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Effect of Orifice Induced Hydrodynamic Cavitation on the Properties of Waste Activated Sludge

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ABSTRACT

Exploring alternative methods to reduce the quantity of wastewater sludge and improve its characteristics is among the prioritized subjects in the field of sludge management. Hydrodynamic cavitation, commonly employed for water and wastewater treatment, also holds the potential for utilization as a pre-treatment method for sludge. In the presented study, the excess sludge obtained from the wastewater treatment facility of a food and beverage manufacturing factory was collected and disintegrated with a orifice-induced hydrodynamic cavitation unit. According to the data obtained, the highest cavitation performance was achieved under the condition where the cavitation number was set to 0.3. In addition, hydrodynamic cavitation performed under the optimum operating conditions, significantly increased the solubility of waste activated sludge. The results showed that the soluble chemical oxygen demand concentration, which was initially determined as 382 mg/l, reached 3,068 mg/l end of the cavitation. 64% of the total Kjeldahl nitrogen and 60% of the total phosphorus of waste-activated sludge were converted into soluble forms by the effects of hydrodynamic cavitation. Moreover, the results of the microbial study indicated that removal rates of indicator bacteria varied between 94% and 99%.

1. Introduction

The continuous increase in consumption tendency has made the intensive use of natural resources inevitable. In order to impede the irreversible destruction of natural resources, environmental protection policies have been developed in the international field. Waste management has an important place among environmental protection policies. It refers to preventing the formation of waste, reduction at its source, reuse, separation according to its characteristics and type, accumulation, collection, temporary storage, transportation, recycling, disposal and the activities of monitoring, control and inspection after disposal processes.

Sewage sludges released from wastewater treatment plants are also considered within the scope of waste management. The most important elements of sludge management are reducing the quantity of sludge produced via wastewater treatment plants, choosing the best technology for processing the sludge and evaluating the beneficial use alternatives of sludge in both treatment and disposal steps. Disintegration processes are minimization methods that support reducing the amount of sludge and obtaining a more stable sludge. External forces are applied to the sludge in the disintegration processes, which are classified under four groups: chemical, biological, thermal and physical/mechanical. Hereby, the complex structure of sludge floc is disturbed, the bacterial cell walls are broken down, and the organic components protected by the cell walls are transferred to the liquid phase (Vranitzky and Lahnsteiner, 2005).

Hydrodynamic cavitation, which is among the mechanical sludge disintegration processes, occurs as a result of the compression of places where liquid passes by using hydraulic devices such as an orifice, valve and venture (Arrojo and Benito, 2008). As the fluid passes through these structures, its speed accelerates because of the contraction in the flow field, and its pressure decreases according to the Bernoulli equation. This pressure, which remains

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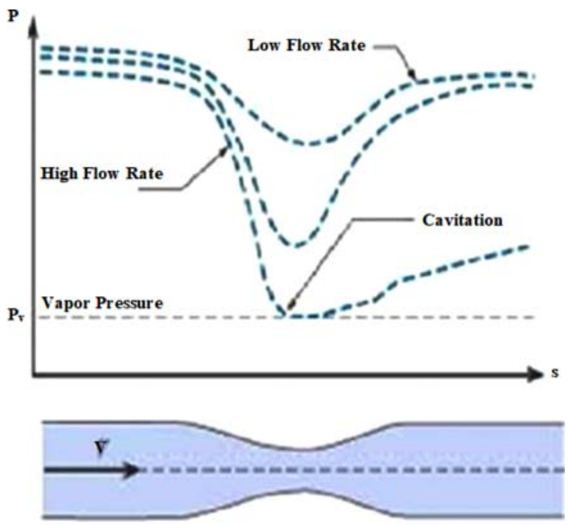

Fig. 1. Formation of Hydrodynamic Cavitation (Gogate and Pandit, 2001)

above the vapor pressure at low flow rates, may be at vapor pressure levels at high flow rates. As the liquid pressure drops to vapor pressure levels, the liquid starts to boil, cavitation microbubbles are formed and cavitation occurs (Fig. 1). With the expansion of the flow area, the pressure is restored and the cavitation bubbles are extinguished. On the other hand, boundary layer segregation occurs with the transition of fluid through the narrow flow area, and a significant sum of energy is getting away in the mode of a sustained pressure fall. The turbulence density, which varies depending on the extent of pressure reduction and the pace of pressure recovery significantly affects the cavitation density (Demir, 2019).

The cavitation density can be adjusted by using different geometric contraction structures and by altering the flow conditions of the fluid. The cavitation number (Cv) is a dimensionless number that is calculated to relate the cavitation density to flow conditions, and can be determined using the following equation, (Albanese et al., 2019; Setyawan et al., 2022):

$$C_v = \frac{P_2 - P_v}{1/2\rho V^2}, \tag{1}$$

where P_2 ($N \cdot m^{-2}$) is the local pressure, Pv ($N \cdot m^{-2}$) is the vapor pressure of the fluid, ρ ($kg \cdot m^{-3}$) is the density of the fluid and V ($m \cdot s^{-1}$) is the velocity of the flow. Cavitation occurs at $C_v < 1$ under the ideal conditions.

The mechanical forces applied to waste-activated sludge in the hydrodynamic cavitation process change many properties of the sludge and enhance the efficiency of the subsequent stabilization procedures such as anaerobic sludge digestion. Machnicka et al. (2009) indicated that the bacterial cells in waste sludge were broken down by the effect of hydrodynamic cavitation, and the organic components protected by the cells were released to the sludge liquid phase, resulting in an increment in the concentrations of soluble chemical oxygen demand (SCOD). Similarly, Mancuso et al. (20 of 21) stated that the hydrodynamic cavitation process significantly increased the soluble organic matter concentration of the sludge. According to the test results, a significant increment in the concentration of SCOD (from 244 to 4.578 mg/l) occurred in the sludge. It was also emphasized in the study that hydrodynamic cavitation is an ecofriendly and economical disintegration method that can be applied to enhance sludge stabilization in aerobic and anaerobic sludge digestion units. This result is also confirmed by the findings of Garlicka et al. (2020) that investigated the effects of hydrodynamic cavitation applications at different energy densities on anaerobic sludge digestion performance. Their study indicated that a cavitation-induced disintegration which has an energy density of 140 kj/l increased the methane yield by 152%.

Hydrodynamic cavitation has some environmental problems such as corrosion, noise and vibration (Wang et al., 2021). However, these environmental problems can be eliminated by taking small precautions. The noise occurring during the hydrodynamic cavitation process can be prevented by the use of sound insulation materials. Vibration can generally be minimized by periodically maintaining the pipelines and connection points of the cavitation device. In order to reduce the effect of corrosion that may occur on pipe, pump and valve surfaces, materials that are resistant to high temperatures and high pressure should be selected. Since these environmental problems can be prevented by taking simple precautions, hydrodynamic cavitation is considered as an effective and promising technology that has attracted the interest of many researchers and has been widely employed in many fields.

Studies evaluating the performances of hydrodynamic cavitators in the field of sludge disintegration mostly focused on the increments in the soluble organic fractions of sludge and its effects on biogas production potential. However, fewer studies have examined the effects of hydrodynamic cavitation on the microbial species and populations, some of which have focused on drinking water and wastewater disinfection (Mezule et al., 2010; Machnicka et al., 2012; Loraine et al., 2012; Dular et al., 2016; Mancuso et al., 2017; Bhat and Gogate, 2021; Topac and Etyam, 2021; Kolbl-Repinc et al., 2022). In the presented study, orifice-induced hydrodynamic cavitation trials were performed with activated sludge from a food processing facility. The orifice-induced hydrodynamic cavitation was preferred in the presented study due to its significant advantages such as encompass improved disintegration, reduced chemical reliance, pathogen reduction, energy efficiency, scalability, process intensification, and the potential for resource recovery (Hilares et al., 2016; Sun et al., 2018; Zupang et al., 2019). Trials were performed with activated sludge from a food processing facility. In order to detail the effectiveness of the applied sludge pretreatment method, the effects on SCOD, soluble total Kjeldahl nitrogen (STKN), soluble total phosphorus (STP), viscosity, suspended solids (SS) and volatile suspended solids (VSS) parameters as well as on *E. coli, Bacillus subtilis* and *Pseudomonas aeruginosa* numbers were assessed.

2. Materials and Methods

2.1. Materials

2.1.1 Waste-Activated Sludge

A waste-activated sludge sample was obtained from a treatment plant that produces canned food in Bursa, Turkey. The wastewater composition of this treatment plant consists of domestic and process water. The general properties of the waste-activated sludge tested in the study are presented in Table 1.

2.1.2 Hydrodynamic Cavitation System

Figure 2 shows the laboratory scale hydrodynamic cavitation system tested for sludge disintegration purpose. This system consists of a reactor in which the waste-activated sludge is filled, a vertical shaft centrifugal pump and an orifice plate. The waste-activated sludge was constantly recirculated through the orifice plate during operation. The volume of the cavitation reactor was 20 L. A vertical shaft centrifugal pump with a motor power of 1.5 kW is used in the system. The pipe leading out from the pump outlet is split into two separate lines: the main line and the bypass line. The orifice plate attached to the main line is the part where cavitation occurs. The speed of the liquid passing through the orifice plate can be changed by opening and closing the valve on the main line. In this way, it is possible to work with different cavitation numbers.

Table 1. Characteristics of Waste Activated Sludge

Parameter	Value
pH	7,10
EC (mS/cm)	16,32
Total Solid (%)	1,99
Volatile Solid (mg/l)	14770
Suspended Solid (mg/l)	18550
Volatile Suspended Solid (mg/l)	14570
Total Kjeldahl N (mg/l)	644
Soluble Kjeldahl N (mg/l)	35
NH_4^+-N (mg/l)	101,5
NO_3^--N (mg/l)	13,3
Total P (mg/l)	354
Soluble P (mg/l)	62
Total COD (mg/l)	17280
Soluble COD (mg/l)	382

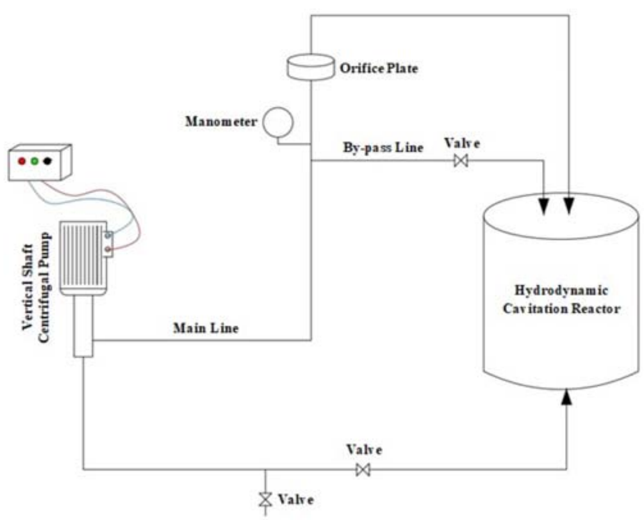

Fig. 2. Hydrodynamic Cavitation System

2.2 Experimental Design

In the initial part of the research, a series of trials were performed to assign the optimum operating conditions for hydrodynamic cavitation. In this direction, with reference to the study carried out by Etyam (2017) a 3 mm diameter orifice plate was preferred, where maximum disintegration was achieved for waste-activated sludge. The velocity of the fluid passing through the orifice is changed by adjusting the valve on the main pipe and the cavitation number is set to the values of 0.3, 0.5, 0.7 and 0.9. Owing to operational issues that hindered the attainment of consistent results, the investigation of lower cavitation numbers remained unfeasible. For each cavitation number, 16 L of waste sludge was cavitated in the hydrodynamic cavitator for 120 minutes. The selection of a 120-minute cavitation duration was made in consideration of prior research on hydrodynamic cavitation, which employed a similar timeframe (Mishra and Gogate, 2010; Joshi and Gogate, 2012; Patil et al., 2014; Gogate and Patil, 2015). In order to evaluate the cavitation efficiency, SCOD and STKN analyses were performed on the samples taken every 30 minutes throughout the experiment. The 0th minute samples which were taken at the beginning of the cavitation considered as control samples. By evaluating the results of the analysis, the cavitation number with the best performance for hydrodynamic cavitation was identified.

In the subsequent part of the research, the studied excess sludge was subjected to cavitation under the conditions with an orifice hole diameter of 3 mm and a Cv of 0.3 (optimal operating condition). To obtain a more detailed insight into the alterations in sludge characteristics, it was chosen to prolong the cavitation duration to 180 minutes. In order to examine the variations in sludge properties caused by hydrodynamic cavitation, SCOD, STKN, STP, viscosity, SS, VSS and bacterial analyses were performed on sludge samples taken every 30 minutes.

2.3 Laboratory Analysis

The pH and electrical conductivity (EC) of the waste-activated sludge samples were quantified with a pH meter and conductivity meter, respectively. The ammonium-nitrogen (NH_4^+-N) and nitrate-nitrogen (NO_3^--N) concentrations in the sludge samples were analysed by steam distillation method using Devarda's alloy and MgO (Keeney and Nelson, 1982). The steam distillation procedure was also employed to determine the total Kjeldahl nitrogen (TKN) levels in the sludge samples that were digested in accordance with Kjeldahl method (Bremner and Mulvaney, 1982). Total phosphorus concentrations in samples were achieved by the ascorbic acid method (APHA, AWWA, WEF, 2018). Total chemical oxygen demand (TCOD) concentrations of the samples were also examined according to Standard Methods (APHA, AWWA, WEF, 2018). Sludge samples were centrifuged (10,000 × g, 4ºC, 20 mins) in order to determine concentrations of STKN, SCOD and SP. Total solid (TS), volatile solid (VS), SS and VSS content of sludge samples were analyzed as specified in Standard Methods (APHA, AWWA, WEF, 2018). A rheometer with a cup and four-blade vane geometry (Anton Paar Compact Rheometer, Physica MCR101) was used for viscosity analysis. All viscosity analysis were performed at 25°C.

Microbial determinations in the study were performed via the pour plate method on Endo agar and nutrient agar (APHA, AWWA, WEF, 2018). Triplicate sets of plates were prepared for sludge samples taken during the hydrodynamic cavitation. The inoculated plates were incubated at 37°C. After an incubation period of 24 h, *E. coli* colonies developing on the surface of Endo agar were counted with the aid of a colony counter. *Bacillus subtilis* and *Pseudomonas aeruginosa* colonies developing on the surface of nutrient agar were also counted with the aid of a colony counter.

2.4 Statistical Analysis

All statistical determinations were analyzed with the statistical software of STATISTICA 10 (Statsoft, USA). The effects of cavitation number and cavitation time in the cavitation experiments performed to determine the optimal operating conditions, were determined by two-way ANOVA test. In the disintegration processes carried out to examine the variations in the sludge characteristics created by the cavitation appearance, the influence of the cavitation time was determined by a one-way ANOVA test. When significant effects were indicated by ANOVA, post hoc analysis was performed using Tukey's HSD multiple comparison test.

3. Results and Discussion

3.1 Determination of Optimum Operating Conditions for Hydrodynamic Cavitation

At the initial part of the research, a series of experiments were performed to find the best conceivable operating conditions for hydrodynamic cavitation. In this direction, with reference to the study carried out by Etyam (2017), a 3 mm diameter orifice plate was preferred, where maximum disintegration was achieved for waste-activated sludge. The velocity of the sludge passing through the orifice plate was changed by adjusting the valve on the main line, and thus it was possible to set the cavitation number to 0.3, 0.5, 0.7 and 0.9. For each cavitation number, 16 L of waste-activated sludge was cavitated in the system for 120 minutes. In order to evaluate the cavitation efficiency and to determine the optimum conditions, sludge samples taken every 30 minutes were analyzed for SCOD and STKN content. As can be seen from Table 2, the influences of cavitation number and cavitation time on the concentrations of SCOD and STKN in sludge samples were found to be statistically significant at the $p < 0.001$ level. The interactions between the cavitation number and the cavitation time were also found to be statistically significant ($p < 0.001$).

Figure 3 clearly indicates that hydrodynamic cavitation significantly increased the SCOD and STKN values throughout the study period. Considering the total COD and total TKN values of the sludge (Table 1), it is possible that the particulate forms in the total fraction will continue to transform into soluble

Table 2. Results of Variance Analysis Regarding the Effects of Cavitation Number and Cavitation Time on SCOD and STKN Concentrations of Waste Activated Sludge

Parameter	Variation	MS	dF	$F_{Statistic}$	p
Independent variable: SCOD					
	Cavitation Number (C_v)	301545	3	147095	<0.001
	Cavitation Time (T)	5668489	4	2073837	<0.001
	$C_v \times T$	285741	12	34847	<0.001
	Error	27	40	-	-
Independent variable: STKN					
	Cavitation Number (C_v)	11992	3	6662	<0.001
	Cavitation Time (T)	715211	4	298005	<0.001
	$C_v \times T$	12306	12	1709	<0.001
	Error	24	40	-	-

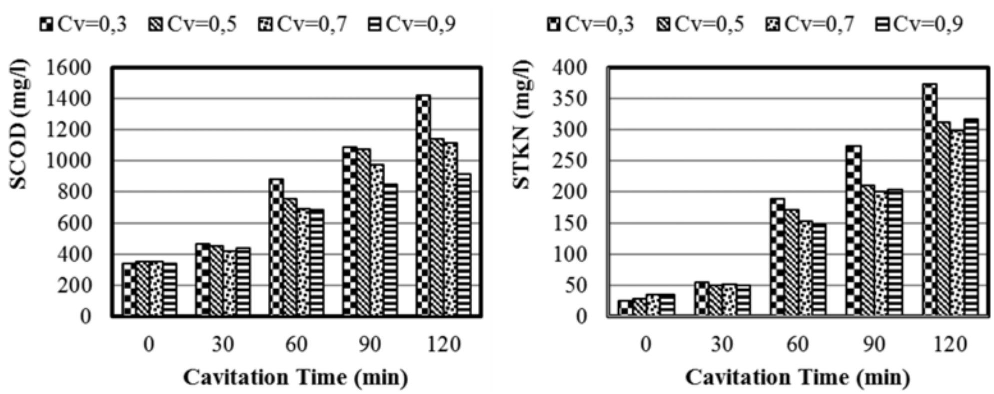

Fig. 3. Changes in SCOD and STKN Concentration of Waste Activated Sludge during Hydrodynamic Cavitation Carried Out at Different Cavitation Numbers

forms with the effect of cavitation applied after 120 minutes. However, the greatest change in quantities occurred after the first 90 minutes of cavitation, with subsequent increases more limited.

The applied hydrodynamic cavitation markedly increased the concentration of SCOD in the sludge in all trials performed at different cavitation numbers (Fig. 3). It was determined that this increase was more pronounced in conditions where the cavitation number was set to 0.3 ($p < 0.001$). After 120 minutes of cavitation, the SCOD concentration in the sludge increased to 1,421 mg/l, 1,138 mg/l, 1,112 mg/l, and 910 mg/l under conditions where the cavitation number was set to 0.3, 0.5, 0.7, and 0.9, respectively. According to the data obtained, the highest cavitation performance in terms of the SCOD parameter was achieved under the conditions where the cavitation number was set to 0.3.

As can be seen in Fig. 3, the variation of STKN concentrations in waste-activated sludge during the cavitation for each cavitation number has a similar trend to the variation of SCOD concentration. The STKN concentration (35 mg/l) in waste-activated sludge increased in all trials with sludge cavitation. Similar to the SCOD results, the increase was more pronounced when the cavitation number was set to 0.3 ($p < 0.001$). After a cavitation period of 120 minutes, STKN values were measured as 374 mg/l, 312 mg/l, 298 mg/l and 317 mg/l under conditions where the cavitation number was adjusted as 0.3, 0.5, 0.7 and 0.9, respectively. Accordingly, the optimal cavitation number in terms of STKN was determined as 0.3.

The effect of cavitation number on process efficiency has also been discussed in other studies. In a study performed by Saharan et al. (2013), it was determined that the optimum cavitation number in wastewater treatment applications varied between 0.15 and 0.25. In another study, the optimal cavitation number was determined as 0.53 for a .2 mm single-hole orifice plate hydrodynamic cavitation reactor. It was also emphasized that under these conditions, more cavities were formed and they collapsed violently to form highly reactive •OH radicals (Randhavane, 2019). In a research conducted by Topaç Şağban et al. (2018), sludge sample was cavitated for 90 minutes in an orifice-induced hydrodynamic cavitation system and several trials were conducted at different cavitation numbers. The results showed that the highest SCOD concentration (1,335 mg/l) was obtained under conditions where the cavitation number was 0.2. Accordingly, it was concluded that a Cv of 0.2 is more effective in increasing the solubility of sludge components.

3.2 Effect of Hydrodynamic Cavitation on Chemical and Biological Properties of Waste-Activated Sludge

In the sludge disintegration studies carried out to examine the variations in the physical and chemical characteristics of waste sludge by cavitation phenomenon, the effect of the cavitation time was determined by a one-way ANOVA test. The results of the statistical tests are presented in Table 3. The consequences of ANOVA clearly indicate that cavitation time has a significant effect on all the measured parameters ($p < 0.001$).

Table 3. Results of Variance Analysis Regarding the Effects of Cavitation Time on Some Physical and Chemical Properties of Waste Activated Sludge

Parameter	Variation	MS	dF	$F_{Statistic}$	p
Independent variable: SCOD					
	Cavitation time	18818074	6	5488605	<0.001
	Error	8	14	-	-
Independent variable: SS					
	Cavitation time	1,1E+08	6	1,6E+07	<0.001
	Error	1,6E+01	14	-	-
Independent variable: VSS					
	Cavitation time	8,2E+07	6	1,2E+07	<0.001
	Error	1,6E+01	14	-	-
Independent variable: Viscosity					
	Cavitation time	0,9096	6	1326	<0.001
	Error	0,0016	14	-	-
Independent variable: STKN					
	Cavitation time	422950	6	123360	<0.001
	Error	8	14	-	-
Independent variable: STP					
	Cavitation time	72980,6	6	21286,0	<0.001
	Error	8,0	14	-	-
Independent variable: *E.Coli*					
	Cavitation time	8,0E+08	6	1,2E+10	<0.001
	Error	1,6E-01	14	-	-
Independent variable: *B.Subtilis*					
	Cavitation time	1,6E+10	6	1,6E+11	<0.001
	Error	2,4E-01	14	-	-
Independent variable: *P.Aeruginosa*					
	Cavitation time	1,4E+10	6	2,1E+11	<0.001
	Error	1,6E-01	14	-	-

3.2.1 Soluble Chemical Oxygen Demand

SCOD is a parameter frequently preferred to assess the efficiency of disintegration techniques. In all disintegration methods applied to waste-activated sludge as a pre-treatment method, it is basically aimed to convert the intracellular and extracellular ingredients in the sludge flocs into soluble forms. The changes in the SCOD

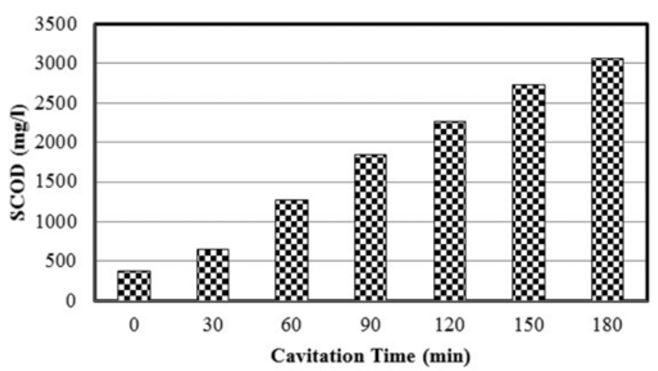

Fig. 4. Changes in SCOD Concentration of Waste Activated Sludge during Hydrodynamic Cavitation

concentration of the waste sludge cavitated in the hydrodynamic cavitation system for 180 minutes under the optimum conditions are presented in Fig. 4.

It is seen that hydrodynamic cavitation markedly caused an increase in the SCOD concentration of the waste-activated sludge (Fig. 4). It was determined that this increase was more pronounced in the first 120 minutes of cavitation. With regard to the end of cavitation period, it was determined that the SCOD concentration, which was initially determined as 382 mg/l, reached 3,068 mg/l levels ($p < 0.001$). The increase in the SCOD concentration depending on the cavitation time clearly reveals that the applied process is effective in increasing the amount of organic matter that passes into soluble form. In waste-activated sludge disintegration trials, the ratio of SCOD/TCOD is evaluated as a measure of the hydrolysis that occurs. Accordingly, alterations in the ratio of SCOD/TCOD were also observed during the hydrodynamic cavitation period. The SCOD/TCOD ratio, which was 0.02 at the beginning of hydrodynamic cavitation, increased depending on the cavitation time and reached 0.18 at the end of the cavitation. The significant increase in this ratio shows that the applied method is effective in increasing the sludge hydrolysis and soluble matter content of the sludge. In a study carried out by Grübel and Machnicka (2010), it was reported that the mechanical forces applied to waste-activated sludge with the hydrodynamic cavitation process disrupted the sludge floc structure, and the organic materials protected by the microbial cell walls passed into the liquid phase and turned into soluble forms. Thus, the SCOD concentration of the waste-activated sludge, which was 42 mg/l, reached 326 mg/l by hydrodynamic cavitation. In a similar study, waste-activated sludge was mechanically disintegrated with an orifice-based hydrodynamic cavitation device. The use of chemical additives (NaOH, H_2O_2 and $Ca(OH)_2$) in combination with hydrodynamic cavitation was also assessed. According to the results, disintegration degrees of 32% to 60% were achieved at the end of the cavitation. It was found that the SCOD/TCOD ratios for the combined treatment of NaOH addition and hydrodynamic cavitation varied between 0.17 – 0.21, while it was 0.15 – 0.22 for the combination of H_2O_2 addition and hydrodynamic cavitation (Topac-Sagban et al., 2018). In the presented study, similar SCOD/TCOD ratios were obtained under Cv 0.3 conditions without the use of any chemicals."

In addition to orifice plate hydrodynamic cavitation, there are also studies examining the effectiveness of different hydrodynamic cavitation designs used for pretreatment of wastewater and waste-activated sludge. Petkovsek et al. (2015) studied the disintegration of waste-activated sludge by using an innovative rotation generator of hydrodynamic cavitation. The results indicated that the initial SCOD concentration of 45 mg/l increased to 602 mg/l by 20 passes through the hydrodynamic cavitation generator. Another study investigated the efficiency of a novel pinned disc rotational generator for hydrodynamic cavitation of waste-activated sludge. The results showed that SCOD in waste sludge increased by 155.8%.

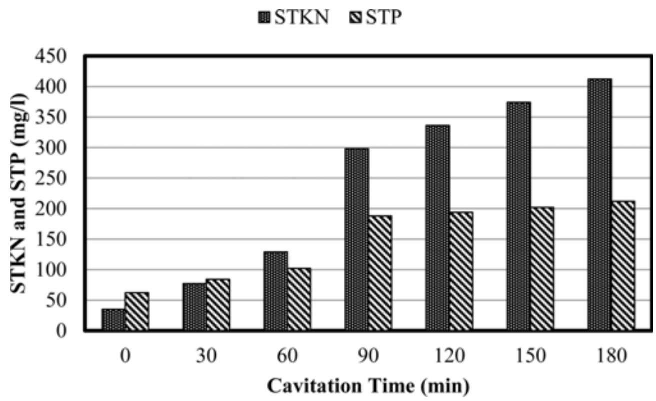

Fig. 5. Changes in STKN and STP Concentration of Waste Activated Sludge during Hydrodynamic Cavitation

3.2.2 Soluble Total Kjeldahl Nitrogen and Soluble Total Phosphorus

The changes in the STKN and STP concentrations of the waste activated sludge disintegrated in the hydrodynamic cavitation system for 180 minutes are presented in Fig. 5. Depending on the cavitation time, the STKN concentration of the waste-activated sludge apparently increased. This increase was more pronounced in the first 90 minutes of cavitation. STKN concentration, which was determined as 35 mg/l at the beginning of cavitation, reached 298 mg/l levels after 90 minutes. It was determined that the STKN concentration, which showed a slight increasing trend after 90 minutes of cavitation, reached 412 mg/l levels at the end of the cavitation time ($p < 0.001$).

Based on these data, it was determined that 64% of the TKN concentration of waste-activated sludge (644 mg/l) was converted into soluble forms by passing into the liquid fraction through the mechanical forces applied to the sludge in hydrodynamic cavitation. This apparent increase in STKN values shows the success of the applied orifice induced hydrodynamic cavitation method in increasing the solubility of the sludge. Therefore, the proposed method has the potential to be used as a pretreatment method that can increase the anaerobic sludge digestion performance.

It is observed that the change in the STP concentration of the waste-activated sludge during the hydrodynamic cavitation period showed a similar trend to the change in the STKN concentration (Fig. 5). The STP concentration, which was determined as 62 mg/l at the beginning, did not show a significant increasing trend until the first 90 minutes of the cavitation. It was determined that it reached 212 mg/l levels at the end of the overall cavitation period ($p < 0,001$). According to the obtained data, it was determined that 60% of the TP concentration of 354 mg/l in waste-activated sludge was converted into soluble forms by the effects of hydrodynamic cavitation.

It has also been emphasized in various studies that soluble forms of nitrogen and phosphorus increase because of the disintegration of flocs and cells in sludge by the cavitation effect. In a study carried out by Dindar et al. (2015), it was found that

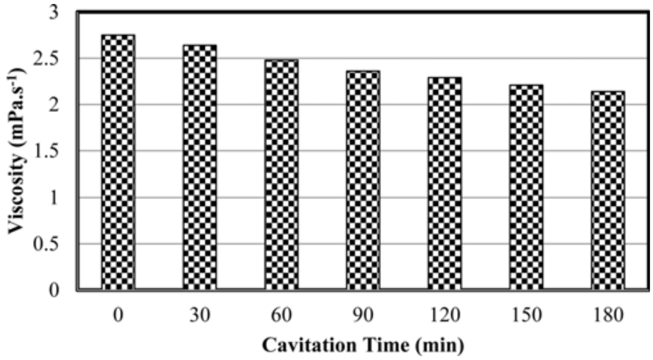

Fig. 6. Changes in Viscosity of Waste Activated Sludge during Hydrodynamic Cavitation

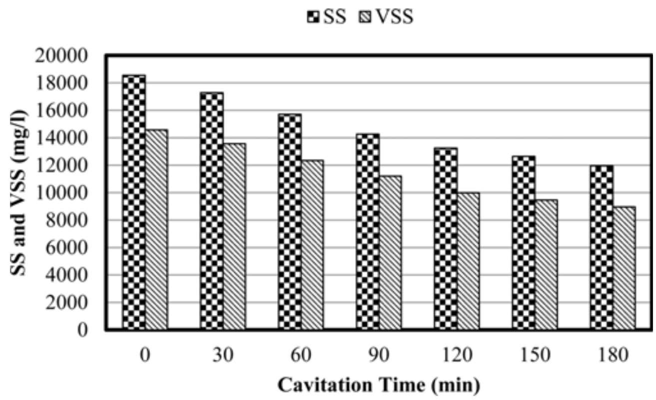

Fig. 7. Changes in SS and VSS Concentration of Waste Activated Sludge during Hydrodynamic Cavitation

hydrodynamic cavitation with orifice plate significantly increased the STKN concentration of waste-activated sludge. Under the conditions where a 3 mm diameter orifice plate was used and the cavitation number was set to 0.2, the STKN concentration of the cavitated sludge increased to 370 mg/l. According to their results, approximately 50% of the nitrogen in the sludge solid phase was converted to soluble forms with the applied process. Similarly, it was reported that NH_4-N and PO_4-P levels in sludge increased during hydrodynamic cavitation regimes, inducing the liberation of extra- and intracellular molecules (Kolbl-Repinc et al., 2022).

3.2.3 Viscosity

The changes in the viscosity of the studied sludge disintegrated in the hydrodynamic cavitation system are presented in Fig. 6. It is seen that the viscosity of the excess sludge decreased depending on the cavitation time and this decrease was more pronounced in the first 120 minutes of the cavitation. The viscosity value, which was 2.75 mPa.s^{-1} at the beginning of cavitation, decreased to 2.14 mPa.s^{-1} at the end of cavitation. The obtained results indicated that the viscosity of the waste-activated sludge decreased by 22% with hydrodynamic cavitation. The decrease in the viscosity of the sludge indicates an increase in its fluidity. Accordingly, the orifice plate hydrodynamic cavitation evaluated in the study can be considered as a pre-treatment alternative that will facilitate the mixing or transport of sludge.

It has been determined in various studies that the disintegration processes applied to sludge reduce the sludge viscosity. In a study examining the effect of hydrodynamic cavitation in a full-scale biogas plant processing agricultural wastes, it was found that the hydrodynamic cavitation process reduced the sludge viscosity by 23 – 27%. It was also stated that the low viscosity caused by hydrodynamic cavitation would facilitate operations such as mixing the sludge in the biogas plant (Garuti et al., 2018). Besides hydrodynamic cavitation, other sludge disintegration processes also reduce the viscosity of the sludge. Bougrier et al. (2006) applied thermal, ultrasound and ozone disintegration processes to waste-activated sludge and determined that the viscosity value of raw sludge decreased to 0.034, 0.009 and 0.014 Pa.s^{-1} by sonication, ozonation and thermal hydrolysis, respectively. Similarly, Ruiz-Hernando et al. (2013) stated that thermal hydrolysis improved the dewaterability of the sludge and reduced the sludge's viscosity by causing cell lysis. Müller et al. (2004) emphasized that the viscosity of waste-activated sludge decreased significantly with the disintegration process and this reduction facilitated the mixing and pumping of the sludge.

3.2.4 Solid Content

To determine the effect of hydrodynamic cavitation on the solid content of the waste-activated sludge, SS and VSS analyses were carried out. The data obtained are presented in Fig. 7. The SS content of the disintegrated sludge showed a decreasing trend depending on the cavitation time. Especially after the first 120 minutes of cavitation, a significant decrease occurred. While SS concentration was 18,550 mg/l at the beginning of cavitation, it decreased to 11,958 mg/l at the end of the cavitation period. These data indicate that the SS concentration of the waste-activated sludge was reduced by 36% by hydrodynamic cavitation.

Sun et al. (2018) investigated the influence of pretreatment by peracetic acid oxidation on the anaerobic digestion of biological sludge. They found that the SS and VSS concentrations of the sludge decreased as the sludge cells were disintegrated during oxidation pretreatment.

In another study, the synergistic effect of hydrodynamic cavitation and disintegration with ozone was investigated (Chanda, 2012). It was determined that hydrodynamic cavitation performed for 90 minutes using a 2 mm diameter orifice plate resulted in a 4% decrease in the sludge SS concentration, while disintegration with ozone using a 35 mg/l O_3 dose resulted in a 19% decrease. As a result of the synergistic effect of both processes, it was stated that there was a 31% decrease in the SS concentration of sludge.

In addition, it was determined that the variation in the VSS content of the waste-activated sludge during the cavitation period had a similar trend to the change in the SS concentration. It was determined that the VSS concentration, which was determined as 14,570 mg/l, decreased to 8,964 mg/l at the end of the cavitation period. The VSS concentration of the waste-activated sludge decreased by 38% with the applied pretreatment method. In a similar study performed by Kim et al. (2019), it was determined that the VSS concentration in waste-activated sludge decreased by approximately 60% with the application of hydrodynamic cavitation. This finding probably indicates that the rotor-stator type hydrodynamic cavitation reactor shows higher oxidation performance than the orifice plate system used in this study.

The VSS/SS ratio determined in waste-activated sludge is used as an index for evaluating the bacterial activity in sludge. When the changes in the VSS/SS ratio during hydrodynamic cavitation are evaluated, it was seen that the initial VSS/SS ratio of 78% decreased to 75% at the end of cavitation. Thus, it can be concluded that a certain part of the sludge becomes more mineralized by the effect of applied hydrodynamic cavitation. It was emphasized in various studies that reductions in the VSS/SS ratio occurred in other disintegration methods. Bougrier et al. (2006) reported that the VSS/SS ratio, which was 78% for raw sludge, decreased to 66% with thermal disintegration. In addition, it was stated that the VSS/SS ratio, which was 78% in raw sludge, decreased to 73% with the disintegration performed at the ozone dose of 0.16 g O_3/g solids.

3.2.5 Microbial Content

The changes in the numbers of *E. coli, Bacillus subtilis* and *Pseudomonas aeruginosa* indicator bacteria in waste-activated sludge samples during the cavitation process are presented in Fig. 8. The initial bacterial counts in waste-activated sludge were

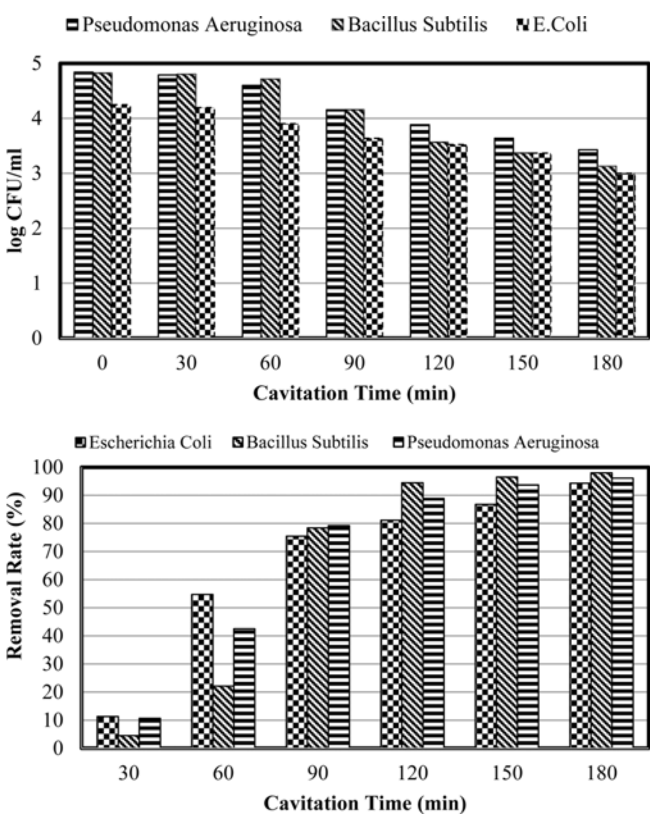

Fig. 8. Changes in the Amount and Removal Rates of *E.coli*, *Bacillus subtilis* and *Pseudomonas aeruginosa* of Waste Activated Sludge during Hydrodynamic Cavitation

4.25, 4.82 and 4.84 log CFU/ml for *E. coli, Bacillus subtilis* and *Pseudomonas aeruginosa*, respectively and the numbers of all three indicator bacteria species decreased depending on the cavitation time. This decrease was evident in the first 60 minutes of cavitation for *E. coli*, and in the first 90 minutes for *Bacillus subtilis* and *Pseudomonas aeruginosa*. After 120 minutes of cavitation, it was identified that there was no considerable alteration in the amounts of *Bacillus subtilis* and *Pseudomonas aeruginosa.* At the end of cavitation, the numbers of *E. coli, Bacillus subtilis* and *Pseudomonas aeruginosa* decreased to 3, 3.12 and 3.43 log CFU/ml, respectively. These data clearly show that hydrodynamic cavitation led to *E. coli, Bacillus subtilis* and *Pseudomonas aeruginosa* inactivation via cell disruption. However, initial removal rate of *Bacillus subtilis* was found to be insignificant compared with *E. coli* and *Pseudomonas aeruginosa*. *Bacillus subtilis* is a gram-positive bacteria species, while *Pseudomonas aeruginosa* and *E. coli* are a gram-negative. The cell wall of gram-negative bacteria is thinner compared to gram-positive bacteria (Mai-Prochnow et al., 2016). Gram-positive bacteria with thicker peptidoglycan cell wall are more resistant to mechanical stress (Hayhurst et al., 2008). Because of this increased resistance compared to other species, the initial removal rate is insignificant (Sarc et al., 2018).

As can be seen from Fig. 8, the most effective removal rates for all three microorganism species were obtained in the first 90 minutes of cavitation. The results of microbial analysis showed that the removal efficiencies obtained by the applied orifice-induced hydrodynamic cavitation process were 94% for *E. coli,* 98% for *Bacillus subtilis* and 96% for *Pseudomonas aeruginosa.*

The disinfection efficiency of hydrodynamic cavitation in water and wastewater has been evaluated in many studies. Mezule et al. (2010) conducted a laboratory study with *E. coli* as a model organism to assess the effect of the hydrodynamic cavitation technique on bacterial viability in drinking water. The results of the study showed that hydrodynamic cavitation is very efficient in preventing the reproduction of *E. coli.* 3 minutes application of hydrodynamic cavitation with an energy input of 490 W/L reduced the ability of *E. coli* to divide by 75%. Similarly, Balasundaram and Harrison (2006) studied the effect of orifice plate-based hydrodynamic cavitation on partial degradation of *E. coli*. According to their results, 40 – 50% of the soluble proteins and enzymes in E. coli were disintegrated with a 400 cycles of cavitation. Moreover the results of their study also showed that *E. coli* cells cultivated at a higher specific growth rate were more easily disrupted by hydrodynamic cavitation than more slowly grown cells. In a similar study conducted by Vitenko and Gashchyn (2014), the results that testify to the disinfection effect of the hydrodynamic cavitation installation of dynamic type were presented. It was reported that the increase of the cavitation impeller speed caused the increase of the *E. coli* inactivation rate. During 14-min treatment under modified Reynolds number of 3 × 105, the initial amount of *E. coli* decreased by 82%, but under modified Reynolds number of 6 × 103, 99% of bacteria were inactivated. Loraine et al. (2012) studied the cavitating jet apparatus for the disinfection of gram-negative *Pseudomonas aeruginosa, Escherichia coli, Klebsiella pneumonia* and *Pseudomonas syringae,* and gram-positive *Bacillus subtilis*. According to their results, hydrodynamic cavitating jets employing several nozzle models to induce cavitation were found to be obviously influential in decreasing the numbers of all bacteria tested. It was reported in another study that the main mechanisms effective in bacteria removal by hydrodynamic cavitation were the shear flow, shock waves, supercritical water conditions, pressure spikes and temperature rises produced by violent collapse of the cavitation bubbles (Dular et al., 2016).

Besides those disinfection studies examining the influence of hydrodynamic cavitation on bacteria in the aquatic environment, there are also some studies examining the bacteria removal efficiency in waste-activated sludge, which is a much more complex medium. In a study by Machnicka et al. (2012), it was aimed to evaluate the evaluate the possible application of nozzle-based hydrodynamic cavitation in the bacteriological hygienization of surplus sludge. It was found that the total number of bacteria decreased by 80% after an exposure of 45 minutes lasting cavitation. Moreover, reduction in the Salmonella population was 100% after the same cavitation period. In a similar study, Kolbl-Repinc et al. (2022) studied the hydrodynamic cavitation performance of an innovative rotary generator with a pin disc. They reported that the mechanical effects of cavitation, such as shear forces and microjets, damaged Epistilys species and yeast cells.

4. Conclusions

The following conclusions can be drawn from the experimental results:

1. The cavitation number (Cv) of 0.3 and the orifice plate hole diameter of 3 mm were determined as optimum operating conditions for the hydrodynamic cavitation system used for the disintegration of excess sludge produced in the wastewater treatment facility of a food and beverage manufacturing factory.
2. Hydrodynamic cavitation is effective in increasing the amount of organic matter in soluble form, which is confirmed by the evident increases in the concentration of SCOD, STKN and STP. SCOD concentration of waste-activated sludge, which was determined as 382 mg/l at the beginning of hydrodynamic cavitation, reached 3,068 mg/l levels. It was determined that 64% of the TKN concentration and 60% of the TP concentration of the waste-activated sludge were converted into soluble forms by the applied method. It is thought that this increase in the soluble organic matter content of waste-activated sludge may positively affect the anaerobic digestion performance and biogas yield of the sludge.
2. The SS and VSS concentrations of the waste-activated sludge were reduced by 36% and 38%, respectively, by hydrodynamic cavitation. The VSS/SS ratio decreased from 78% to 75%. The viscosity of waste-activated sludge, which was determined as 2.75 mPa.s^{-1} at the beginning of hydrodynamic cavitation, decreased by 22%. Accordingly, it is predicted that the increased fluidity of waste-activated sludge will facilitate mixing and pumping processes.
3. The obtained data show that orifice-induced hydrodynamic cavitation is effective in removal of bacteria found in waste-activated sludge. The removal rates of *Escherichia coli*, *Pseudomonas aeruginosa* and *Bacillus subtilis* indicator bacteria varied between 94% and 99%.

The principal objective of this investigation was to ascertain alterations in certain characteristics of sludge subsequent to processing with an orifice plate hydrodynamic cavitation system. Furthermore, the intent was to elucidate the viability of employing this technique as a pre-treatment method for sludge. As a consequence, the comprehensive evaluation of the study confirmed that orifice-based hydrodynamic cavitation is an auspicious sludge pretreatment technology that can improve anaerobic digestion efficiency, facilitate mixing and pumping operations, and support sludge disinfection.

The following suggestions were presented for future work: 1) Numerous research on the synergistic effect and mechanism between hydrodynamic cavitation and other disintegration methods is needed. It is predicted that combined methods will increase the disintegration effectiveness. 2) Most of the studies on hydrodynamic cavitation are at laboratory scale. It is necessary to investigate the applicability of hydrodynamic cavitation on an industrial scale. 3) Studies should not only determine the effect of hydrodynamic cavitation on the microbial content of waste activated sludge, but studies that determine its effect on various micropollutants should be encouraged. 4) During the studies, parameters such as electricity consumption, water consumption and maintenance costs etc. can be monitored to obtain an idea about the energy consumption of the hydrodynamic cavitation system. Nowadays, when natural resource consumption is constantly increasing, it is very important to calculate the total amount of energy consumed in further studies. 5) As the outlet pressure of the HC devices also affects the cavitation behavior, studies should be carried out to determine the outlet pressure or the ration of inlet pressure and outlet pressure.

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References

APHA, AWWA, WEF (2018) Standart methods for the examination of water and wastewater. American Public Health Association, Baltimore, USA

Arrojo S, Benito Y (2008) A theoretical study of hydrodynamic cavitation. *Ultrasonics Sonochemistry* 15:203-211, DOI: 10.1016/j.ultsonch.2007.03.007

Albanese L, Baronti S, Liguori F, Meneguzzo F, Barbaro P, Vaccari FP (2019) Hydrodynamic cavitation as an energy efficient process to increase biochar surface area and porosity: A case study. *Journal of Cleaner Production* 210:159-169, DOI: 10.1016/j.jclepro.2018.10.341

Balasundaram B, Harrison ST (2006) Study of physical and biological factors involved in the disruption of *E. coli* by hydrodynamic cavitation. *Biotechnology Progress* 22(3):907-913, DOI: 10.1021/bp0502173

Bhat AP, Gogate PR (2021) Cavitation-based pretreatment of wastewater and waste sludge for improvement in the performance of biological processes: A review. *Journal of Environmental Chemical Engineering* 9(2):104743, DOI: 10.1016/j.jece.2020.104743

Bougrier C, Albasi C, Delgenes JP, Carrere H (2006) Effect of ultrasonic, thermal and ozone pre-treatments on waste activated sludge solubilisation and anaerobic biodegradability. *Chemical Engineering and Processing: Process Intensification* 45(8):711-718, DOI: 10.1016/j.cep.2006.02.005

Bremner JM, Mulvaney CS (1982) Nitrogen-total. In: Page AL (ed) Methods of soil analysis, Part 2. Chemical and microbiological properties. SSSA, ASA, Madison, Madison, WI, 595-622

Chanda SK (2012) Disintegration of sludge using ozone-hydrodynamic cavitation. MSc Thesis, Faculty of Graduate Studies (Civil Engineering), The University of British Columbia, Vancouver, Canada

Demir E (2019) The effect of hydrodynamic cavitation on biogas efficiency in anaerobic digestion of sewage sludges. MSc Thesis, Bursa Uludağ University, Graduate School of Natural and Applied Sciences, Department of Environmental Engineering, Bursa (in Turkish)

Dindar E, Topaç Şağban FO, Baskaya HS (2015) Variations of soil enzyme activities in petroleum-hydrocarbon contaminated soil. International *Biodeterioration & Biodegradation* 105:268-275, DOI: 10.1016/j.ibiod.2015.09.011

Dular M, Griessler Bulc T, Gutierrez Aguirre I, Heath E, Kosjek T, Klemencic AK, Oder M, Petkovsek M, Racki N, Ravnikar M, Sarc A, Sirok B, Zupanc M, Žitnik M, Kompare B (2016) Use of hydrodynamic cavitation in (waste)water treatment. *Ultrasonics Sonochemistry* 29:577-588, DOI: 10.1016/j.ultsonch.2015.10.010

Etyam C (2017) Disintegration of waste activated sludge by hydrodynamic cavitation assisted methods. MSc Thesis, Bursa Uludağ University, Graduate School of Natural and Applied Sciences, Department of Environmental Engineering, Bursa (in Turkish)

Garlicka A, Zubrowska-Sudol M, Umiejewska K, Roubinek O, Palige J, Chmielewski A (2020) Effects of thickened excess sludge pre-treatment using hydrodynamic cavitation for anaerobic digestion. *Energies* 13(10):2483, DOI: 10.3390/en13102483

Garuti M, Langone M, Fabbri Piccinini S (2018) Monitoring of full-scale hydrodynamic cavitation pretreatment in agricultural biogas plant. *Bioresource Technology* 247:599-609, DOI: 10.1016/j.biortech.2017.09.100

Gogate PR, Pandit AB (2001) Hydrodynamic cavitation reactors: A state of the art review. *Reviews in Chemical Engineering* 17(1):1-85, DOI: 10.1515/REVCE.2001.17.1

Gogate PR, Patil PN (2015) Combined treatment technology based on synergism between hydrodynamic cavitation and advanced oxidation processes. *Ultrasonics Sonochemistry* 25:60-69, DOI: 10.1016/j.ultsonch.2014.08.016

Grübel K, Machnicka A (2010) Hydrodynamic disintegration of foam biomass to upgrade of wastewater. *The Journal of Society of Ecological Chemistry and Engineering* 17(2):137-148

Hayhurst EJ, Kailas L, Hobbs JK, Foster SJ (2008) Cell wall peptidoglycan architecture in Bacillus Subtilis. *Proceedings of the National Academy of Sciences U.S.A.* 105:14603-14608, DOI: 10.1073/PNAS.0804138105

Hilares RT, dos Santos JC, Ahmed MA, Jeon S, da Silva SS, Han JI (2016) Hydrodynamic cavitation-assisted alkaline pretreatment as a new approach for sugarcane bagasse biorefineries. *Bioresource Technology* 214:609e614, DOI: 10.1016/j.biortech.2016.05.004

Joshi RK, Gogate PR (2012) Degradation of dichlorvos using hydrodynamic cavitation based treatment strategies. *Ultrasonics Sonochemistry* 19(3):532-539, DOI: 10.1016/j.ultsonch.2011.11.005

Keeney DR, Nelson DW (1982) Nitrogen-inorganic forms. In: Page AL (ed) Methods of soil analysis, Part 2. Chemical and microbiological properties. SSSA, ASA, Madison, WI, 643-693

Kim H, Sun X, Koo B, Yoon JY (2019) Experimental investigation of sludge treatment using a rotor-stator type hydrodynamic cavitation reactor and an ultrasonic bath. *Processes* 7:790, DOI: 10.3390/pr7110790

Kolbl-Repinc S, Bizjan B, Budhiraja V, Dular M, Gostiša J, Brajer Humar B, Kaurin A, Kržan A, Levstek M, Arteaga JFM, Petkovše M, Rak G, Stres B, Širok B, Žagar E, Zupanc M (2022) Integral analysis of hydrodynamic cavitation effects on waste activated sludge characteristics, potentially toxic metals, microorganisms and identification of microplastics. *Science of the Total Environment* 806(4):151414, DOI: 10.1016/j.scitotenv.2021.151414

Loraine G, Chahine G, Hsiao CT, Choi JK, Aley P (2012) Disinfection of gram-negative and gram-positive bacteria using dynajets hydrodynamic cavitating jets. *Ultrasonics Sonochemistry* 19(3):710-717, DOI: 10.1016/j.ultsonch.2011.10.011

Machnicka A, Grübel K, Rusin A (2012) Hygienisation of surplus activated sludge by hydrodynamic cavitation. *Ecological Chemistry and Engineering S* 19(3):415-421, DOI: 10.2478/v10216-011-0031-x

Machnicka A, Grübel K, Suschka J (2009) The use of hydrodynamic disintegration as a means to improve anaerobic digestion of activated sludge. *Water SA* 35(1):129-132, DOI: 10.4314/wsa.v35i1.76715

Mai-Prochnow A, Clauson M, Hong J, Murphy AB (2016) Gram positive and gram negative bacteria differ in their sensitivity to cold plasma. *Scientific Reports* 6:38610, DOI: 10.1038/srep38610

Mancuso G, Langone M, Andreottola G (2017) A swirling jet-induced cavitation to increase activated sludge solubilisation and aerobic sludge biodegradability. *Ultrasonics Sonochemistry* 35:489-501, DOI: 10.1016/j.ultsonch.2016.11.006

Mancuso G, Langone M, Di Maggio R, Toscano A, Andreottola G (2021) Effect of hydrodynamic cavitation on flocs structure in sewage sludge to increase stabilization for efficient and safe reuse in agriculture. *Bioremediation Journal* 41-52, DOI: 10.1080/10889868.2021.1900055

Mezule L, Tsyfansky S, Yakushevich V, Juhnaa T (2010) A simple technique for water disinfection with hydrodynamic cavitation: effect on survival of *Escherichia coli*. *Desalination* 251:152-159, DOI: 10.1016/j.desal.0000.00.000

Mishra KP, Gogate PR (2010) Intensification of degradation of Rhodamine

B using hydrodynamic cavitation in the presence of additives. *Separation and Purification Technology* 75:385-391, DOI: 10.1016/j.seppur.2010.09.008

Müller JA, Winter A, Strünkmann G (2004) Investigation and assessment of sludge pre-treatment processes. *Water Science and Technology* 49(10):97-104, DOI: 10.2166/wst.2004.0618

Patil PN, Bote SD, Gogate PR (2014) Degradation of Imidacloprid using combined advanced oxidation processes based on hydrodynamic cavitation. *Ultrasonics Sonochemistry* 21(5):1770-1777, DOI: 10.1016/j.ultsonch.2014.02.024

Petkovšek M, Mlakar M, Levstek M, Stražar M, Širok B, Dular M (2015) A novel rotation generator of hydrodynamic cavitation for waste activated sludge disintegration. *Ultrasonics Sonochemistry* 26:408-414, DOI: 10.1016/j.ultsonch.2015.01.006

Randhavane SB (2019) Comparing geometric parameters of a hydrodynamic cavitation process treating pesticide effluent. *Environmental Engineering Research* 24(2):318-323, DOI: 10.4491/eer.2018.227

Ruiz-Hernando M, Martinez-Elorza G, Laband J, Llorens J (2013) Dewaterability of sewage sludge by ultrasonic, thermal and chemical treatments. *Chemical Engineering Journal* 230:102-110, DOI: 10.1016/j.cej.2013.06.046

Saharan VK, Rizwani MA, Malani AA, Pandit AB (2013) Effect of geometry of hydrodynamically cavitating device on degradation of orange-G. *Ultrasonics Sonochemistry* 20(1):345-353, DOI: 10.1016/j.ultsonch.2012.08.011

Sarc A, Kosel J, Stopar D, Oder M, Dular M (2018) Removal of bacteria legionella pneumophila, escherichia coli, and bacillus subtilis by (super)cavitation. *Ultrasonics Sonochemistry* 42:228-236, DOI: 10.1016/j.ultsonch.2017.11.004

Setyawan, M, Mulyono, P, Sutijan, Harun, R, Budiman, A (2022) Mathematical modeling of hydrodynamic cavitation as low energy extraction technique to remove lipid from nannochloropsis sp. *Frontiers in Renewable Energy (FREE)* 1:1-12, DOI: 10.22146/free.v1i1.3312

Sun D, Qiao M, Xu Y,Ma C, Zhang X (2018) Pretreatment of waste activated sludge by peracetic acid oxidation for enhanced anaerobic digestion. *Environmental Progress & Sustainable Energy* 37(6):2058-2062, DOI: 10.1002/ep.12896

Topaç FO, Etyam C (2021) Biostimulating effects of disintegrated waste activated sludge on soil enzyme activities. *KSCE Journal of Civil Engineering* 25(7):2360-2368, DOI: 10.1007/s12205-021-1499-2

Topaç Şağban FO, Dindar E, Çırakoğlu C, Keskinler B (2018) Hydrodynamic cavitation of waste-activated sludge. *Environmental Engineering Science* 35(8):775-784, DOI: 10.1089/ees.2016.0408

Wang B, Su H, Zhang B (2021) Hydrodynamic cavitation as a promising route for wastewater treatment - A review. *Chemical Engineering Journal* 412:128685, DOI: 10.1016/j.cej.2021.128685

Vitenko T, Gashchyn O (2014) Mechanism and kinetic regularities of inactivating effects of cavitation on microorganisms. *Chemistry and Chemical Technology* 8(4):431-440, DOI: 10.23939/chcht08.04.431

Vranitzky R, Lahnsteiner J (2005) Sewage sludge disintegration using ozone - A method of enhancing the anaerobic stabilization of sewage sludge. Va Tech Wabah, R&D Process Engineering, Siemensstrasse 89, Vienna, Austria

Zupanc M, Pandur Z, Perdih TS, Stopar D, Petkovsek M, Dular M (2019) Effects of cavitation on different microorganisms: The current understanding of the mechanisms taking place behind the phenomenon. A Review and Proposals for Further Research. *Ultrasonics Sonochemistry* 57:147-165, DOI: 10.1016/j.ultsonch.2019.05.009