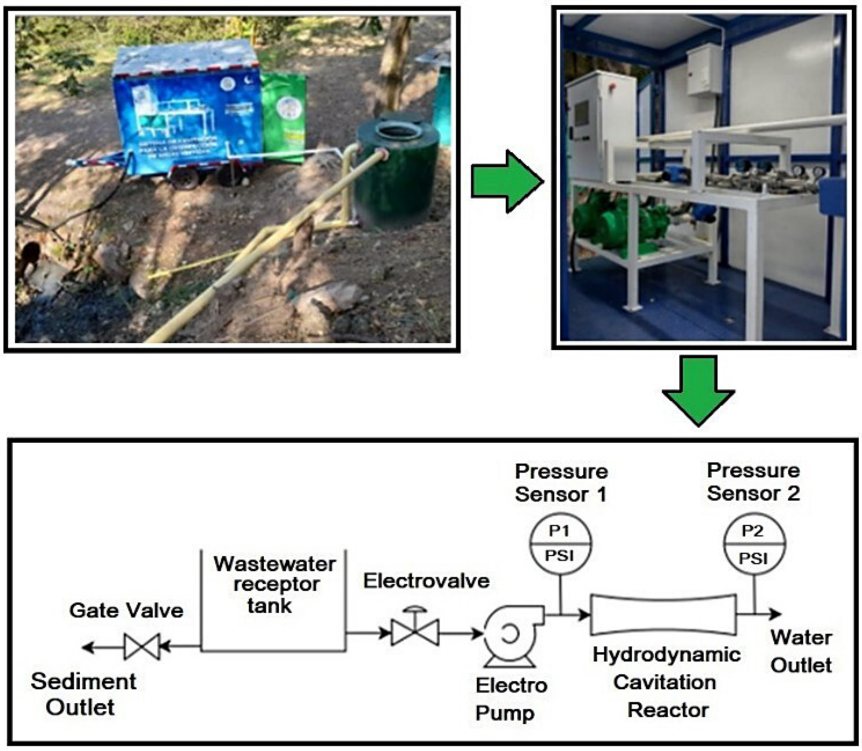

Figure 4. HC system schematic

scope is identifying parasites, protozoa, or viruses. It is also important to clarify that, in order to minimize the influence of the composition of a sample on the detection and quantification of microorganisms, the sterility of the culture media and materials was examined in each test performed, tests with a known concentration of microorganisms were elaborated, as well as analysis of blank samples, following the standard norms for this type of tests, which are designed to minimize possible interferences that the analytical methods may cause, ensuring the reliability of our results.

Disinfection efficacy calculations

Disinfection efficacy calculations were performed following the instructions of (Del Álamo et al., 2022), and log reduction was determined using Equation (1).

$$LR = Log_{10}\left(\frac{N_0}{N}\right) \quad (1)$$

where: N_0 is the number of viable microorganisms recovered before the disinfection process, and N is the number of viable microorganisms recovered after the cavitation procedure.

The percentage reduction was calculated for each sample by comparing the number of CFU/ml before the disinfection process with the number of CFU/ml after the disinfection process, according to Equation (2).

$$P_r = 100 * \frac{N_0 - N}{N_0} \quad (2)$$

RESULTS AND DISCUSSION

The results related to the microorganism reduction and the LR and Pr values obtained for each experimental reactor are highlighted below.

Effect on the microbial load

Table 3 shows the measurements of each parameter's initial and final concentrations analyzed for each test. The values correspond to colony-forming units per 100 mL (CFU/100 mL). Likewise, Table 4 shows the data corresponding to the logarithmic reduction (LR) values for each reactor and experiment. Table 5 shows the results of the calculation of the reduction percentage Pr.

All parameters showed a reduction in initial concentrations after the cavitation process, except for molds and yeasts in the CAV-A reactor in the third test. The Kruskal-Wallis nonparametric test was used to compare the results of each parameter for each reactor. Nonparametric tests do not require the assumption of a distribution of the data. It is suitable for samples with a limited amount of data as long as they are independent, as is the case of the experiments carried out with each type of reactor in this research.

When the Kruskal-Wallis test was performed, no statistically significant differences were found between the results of the tests realized in each

Table 3. Initial and final concentrations

Parameters	TEST 1	TEST 2	TEST 3
CAV-A			
Initial concentration			
E. coli	$1.13x10^8$	$3.0x10^8$	$8.0x10^7$
Total coliforms	$2.90x10^8$	$4.66x10^7$	$1.83x10^8$
Mesophilic aerobes	$1.4x10^{12}$	$1.86x10^8$	$7.0x10^7$
Molds and yeasts	$3.30x10^5$	$1.53x10^5$	$2.30x10^4$
Final concentration			
E. coli	$5.60x10^7$	$2.66x10^7$	$6.0x10^7$
Total coliforms	$1.13x10^8$	$4.0x10^7$	$1.56x10^8$
Mesophilic aerobes	$1.60x10^{10}$	$1.53x10^8$	$6.0x10^7$
Molds and yeasts	$2.13x10^5$	$1.33x10^5$	$2.30x10^4$
CAV-2A			
Initial concentration			
E. coli	$4.0x10^7$	$1.30x10^8$	$4.66x10^7$
Total coliforms	$3.23x10^8$	$5.60x10^8$	$1.43x10^8$
Mesophilic aerobes	$2.60x10^8$	$4.60x10^8$	$1.23x10^8$
Molds and yeasts	$7.13x10^8$	$7.60x10^7$	$2.0x10^4$
Final concentration			
E. coli	$3.60x10^7$	$6.30x10^7$	$2.66x10^7$
Total coliforms	$1.13x10^8$	$1.30x10^8$	$1.06x10^8$
Mesophilic aerobes	$6.0x10^7$	$6.0x10^7$	$4.0x10^7$
Molds and yeasts	$4.93x10^8$	$7.0x10^7$	$3.30x10^3$
CAV-V			
Initial concentration			
E. coli	$6.33x10^7$	$5.66x10^7$	$1.30x10^8$
Total coliforms	$8.0x10^7$	$1.06x10^8$	$2.16x10^8$
Mesophilic aerobes	$1.06x10^1$	$7.0x10^7$	$1.96x10^8$
Molds and yeasts	$6.33x10^5$	$2.60x10^4$	$3.30x10^4$
Final concentration			
E. coli	$2.60x10^7$	$1.66x10^7$	$1.0x10^7$
Total coliforms	$2.60x10^7$	$2.0x10^7$	$3.06x10^7$
Mesophilic aerobes	$8.66x10^8$	$1.66x10^7$	$2.0x10^7$
Molds and yeasts	$1.03x10^5$	$3.30x10^3$	$3.30x10^3$

Table 4. Logarithmic reduction

Parameters	TEST 1	TEST 2	TEST 3
CAV-A			
E. coli	0.3	1.05	0.12
Total coliforms	0.41	0.07	0.07
Mesophilic aerobes	1.81	0.08	0.07
Molds and yeasts	0.19	0.06	0
CAV-2A			
E. coli	0.05	0.31	0.24
Total coliforms	0.46	0.63	0.13
Mesophilic aerobes	0.64	0.88	0.49
Molds and yeasts	0.16	0.04	0.78
CAV-V			
E. coli	0.39	0.53	1.11
Total coliforms	0.49	0.72	0.86
Mesophilic aerobes	3.09	0.62	0.99
Molds and yeasts	0.79	0.9	1

Table 5. Percentage reduction (%)

Parameters	TEST 1	TEST 2	TEST 3
CAV-A			
E. coli	50	91	25
Total coliforms	61	14	15
Mesophilic aerobes	98	18	14
Molds and yeasts	35	13	0
CAV-2A			
E. coli	10	52	43
Total coliforms	65	77	26
Mesophilic aerobes	77	87	67
Molds and yeasts	31	8	84
CAV-V			
E. coli	59	71	92
Total coliforms	68	81	86
Mesophilic aerobes	100	76	90
Molds and yeasts	84	87	90

Table 6. Significance values of the Kruskal-Wallis test

Efficiency LR / Pr	Parameter	Value significance
LR	E. coli	0,1479
	Total coliforms	0,0582
	Mesophilic aerobes	0,3932
	Molds and yeasts	0,0608
Pr	E. coli	0,1479
	Total coliforms	0,0582
	Mesophilic aerobes	0,3932
	Molds and yeasts	0,0608

reactor (Table 6). The significance values (p) for LR and Pr are above the significance level (a = 0.05). In other words, there is statistically no significant difference between the operation of the three reactors. However, this does not mean that these differences do not exist. For descriptive purposes, the average LR and Pr results for each parameter and reactor are plotted in Figures 5 and 6. The bar heights in these figures represent the mean LR and Pr values, while the associated error bars (lines centered on the columns) indicate the standard deviation. A visual analysis confirms that the CAV-V reactor (Venturi geometry) achieved the highest overall performance for the four microbiological parameters evaluated in the three test runs. The CAV-V reactor had better averages for LR and Pr in all parameters and lower standard deviations concerning reactors with fin-type geometry (CAV-A and CAV-2A).

In the best-performing reactor (CAV-V), the highest standard deviation occurred in the LR and Pr of the *E.Coli* parameter (13.64 for Pr and 0.31 for LR). *E.Coli* is an important indicator of water safety due to the recurrent presence of this bacterium in human and animal feces (Price & Wildeboer, 2017). However, it should be noted that the reduction percentages for this parameter were higher than 50% in the three tests, even reaching 92% in test 3. The parameter with the lowest dispersion was Molds and yeasts, with values of 0.09 for LR and 2.57 for Pr.

As noted in the introduction, the microbial load reduction is due to the generation and abrupt collapse of bubbles inside each reactor. This process generates extreme localized increases in temperature (up to or greater than 10,000 K) and pressure (up to or greater than 1000 atm) within microsecond intervals. These conditions are sufficient to cause rupture of the cell membrane of the present microorganisms. Additionally, cavitation produces free radicals, such as OH^{-1}, which can damage the microorganisms' DNA following cell membrane rupture (Muñoz et al., 2025)

It is crucial to keep in mind that these results are due to a cavitation process without recirculation since, as explained, the process was carried out in situ, in an actual discharge on the Fonce River in San Gil, Santander, Colombia, and in a flow that does not receive previous primary and secondary treatments. This fact constitutes, undoubtedly, the main contribution of this research to the worldwide studies developed on the subject, most of which have been laboratory experimental works.

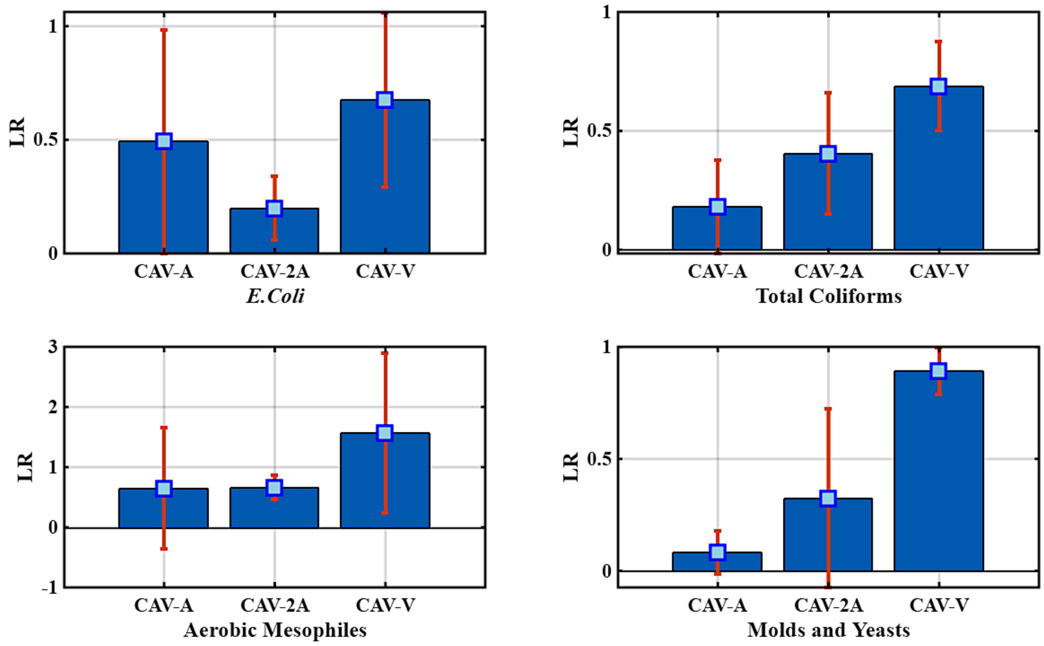

Figure 5. LR averages

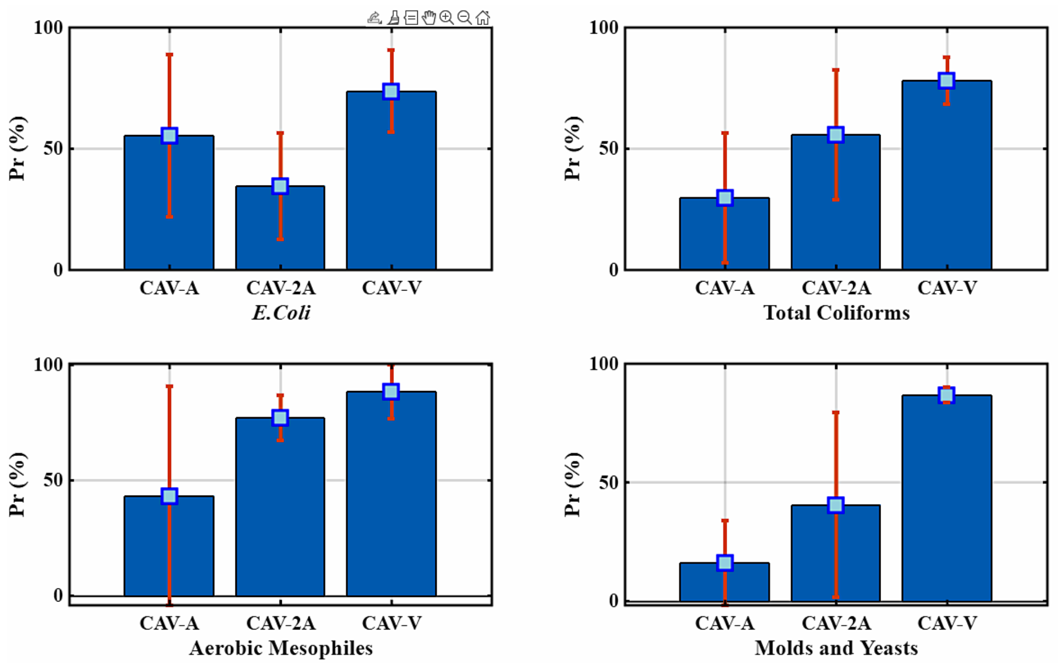

Figure 6. Pr averages

Indeed, as reported, several studies highlight the efficiency of hydrodynamic cavitation for the disinfection of water contaminated with microorganisms, especially *E. coli*. Two detailed reviews of these works in the last decades are presented by Sun et al., (2020) and M. Yadav et al., (2021). They synthesize disinfection results obtained using various reactors with disinfection rates that, in several cases, are close to or equal to 100%. However, many of these studies are laboratory-based, employing water samples where the microorganism's requiring treatment are cultivated under controlled conditions.

Thus, for example, (Arrojo et al., 2008), experimented with the disinfection of 50 liters of saline solution (1 g/L NaCl in deionized water) in which *E. coli* colonies were diluted with a concentration close to 1x107 CFU/mL. A Venturi cavitation reactor and an orifice plate reactor with three holes were employed in a recirculating system connected to a 9 kW pump. After 120 minutes of operation, the concentration of *E. coli* in the Venturi-type reactor decreased by more than 80%.

On the other hand, in the work of Jain et al., (2019) a system with a 12 L tank arranged with distilled water in which *E. coli* were diluted with an initial concentration of the order of 103 CFU/mL, operated through a vortex diode-type reactor achieves removal percentages of 99%, with a pressure drop of 0.5 bar. The system also examined the disinfection of *S. aureus* in distilled water for the same concentration level, reaching 98% elimination with an increase in the pressure drop.

In Mane et al., (2020), on the other hand, the mixture of HC with injection of natural oils, including eucalyptus and clove oil, was tested for the disinfection of 20L of distilled water artificially contaminated with *E. coli* and *S. aureus*, with initial concentrations of the order of 104 CFU/mL. The reactor geometries employed were vortex diode and orifice types. The best performance for *E. coli* was achieved with the vortex reactor, with a percentage of elimination of approximately 100% in 120 minutes and 90 minutes when clove oil was added to the system. For *S aureus*, the best performance was achieved with vortex diode geometry, with a reduction of close to 90% after 60 minutes when clove and eucalyptus oil were added. Without adding oils, the reduction of *S. aureus* reached 80%.

Similarly, for *E. coli* reduction, Sun et al., (2021) details an experiment in which a 22-kW hydrodynamic cavitation rotary reactor was tested, with a unique design of the cover added to the rotor that favored the generation of cavitation in the surrounding fluid. The reactor was tested at speeds between 2600 and 4200 rpm and flow rates between 1.4 and 2.6 m3/s. The experiment was done in a recirculating system for a volume of 15 L of distilled water, to which *E. coli* bacteria were previously added with an initial concentration of approximately 106 CFU/mL. An LR of 6.57 and a 100% reduction was achieved after 4 minutes of operation for a flow rate of 1.4 m3/s with a rotor at 4200 rpm.

In the case of the studies consulted on the disinfection of water from natural sources contaminated by humans, experiments were also conducted in the laboratory. Indeed, Zezulka et al., (2020), deals with water contaminated with cyanobacteria and treated by means of indirect hydrodynamic cavitation, through the emission of a high-pressure water jet that is directed against the flow of contaminated water. The cavitation system was complemented with the use of hydrogen peroxide and tested on water samples from Lake Brno in the Czech Republic, which were treated within 24 hours of sampling, achieving an inhibition of cyanobacterial photosynthesis by up to 60%, as well as a continuous reduction in colony formation.

Another work aimed at the disinfection of water from a natural environment is that of Y. Patil et al., (2023), in which an orifice plate

Table 7. Comparison of results

Author	Environment	Microorganisms reduced	Order C_0 (CFU/mL)	Reactor	Vol. (L)	Recirculation time (min)	Pr(%)/LR
(Arrojo et al., 2008)	Lab.	*E. coli*	10^7	Venturi	50	120	Pr: 80 LR: Nr
(Jain et al., 2019)	Lab.	*E. coli* *S. aureus*	10^3	Vortex diode	12	60	Pr: 99 LR: Nr Pr: 98 LR: Nr
(Mane et al., 2020)	Lab.	*E. coli* *S. aureus*	10^4	Vortex diode and natural oil	20	90 60	Pr:100 LR: Nr Pr: 90 LR: Nr
(Sun et al., 2021)	Lab.	*E. coli*	10^6	Rotative	15	4	Pr: 100 LR: 6.57
(Zezulka et al., 2020)	Lab. with water samples from a lake	Cyanobacteria	Nr	Indirect, water jet and H_2O_2	10	120	Inhibition 60
(Patil et al., 2023)	Lab. with water samples from a lake	Unspecified	Nr	Orifice	5	60	Pr: 95 LR: Nr
Present study	Natural: actual discharge into a river	*E. coli* *T. coliforms*	10^7	Venturi	1800	Steady flow, no recirculation	Pr:92 LR:1.11 Pr:86 LR:0.86

Note: Nr – not reported, Lab – laboratory.

reactor was used to disinfect water samples taken from Padmakshi Lake, in Warangal, Telangana State, India, a lake located in a residential area and polluted with domestic wastewater. The work shows results of COD and BOD reduction of water treated with HC plus H_2O_2 of 64% and reports a reduction of microorganisms of more than 95%, without specifying the type of microorganisms reduced.

The reduction rates in the present study are lower than many of the previous research reported; lower, for example than the works of Salve et al., (2019) and Y. Chen & Martynenko, (2016), which exhibit 100% reductions for *E. coli*, or than the work of Gregersen et al., (2020) which shows a 5 log reduction for this microorganism, but, it is crucial to remember that those works were conducted in a controlled laboratory environment. In contrast, as outlined above, this study was conducted in the unique setting of a real-time wastewater discharge over the Fonce River. The highest Pr values were obtained for the parameter Aerobes and mesophiles, with a reduction of up to 100% in the CAV-V reactor. For *E. coli*, in the same reactor, the maximum Pr was 92%. These values, when compared to literature, are significant as this research reduces microorganisms in wastewater from a continuous and direct discharge over a river. Table 7 summarizes the comparison between the best results of this research and other important related works.

CONCLUSIONS

Nine pioneering experiments were conducted employing three hydrodynamic cavitation reactors (CAV-A, CAV-2A, and CAV-V) to analyze the reduction of four microorganism groups in urban wastewater. This work is the first of its kind to utilize samples taken directly from a permanent discharge point on the Fonce River (San Gil, Santander, Colombia). The results obtained correspond to a single-pass treatment of the wastewater through the reactor.

All experiments confirmed a decrease in the microbiological load across the four groups analyzed. The Venturi-type reactor (CAV-V) demonstrated the highest performance among the designs tested, achieving significant results. Robust overall reduction was observed, with average logarithmic reduction (LR) values exceeding 0.6 and percentage reduction (Pr) values above 70% for the entire set of microbial groups. The greatest average reduction was recorded for Aerobic Mesophilic in the CAV-V (LR, 1.57±1.09, Pr, 88.67±9.84). Significantly, for the pathogenic indicator *E. coli*, system achieved a substantial reduction (LR of 0.68± 0.31 and Pr of 74±13.64).

The results of this research demonstrate the feasibility of applying hydrodynamic cavitation as an alternative tertiary treatment for urban wastewater in continuous flow scenarios for environmental discharge. This opens significant avenues for future investigation. Further research is needed to test HCRs on urban wastewater that has already undergone primary and secondary treatment processes, particularly when combined with other disinfection methods and considering storage systems that allow for the recirculation of treated water through the reactor.

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