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Unlocking Biodegradability: Pretreatment of Dairy Industry wastewater by Hydrodynamic Cavitation.

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Abstract

The effectiveness of traditional biological treatment methods is frequently restricted by the high organic content and poor biodegradability of effluent from the dairy industry. Enhancing such effluents biodegradability before biological treatment might greatly improve treatment effectiveness and environmental compliance. By investigating its effects on the biodegradability index (BI) under different operating conditions, this study aims to determine the effectiveness of hydrodynamic cavitation (HC) as a method of pretreatment for dairy effluent. Orifice plates with different geometries were used to create hydrodynamic cavitation, and the procedure was run at various pH levels, temperatures, and inlet pressures. A total of seven orifice plate designs were tested. BI was calculated before and after treatment under each condition to assess the improvement in biodegradability. At an intake pressure of 2 bar, the highest improvement in BI was noted, rising from 0.34 to 0.58. At 1 bar, BI improved from 0.36 to 0.52, while pressures above 2 bar led to a decline in BI, establishing 2 bar as the optimal pressure. Among the orifice plates, the configuration with three holes with 3 mm diameter resulted in the highest BI increase from 0.35 to 0.66. Additionally, operation at 30°C and pH 10 yielded the most favorable results in terms of biodegradability enhancement. Hydrodynamic cavitation has demonstrated strong potential as a pretreatment method for dairy wastewater, significantly improving its biodegradability under optimized conditions. This enhancement can contribute to more effective biological treatment and support sustainable wastewater management in the dairy industry.

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Abbreviations

HC	-	hydrodynamic cavitation
COD	-	chemical oxygen demand
BOD	-	biochemical oxygen demand
BI	-	biodegradability index (BOD5:COD ratio)
TOC	-	total organic carbon
AOP's	-	advanced oxidation processes
OH	-	hydroxyl free radical
H	-	hydrogen free radical

Introduction

In India, the dairy sector makes a substantial contribution to both national development and the nation's overall food output. Milk is regarded as one of the most important sources of essential nutrients required for human health.[1] Nonetheless, the dairy sector also uses a lot of water, especially for processes like sanitization and cleaning. Significant amounts of wastewater are produced as a result of the frequent use of large amounts of water, detergents, and sanitizing agents.[2]

The collection and treatment of this wastewater in compliance with regional pollution control laws is one of the main issues facing the dairy industry.[3] High concentrations of nitrogen, phosphate, oil, grease, and chemical and biochemical oxygen demand (COD and BOD_5) are characteristics of dairy wastewater.[4] Despite the widespread use of biological treatment methods such as dissolved air flotation, activated sludge, rotating biological contactors, trickling filters, and anaerobic lagoons, the dairy industry often struggles to meet regulatory discharge standards.[5] In particular, the final treated effluent frequently exceeds permissible limits for chemical oxygen demand (COD)and biochemical oxygen demand (BOD) levels.[6] This emphasizes the necessity of better pretreatment techniques to boost biological treatment procedures effectiveness. The BOD_5/COD ratio, often known as the biodegradability index (BI), is a crucial metric in determining whether wastewater is suitable for biological treatment.[7] A BI value greater than 0.5 generally indicates that the wastewater is readily biodegradable, while a value between 0.3 and 0.5 suggests the need for seeding or acclimatization of microorganisms, due to the slower breakdown of pollutants. If the BI is below 0.3, the wastewater is considered poorly biodegradable.[8] Therefore, improving the BI prior to biological treatment becomes essential for effective wastewater management.[9]

Advanced oxidation processes, or AOPs, have become popular pretreatment choices for improving wastewater's biodegradability.[9–10] Because of its effectiveness and scalability, hydrodynamic cavitation (HC) has drawn interest among these.[11–14] Low-pressure zones are created downstream in HC when fluid flows through a restriction, such as an orifice plate. Vapor cavities or bubbles develop when the pressure in these areas drops below the fluid's vapor pressure. Hydroxyl radicals (•OH) are created as a result of the localized high temperatures and pressures created by the subsequent collapse of these cavities. These extremely reactive radicals have the ability to convert complex organic molecules into less hazardous, simpler compounds, which lowers COD and raises BOD_5 levels.[13–17]

It has been demonstrated that using HC as a pretreatment technique can increase the biodegradability of dairy effluent and make it more suitable for biological treatment procedures.[9,17] By altering operating parameters such inlet pressure, orifice plate shape, temperature, and pH, this study examines the effect of HC on improving biodegradability in dairy effluent.

Material and Methods

Experimental Set up

The experimental setup included a 20-liter holding tank equipped with an internal helical cooling coil to regulate the temperature of the wastewater. This arrangement ensured that a constant temperature was maintained throughout the experimental runs, as illustrated in Figure 1. The coil was connected to tap water through inlet and outlet hose pipes, allowing temperature regulation to approximately 30 °C throughout the experiments. The wastewater was circulated through the system using a reciprocating pump, and the mainline was fitted with an orifice meter, a cavitating device. The orifice plate was installed using flange arrangements, enabling easy replacement with plates of different geometries depending on the experimental conditions.

The setup also featured a bypass line connected in parallel with the mainline. Both lines had an internal diameter of 1 inch. A flow control valve (V2) on the bypass line allowed the adjustment of flow and pressure through the cavitating device. Valves V1 and V3, positioned at the pump's inlet and outlet respectively, were kept fully open during the experiments to ensure steady flow. In order to track the pressure differential over the cavitation zone, pressure gauges (P1 and P2) were positioned upstream and downstream of the orifice.

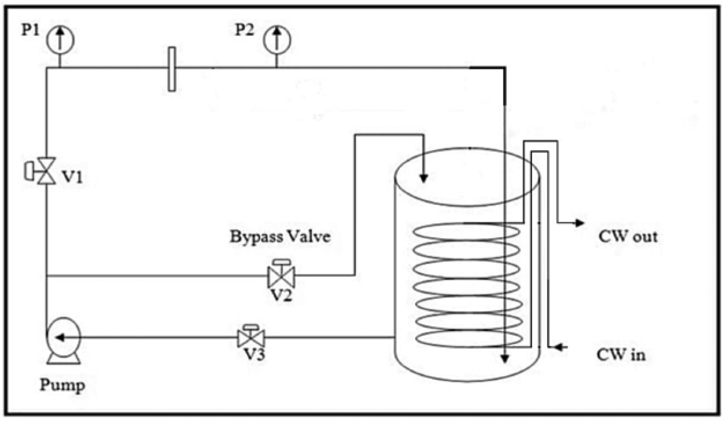

Fig. 1: Schematic flowchart of hydrodynamic cavitation setup

Experimental Protocol

Samples of dairy effluent were gathered at a milk processing plant in the Indian state of Maharashtra, close to Kolhapur. (For reasons of confidentiality, the name of the facility is not disclosed.) A 20-liter high-density polyethylene (HDPE) carboy was used to collect the effluent sample from the dairy's Effluent Treatment Plant (ETP) output. The samples were kept between 4 and 5 °C after being collected and delivered in a chilled environment. The samples were allowed to come to room temperature (around 30 °C) before the experiment. Table 1 summarizes the physicochemical properties of the raw wastewater, which were examined in triplicate.

Table 1: Characteristics of dairy wastewater.

Parameter	Observed Values	Unit
pH	6.4	-
COD	2745	mg/L
BOD_5	964	mg/L
TDS	680	mg/L
TSS	90	mg/L
BOD_5:COD ratio	0.35	-
Oil & Grease (%)	0.07	%

Procedure for Experimentation and Analysis

Before each run, the experimental system was thoroughly rinsed with distilled water followed by alkaline cleaning solution to eliminate any residual contaminants. Each experimental run was performed using 15 liters of wastewater, operated in batch recirculation mode for a total duration of 4 hours. At 60-minute intervals samples were taken out. It was investigated how the biodegradability index (BOD_5/COD) was affected by operating parameters like pH, temperature, orifice plate shape, and inlet pressure. The COD and BOD_5 of the samples were analyzed using Standard Operating Procedures (SOPs) based on APHA Standard Methods.[18] The results are shown as mean ± standard deviation, and all experiments were carried out in triplicate.

Appropriate error control measures were implemented, and instrument calibration was performed prior to each experimental set.

Results

To achieve the objectives of this research, a series of experiments were conducted using a hydrodynamic cavitation system, focusing on the influence of both geometric and operational parameters. The study aimed to optimize conditions that enhance the biodegradability of dairy wastewater, thereby improving the efficiency of subsequent biological treatment processes. Key parameters investigated included inlet pressure, temperature, pH, and the geometry of the orifice plate. Each parameter was systematically varied to evaluate its effect on the biodegradability index (BI). The findings from this study contribute to identifying optimal pretreatment conditions that can significantly improve the biological treatability of dairy wastewater.

Biodegradability of Dairy Wastewater as Affected by Inlet Pressure

In a series of studies, the cavitating device's input pressure was varied from 1 bar to 4 bar in order to examine the impact of inlet pressure on the biodegradability of dairy effluent. The cavitating device used in the trials was orifice plate P4, which has a single hole and a diameter of 3 mm. The system temperature was kept constant at 30°C.Over the course of the 240-minute operation, samples were taken at regular intervals of 60 minutes. Standard Operating Procedures (SOPs) based on APHA standard methods were followed in the measurement of BOD_5 and COD levels for every sample.[18]

The biodegradability index (BI) was then calculated as the ratio of BOD_5 to COD. The variation in BI with changes in inlet pressure is illustrated in Figure 2. The results indicate a positive correlation between increasing inlet pressure and BI up to a certain point. At 1 bar, the BI increased from 0.36 to 0.52 over the 240-minute treatment period. Raising the pressure to 2 bar further improved the BI, although the increase was less pronounced compared to the rise from 1 to 2 bar. Notably, no significant enhancement was observed between 2 and 3 bar, and a subsequent decline in BI was recorded when the pressure was increased to 4 bar.

This pattern suggests that while increasing pressure enhances cavitation intensity and hydroxyl radical formation, exceeding the optimum pressure leads to bubble coalescence and cushioned collapses, which reduce cavitation efficiency. Based on these findings, 2 bar was identified as the optimum inlet pressure for subsequent experimental runs.

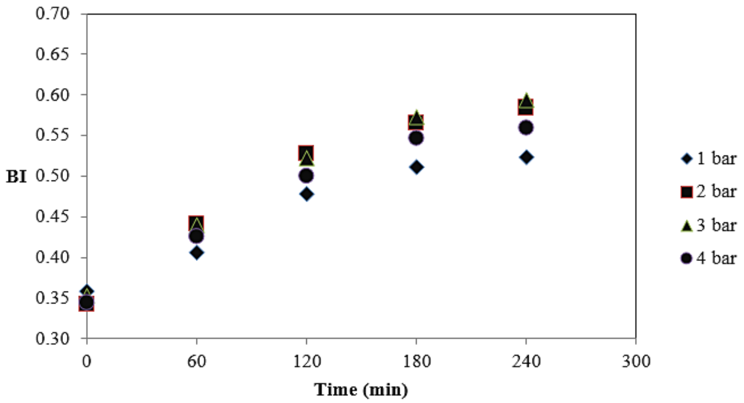

Fig. 2: Effect of inlet pressure across the orifice plate on the enhancement of the biodegradability index (BI) of dairy wastewater

Effect of the Geometry of the Constriction on Biodegradability Index (BI)

To examine the influence of orifice geometry on the enhancement of the biodegradability index (BI), experimental runs were conducted using a series of orifice plates designated as P1, P2, P3, P4, P5, P6, and P7. These plates differed in terms of their number of holes and hole diameters, with their specific geometrical configurations summarized in Table 2. The flow distribution, turbulence creation and pressure recovery profile downstream of the constriction are all directly impacted by the shape of these plates, and these factors are crucial for the intensity of cavitation and the production of hydroxyl radicals (•OH).[19]

Key design parameters considered in this study include the α and β ratios:

- α represents the ratio between the combined perimeter of all the holes and the total open area provided by the orifice plate.
- β denotes the ratio of the total open flow area (sum of hole areas) in the orifice plate to the cross-sectional area of the connecting pipe.[20-21]

The operating temperature was kept constant at 30°C throughout the experiments, and the inlet pressure was held at 2 bar. By systematically varying the orifice plate geometries while keeping other operational conditions constant, the relationship between orifice design and its effect on BI enhancement through hydrodynamic cavitation was established

Table 2: Details of geometry of each plate.

Plate No.	Dia. of hole (dh) in mm	No. of holes	Flow area in mm²	α (mm^{-1})	β	Total perimeter (mm)
P1	2	1	3.14	2	0.0064	6.28
P2	2	3	9.42	2	0.0192	18.84
P3	2	5	15.7	2	0.032	31.4
P4	3	1	7.065	1.33	0.0144	9.42
P5	3	3	21.195	1.33	0.0432	28.26
P6	4	1	12.56	1.00	0.0256	12.56
P7	6	1	28.26	0.67	0.0576	18.84

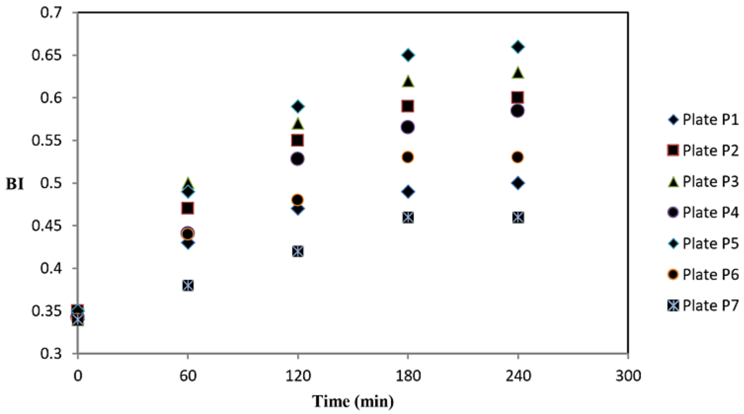

Fig. 3: Influence of orifice plate geometry on the improvement of wastewater biodegradability at an inlet pressure of 2 bar.

Effect of α

Figure 3 shows how the biodegradability index (BI) of dairy wastewater is affected by the geometrical parameters α and β. Plate P5 demonstrated the highest improvement in BI compared to all other plates. Plates P1, P2, and P3, despite having higher α value, exhibited lower enhancements in BI when compared to plate P5. This indicates that the combined influence of both the number and distribution of holes in plate P5 resulted in more effective cavitation and hydroxyl radical generation. Similarly, plates P6 and P7, with lower α values, produced significantly less improvement in BI than plate P5, reaffirming the importance of optimizing both α and β values.

Interestingly, although plates P4 and P5 possessed identical α values, plate P5 achieved a noticeably greater rise in BI. This finding emphasizes that, besides α alone, the distribution and total flow area (β) also play crucial roles in governing cavitation intensity and the resulting wastewater biodegradability improvement.

Effect of β

The experimental results indicate a distinct relationship between the flow area ratio (β) and the biodegradability index (BI) of dairy wastewater treated by hydrodynamic cavitation. As shown in Figure 3, increasing the β value gradually enhances the biodegradability index (BI), with improvements observed from plate P1 up to plate P5. The maximum enhancement was observed with plate P5, which exhibited a β value of 0.0432. Under these conditions, the BI increased significantly, indicating that this β value provides the most favorable balance between flow area and cavitation intensity.

In contrast, plate P7, which had the highest β value of 0.0576, resulted in the lowest improvement in BI, increasing only from 0.34 to 0.46. Based on these findings, β = 0.0432, as achieved with plate P5, was identified as the optimum flow area ratio for maximizing biodegradability enhancement under the given experimental conditions.

Effect of Temperature

Using orifice plate P5, the impact of temperature on the biodegradability index (BI) of dairy effluent was examined between 20°C and 40°C while keeping the inlet pressure constant at 2 bar. Figure 4 displays the outcomes of the experiment. As the temperature rose from 20°C to 30°C, it was found that the BI gradually climbed. It peaked at 30°C, following which it began to fall around 40°C. At the optimum temperature of 30°C, the BI improved significantly from 0.35 to 0.66, which was the highest increase recorded across the temperature range. These results led to the conclusion that, in the conditions under study, 30°C was the optimum operating temperature for optimizing the biodegradability index.

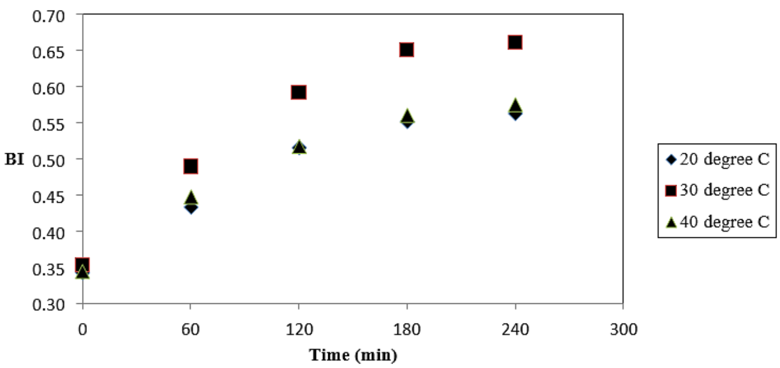

Fig. 4: Effect of temperature on Biodegradability index at inlet pressure of 2 bars with orifice plate P5.

Effect of pH

Using orifice plate P5 and a constant inlet pressure of 2 bar, the impact of pH on the biodegradability index (BI) of dairy effluent was investigated at the previously established optimum temperature of 30°C. Three starting pH values 4, 7, and 10 were used in the studies to evaluate the impact of pH. Throughout the studies, the wastewater's pH was meticulously monitored and altered by adding the right amounts of base or acid.Samples were withdrawn at 60-minute intervals over the treatment period, and BI was determined for each condition. The results, illustrated in Figure 5, indicate a clear trend: as the pH increased, the biodegradability index also improved. The highest BI increase was recorded at pH 10, indicating that alkaline circumstances greatly improve the hydrodynamic cavitation process's degrading efficiency. These results showed that, in the experimental conditions under study, pH 10 was the optimum pH for maximizing the biodegradability of dairy wastewater.

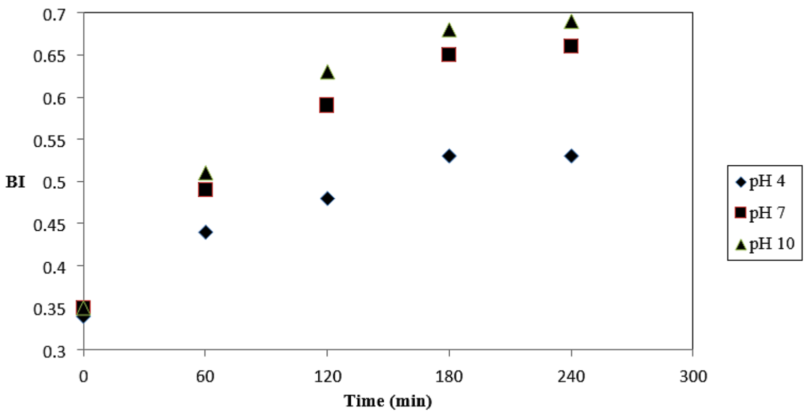

Fig. 5: Effect of pH on biodegradability index of waste water at inlet pressure of 2 bars, orifice plate P5 and temperature of 30ºC

Discussion

Effect of Inlet Pressure on Biodegradability Index (BI)

The results of the experiment show a direct relationship between the improvement of the biodegradability index (BI) of dairy effluent and inlet pressure. The BI significantly improved from 0.35 to 0.66 when the inlet pressure was raised to 2 bar. This improvement is explained by the enhanced cavitation intensity and turbulence, which promote the violent bubble collapse that produces hydroxyl radicals (•OH).[20–23] Beyond the optimal pressure of 2 bar, a decline in BI was observed, which may be due to excessive bubble coalescence leading to cushioned collapses, thereby reducing the intensity of localized micro-hotspots.[20-23] Statistical comparison using oneway ANOVA confirmed the significance of this pressure-dependent trend ($p< 0.05$).

Effect of Orifice Geometry on Biodegradability

Effect of Throat Perimeter Ratio (α)

Based on the experimental findings for the throat perimeter ratio (α), it was noted that although plates P4 and P5 had identical orifice diameters, their performance varied as a result of differences in the number of holes. Plate P5, which had a greater number of smaller holes, provided a larger cumulative flow area, resulting in a higher biodegradability index (BI) compared to P4. Similarly, plates P6 and P7 exhibited lower BI values than P5, which is attributed to their larger orifice openings. These larger openings reduced the fluid velocity at the orifice throat, thereby diminishing cavitation intensity and the generation of hydroxyl radicals (•OH), ultimately leading to reduced biodegradability enhancement. Notably, while plates P1, P2, and P3 shared identical α values, those with a greater number of holes consistently produced higher BI values.

This suggests that increased turbulence frequency and enhanced cavitation events are associated with a higher throat perimeter, even when the flow area remains constant. This behavior aligns with findings reported by Rajoriya *et al.*, who observed that increasing the throat perimeter promotes more intense cavity collapse and greater production of •OH radicals, thereby improving pollutant degradation efficiency.[24-25] In their studies on the decolorization of Reactive Blue 13, similar trends were reported. Moreover, Sivakumar and Pandit documented comparable observations during the degradation of Rhodamine B, where orifice plates with multiple small holes outperformed those with fewer, larger holes due to more efficient cavitation dynamics.[26-27]

Effect of Flow Area Ratio (β)

The results clearly indicate that an increase in the flow area ratio (β) initially contributes to a significant enhancement in the biodegradability index (BI) of dairy wastewater. The maximum improvement was recorded at β = 0.0432, where the larger effective flow area encourages a greater number of cavitational events, thereby increasing the production of hydroxyl radicals (•OH). These radicals are highly reactive and responsible for converting complex organic pollutants into simpler, biodegradable substances, resulting in a noticeable rise in BI.

However, when β exceeds the optimal value—particularly at β = 0.0576 as seen with orifice plate P7—the velocity at the orifice throat decreases due to the larger throat diameter. This reduction in velocity compromises the intensity of cavitation, leading to weaker bubble collapses and diminished •OH radical formation, ultimately lowering the efficiency of organic degradation and reducing the BI.

These observations align well with earlier studies by Rajoriya *et al*. and Sivakumar and Pandit, who similarly noted that the efficiency of hydrodynamic cavitation for dye degradation depends strongly on optimizing the geometric parameters of the cavitating device.[24-28] Based on the observed results, orifice plate P5, which exhibited the highest BI enhancement at the optimal β value, was selected as the preferred configuration for further experimental investigations.

Effect of Temperature on Biodegradability Index (BI)

The experimental findings unequivocally show that temperature has a substantial and intricate impact on how well hydrodynamic cavitation (HC) works to raise the biodegradability index (BI) of effluent from dairy farms. A higher temperature raises the liquid's vapor pressure, encouraging the growth of additional cavitation bubbles and hastening the production of hydroxyl radicals (•OH). The breakdown of greater molecular weight organic compounds into simpler, biodegradable molecules is the result of these radicals,resulting in an increase in BI up to a temperature of 30°C.

At temperatures exceeding this point, the liquid's vapor pressure rises significantly, resulting in the generation of cavitation bubbles with a high vapor content. These vapor-filled cavities tend to collapse less violently due to cushioning effects, thereby reducing the intensity of micro-hotspots and subsequent hydroxyl radical generation.[29] This phenomenon ultimately leads to a decline in BI at temperatures exceeding the optimal 30°C.

The results in the literature are in agreement with this non-linear temperature effect. According to Wang *et al*., when alachlor was broken down with HC, reaction rates rose between 30°C and 40°C, but additional increases up to 60°C resulted in a notable decrease in degradation efficiency.[30] In a similar vein, Yi *et al*. found that the oxidation rate for Rhodamine B degradation increased from 15°C to 25°C but then fell after this.[31] Using HC in conjunction with Fe2+-doped TiO_2, Li *et al*. confirmed similar results, observing that the degradation efficiency rose to 40°C and then decreased at higher temperatures.[32]

Considering these findings, 30°C was determined to be the most effective operating temperature for this study, providing the highest improvement in biodegradability without encountering the adverse effects associated with excessive vapor content within cavitation bubbles.

Effect of pH on Biodegradability Index (BI)

The influence of pH on the biodegradability of dairy wastewater treated by hydrodynamic cavitation (HC) was shown to be substantial. At higher initial pH values, the increasing concentration of hydroxide ions (OH^-) in the solution enhances the formation of hydroxyl free radicals (•OH) during cavitation. Complex, high molecular weight organic molecules can be broken down by these extremely reactive radicals into simpler, biodegradable intermediates. As a result, the enhancement of biodegradability was more pronounced in alkaline conditions, where the cavitational process is primarily governed by hydroxyl radical-induced oxidation.[33-34] On the other hand, free hydroxide ion availability falls in acidic or neutral environments, increasing the likelihood of a recombination process between protons (H^+) and hydroxyl radicals. This reaction limits the oxidative destruction of organic molecules by lowering the concentration of free •OH radicals in the system. As the pH decreases, protons increasingly scavenge the generated hydroxyl radicals, thereby lowering the overall treatment efficiency and reducing the biodegradability index.[30]

These trends are consistent with prior studies involving advanced oxidation processes. Sono-chemical degradation of polycyclic aromatic sulfur hydrocarbons and the photocatalytic degradation of alachlor under varying pH conditions similarly reported enhanced degradation rates under alkaline conditions, with reduced performance at lower pH values due to radical scavenging and recombination effects.[35-36]

Conclusion

Based on the experimental findings, it can be inferred that hydrodynamic cavitation (HC) serves as a highly effective advanced oxidation process (AOP) for the pretreatment of dairy industry effluents. The process generates hydroxyl radicals (•OH), which are instrumental in breaking down complex organic contaminants in the wastewater into simpler and less hazardous substances. This leads to a significant decrease in chemical oxygen demand (COD) and a corresponding increase in biochemical oxygen demand (BOD_5), thereby enhancing the biodegradability index (BI) of the wastewater.

The efficiency of the hydrodynamic cavitation process is largely dependent on the generation rate of hydroxyl radicals, which is influenced by key parameters such as orifice plate geometry, inlet pressure, operating temperature, and pH. From the present study, the optimum operating conditions were identified as an inlet pressure of 2 bar, a temperature of 30°C, and a pH of 10. Among the tested configurations, orifice plate P5, with three holes of 3 mm diameter, exhibited the highest improvement in the biodegradability index, emphasizing the importance of geometric design in optimizing cavitation intensity.

In summary, enhancing the biodegradability of dairy wastewater through hydrodynamic cavitation improves the performance of downstream biological treatment processes. This approach not only increases the treatment efficiency but also supports environmental sustainability by reducing pollutant loads and improving the overall treatability of dairy effluents. Hence, hydrodynamic cavitation presents itself as a viable and promising pretreatment strategy for addressing the challenges in dairy wastewater management.

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Conflict of Interest

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Data Availability Statement

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Ethics Statement

This research did not involve human participants, animal subjects, or any material that requires ethical approval.

Informed Consent Statement

This study did not involve human participants, and therefore, informed consent was not required.

Clinical Trial Registration

This research does not involve any clinical trials.

Author Contributions

- **Arvind Vilas Patil:** Conceptualization, Methodology, Data Collection, Analysis, Project Administration, Writing – Original Draft, Writing – Review & Editing,
- **Sunil Vamanrao Aneka:** Supervision
- **Prashant Pandurang Patil:** Supervision

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