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Challenges of Hydrodynamic Cavitation of Organic Wastes

Aleksandra Szaja *, Agnieszka Montusiewicz and Magdalena Lebiocka

Faculty of Environmental Engineering, Lublin University of Technology, Nadbystrzycka 40B, 20-618 Lublin, Poland
* Correspondence: a.szaja@pollub.pl; Tel.: +48-81-538-40-08; Fax: +48-81-538-19-97

Abstract: The aim of this study was to evaluate the effectiveness of hydrodynamic cavitation (HC) as a pre-treatment method for selected organic wastes. In these HC experiments, municipal wastewater (MW) and mature landfill leachate (MLL) as well as mixtures of lignocellulosic waste (LB) suspended in these waste streams were investigated. For all HC tests, the same operational parameters were assumed: an inlet pressure of 7 bar, and 30 recirculations through the cavitation zone. A steel orifice plate with a conical concentric hole of 3/10 mm was used as the HC inductor. In almost all the materials analysed, solubilisation and decomposition of complex organic matter were observed, which were confirmed by an improved biodegradability index (BI) and soluble chemical oxygen demand (SCOD) content in the cavitated mixtures. The exception was the series with sole MW; in this case, the BI was reduced. In turn, regarding the multicomponent mixtures, more beneficial results were found for LB and MW, which were confirmed by improved BI, alkalinity and SCOD content. The results obtained indicate that HC might be applied as a pre-treatment method for selected organic wastes for further biomethane production. However, a key factor in its successful application is the selection of suitable operational conditions chosen individually for each waste type.

Keywords: hydrodynamic cavitation; municipal wastewater; mature landfill leachate; lignocellulosic waste; biodegradability index; anaerobic digestion

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1. Introduction

Currently, the rapid population rise and related increased food demand are leading to the progressive development of the agricultural sector. It is recognised as a significant contributor of anthropogenic global warming, as well as a source of substantial amounts of organic wastes [1]. It should also be pointed out that agricultural production is responsible for 90% of global freshwater and 30% of global energy consumption [2]. Importantly, the majority of its energetic demand is met from non-renewable sources [3]. Therefore, to reduce its harmful impact on environment, sustainable solutions should be applied in this sector.

In recent years, hydrodynamic cavitation (HC) has proven its effectiveness in many fields [4–6]. It has been widely applied in water and wastewater treatment to remove bio-refractory compounds, such as pharmaceuticals, dyes, pesticides, pharmaceuticals, organic sulfide, phenol, cyanide, bitumen, oil and grease, fuel and chlorocarbon [7]. It has been commonly used as a disinfection method [8] and in landfill leachate treatment [9]. Moreover, HC has been also employed in many industrial applications, e.g., biodiesel generation [10], active compound extraction [11] as well as food production [12]. It has been used as pre-treatment method with lignocellulosic biomass, waste activated sludge, chitosan and alga. However, compared with other emerging technologies (microwave, ultrasound, gamma ray, and pulsed electric field) there is a limited number of studies in this area. Despite the recent progress in this field, many mechanisms within HC are still not well understood [8].

HC involves the formation, sequential growth and collapse of microbubble cavities, occurring when the local liquid pressure drops below the saturated vapour pressure.

Large magnitudes of energy are released over a very small location. The emerging high temperature of 5000–10,000 K and pressure of 1000–2000 atm initiate various physical processes and chemical reactions. Additionally, this phenomenon is also accompanied by the formation of free radicals that may accelerate the chemical reactions or/and influence their mechanisms [4,6,8]. Due to its complexity and multi-stage nature, it is difficult to estimate the effect of cavitation on the removal of a given pollutant [5]. Therefore, each case should be considered individually. Many factors may influence the results of HC, such as type of cavitating reactor, operating inlet pressures, cavitation number, temperature, pH as well as the initial concentration of the pollutant. Moreover, the physicochemical properties of the applied liquid, including its vapour pressure, viscosity and surface tension, play a key role [6,7,13,14].

Additional factors should be considered when HC is applied as a pre-treatment method for lignocellulosic waste (LB). In this process there may be more difficulties and disturbances compared with HC of sole liquids. In this case, additional aspects should be considered, e.g., the characteristics of the treated biomass. Nonetheless, the crucial factor is the applied liquid (carrier) in which the solid waste is suspended [6]. With the aim of ensuring sustainable development, the utilisation of waste streams for this purpose is highly recommended. The application of an inappropriate carrier could possibly lead to secondary pollution caused by the toxic products generated within HC. This concern may limit the subsequent use of pre-treated lignocellulosic biomass [12,15].

Another limiting factor is the dry matter content in the cavitated mixture (solid/liquid ratio, S/L ratio). Depending on the construction of cavitation reactor, the characteristics of the treated biomass and operational parameters, the typical dry matter content varies between 1 and 16% [16,17]. Importantly, previous studies indicate that low-solid loading (<5% solids, *w*/*w*) allowed for higher efficiency in terms of destruction of refractory compounds. This effect is achieved mainly due to the high mass transfer rate and mixing effect [13]. Nevertheless, the average (5–15% solids, *w*/*w*) and high solid loadings (≥15% solids, *w*/*w*) are more profitable because of lower energy consumption [6,15,16]. Taking into the consideration these issues, the HC of LB is still challenging; therefore, thorough studies in this field should be conducted.

The current geopolitical situation and the energy crisis are drawing attention to the possible application of various organic wastes in the anaerobic digestion process (AD) [18]. Especially the problem of effective application of lignocellulosic biomass is an urgent topic, mainly due to large quantities of these by-products generated globally [8]. It should be noted that many of the materials in this group include agricultural by-products. However, mainly due to its complex hierarchical structure and the recalcitrant nature of LB, its effective anaerobic bioconversion is still difficult and problematic. The challenges include low biogas yields, the instability of the process, as well as poor quality of the digestate [19]. Therefore, the appropriate selection of the pre-treatment method is a key factor to enable the effective utilisation and valorisation of LB prior to its conversion in biological processes [20].

It should be noted that compared with other water/waste-water treatment technologies, HC presents several advantages, such as simple device design and easy operation, relatively low energy consumption, and a lack of reagent dosing [12,21]. Additionally, this oxidation technique might be easily combined with conventional and well-recognised technologies typically applied in waste management and wastewater treatment.

This study presents the experiences in the field with the application HC as a pre-treatment method for selected organic wastes. In the experiments, the sole waste streams included municipal wastewater (MW) and mature landfill leachate (MLL) as well as their multicomponent mixtures with lignocellulosic biomass. The influence of HC was evaluated on the basis of biodegradability index (BI) and parameters crucial in the AD process. To date, such a comparative and multifaceted investigation has not yet been conducted. Moreover, it should be emphasised that previous studies in the field application HC as a pre-treatment method of LB included additional alkaline/acid processes or even enzymatic methods that could also increase the operational costs of such technologies [8]. The studies concerning waste streams are not common. The presented results are particularly important in the context of the practical use of this technology. This method might be considered as a cost effective and environmental technology that can be easily implemented at existing facilities, such as biogas or wastewater treatment plants. It has the potential to improve their energy balance, thereby allowing more effective management and exploitation of the energetic potential of selected organic wastes, especially lignocellulose biomass.

2. Materials and Methods

2.1. Characteristic of Substrates

Three substrates were used in the present study: MW, MLL and LB represented by brewery spent grain.

The first component was sourced from the Hajdów municipal wastewater treatment plant with an average flow of 120,000 m^3/d (Lublin, Poland) involving mechanical and biological steps. This sample of 35 L was taken after mechanical treatment from the effluent of the primary settling tank.

The MLL sample originated from the municipal solid waste landfill located in Rokitno (Lublin, Poland). This facility has been operated for over 20 years and is used for disposal of non-hazardous municipal solid waste from residential urban areas. The total area of this landfill is over 38 ha. A 35 L sample was taken from a leachate storage tank.

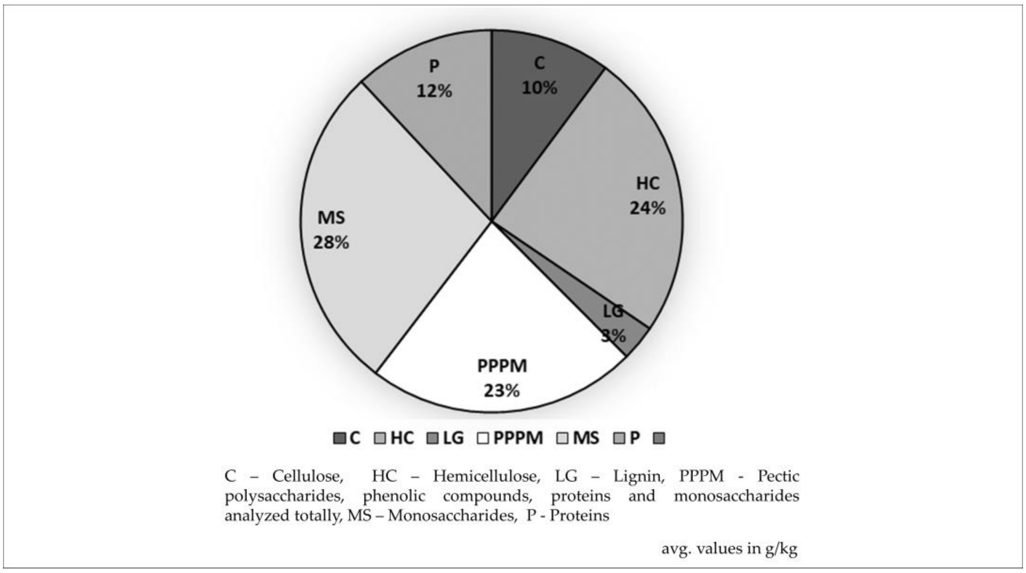
In the present study, brewery spent grain was adopted as LB. It was obtained from a craft brewery situated in Lublin (Poland) using barley for beer production. It was used in fresh form and was only milled to obtain a particle size of 2 mm.

After collection, all the samples used in the present study were immediately transported to the laboratory. For each HC, new portions of substrates were taken; their composition was estimated after each subsample collection. The detailed characteristic of all the substrates is presented in Table 1, and the composition of LB is presented in Figure 1.

Table 1. Characteristics of substrates (average values and standard deviation).

Parameter	Unit	Lignocellulosic Waste (LB)	Municipal Wastewater (MW)	Mature Landfill Leachate (MLL)
Chemical oxygen demand (COD)	mg/L	323.3 ± 8.1 *	533.5 ± 52	6095 ± 62.9
Soluble chemical oxygen demand (SCOD)	mg/L		471 ± 40	4736 ± 48.9
Biological oxygen demand (BOD_5)	mg/L		256.9 ± 12	263 ± 19.8
Total organic carbon (TOC)	g/kg	46.2 ± 1.1	1792	
Biodegradability Index (BI)	-		0.4760 ± 0.03	0.0435 ± 0.01
Total solids (TS)	g/kg	235.1 ± 5.4	0.8 ± 0.02	14.5 ± 0.04
Volatile solids (VS)	g/kg	228.6 ± 4.3	0.62 ± 0.01	3.25 ± 0.7
Alkalinity (ALK)	mg/L		526 ± 47	14573 ± 329
pH	-		7.42 ± 0.07	8.09 ± 0.05
Volatile fatty acids (VFA)	mg/L		158.9 ± 27	1171 ± 49
Total nitrogen (TN)	mg/L		79 ± 5	3552 ± 167
Total phosphorus (TP)	mg/L		21.4 ± 2.1	20.8 ± 2.3
Ammonium nitrogen ($N\text{-}NH_4^+$)	mg/L		58 ± 2.2	1888 ± 150
Ortho-phosphate phosphorus ($P\text{-}PO_4^{3-}$)	mg/L		17.1 ± 1.2	22.5 ± 1.5
Phenols	g/kg TS	0.24 ± 0.01		

* g/kg.



C – Cellulose, HC – Hemicellulose, LG – Lignin, PPPM - Pectic polysaccharides, phenolic compounds, proteins and monosaccharides analyzed totally, MS – Monosaccharides, P - Proteins

avg. values in g/kg

Figure 1. The composition of LB used in the experiment.

2.2. Operational Set Up and Laboratory Installation

In the present study, four experimental series were conducted. In the first two, the HC of sole carriers (MW and MLL) were investigated. In the remaining series, the HC of LB suspended in MW or MLL was examined. The same operational parameters were used in all the experiments. The HC employed 30 recirculations through the cavitation zone, and the inlet pressure was maintained at 7 bar. A steel orifice plate with a conical concentric hole of 3/10 mm (inlet/outlet diameter) was employed as the HC inductor. The estimated cavitation numbers are presented in Table 2. HC was conducted for 30 min. For the HC of multi-component mixtures, 900 g of wet LB was suspended in 30 L of applied medium to maintain as S/L ratio of 1%. Each experimental series was repeated three times under the same operational conditions. The adopted operational parameters as well as HC inductor were selected based on previous experiences regarding improving the biodegradability of various organic wastes [22]. It should be pointed out that optimization study it is not included in the scope of this research. The results presented in the tables and figures are average values.

Table 2. The experimental set-up with detailed operational parameters.

Mixture Composition	Cavitation Number Cv [-]	Orifice Velocity v_o [m/s]	Fully Recovered Downstream Pressure p2 [Pa]	Flow Rate Q [L/s]
MW	0.032	77.38	95879	0.547
MLL	0.033	75.44	95821	0.533
LB + MW	0.036	72.15	95879	0.513
LB + MLL	0.039	69.32	95821	0.492

The main elements of the laboratory installation included a HC reactor, a circulation tank with an active volume of 30 L, a centrifugal pump (maximum operating pressure of 16 bar, variable speed of 1000–3000 rpm and power rating of 2.2 kW) and connecting pipes with control valves. To monitor the HC, the installation was additionally equipped with a manometer, an electromagnetic flow meter (0.05 L/min resolution) and piezoelectric pressure gauges. The data was collected and archived by a computer unit. The scheme of the device is shown in Figure 2.

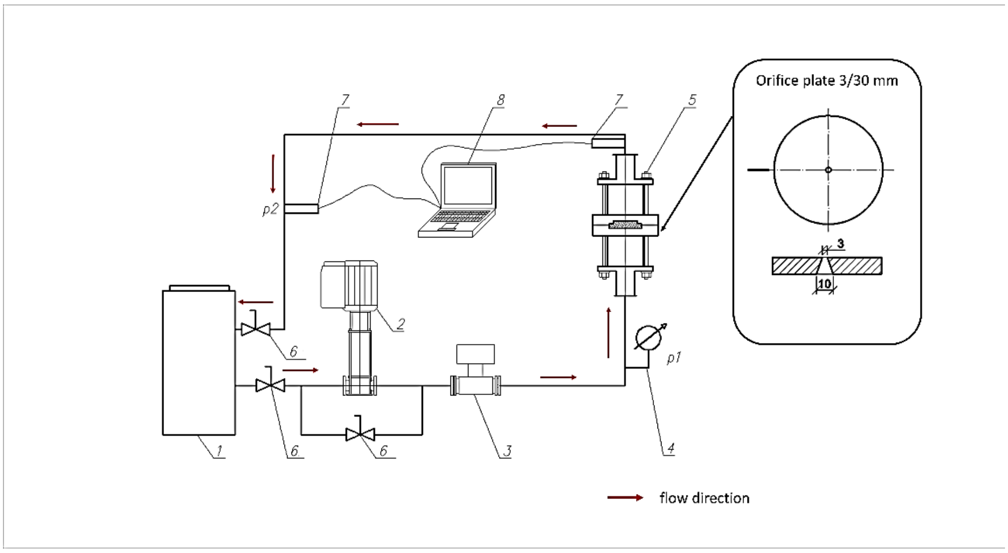


Figure 2. Scheme of laboratory installation 1—circulation tank, 2—pump, 3—electromagnetic flow meter, 4—manometer, 5—cavitation reactor, 6—valve, 7—piezoelectric pressure gauges, 8—computer unit.

The HC was operated in a closed loop arrangement. The operating principle was as follows: the cavitated medium was pumped from circulation tank, then it was discharged to the HC reactor using connecting pipes, and subsequently it was returned to the tank.

2.3. Analytical Methods

In the present study, to estimate the changes that occurred within HC, the characteristics of substrates before and after cavitation was also analysed. In all cases, the analogous parameters were examined: total chemical oxygen demand (COD), soluble chemical oxygen demand (SCOD), biochemical oxygen demand (BOD_5), total solids (TS), volatile solids (VS), volatile fatty acids (VFA), alkalinity (ALK), as well as pH. Moreover, the composition of the applied materials was determined after each delivery. In this case, total nitrogen (TN), total phosphorus (TP), ammonium nitrogen (NH_4^+-N), as well as ortho-phosphate phosphorus (PO_4^{3-}-P) were additionally estimated. The SCOD, VFA, ALK, NH_4^+-N and PO_4^{3-}-P were analysed in the supernatant obtained by filtering the sample through a 0.45 μL pore-size filter. Most of the analyses were performed using a Hach Lange UV–VIS DR 3900 (Hach, Loveland, CO, USA) and standard cuvette tests appropriate for the given parameter. In turn, the TS and VS contents were determined using the Standard Methods for the Examination of Water and Wastewater [23] (APHA, 2005). The pH values were measured with an electronic pH meter CP-501 (ELMETRON, Poland). TOC was determined using a Shimadzu TOC-5050A total organic carbon analyser. Additionally, in LB the following fibre fractions were analysed: cellulose (C), hemicellulose (HC), lignin (L), pectic polysaccharides, phenolic compounds, proteins and monosaccharides (analysed totally, marked as PPPM), monosaccharides (MS), and proteins (P). They were established by means of a modified Van Soest method [24]. This method involves the application of two detergents: neutral (sodium dodecyl sulfate, EDTA, pH 7.0) and acidic (cetyltrimethyl ammonium bromide in 1 N H_2SO_4).

BI was also investigated and was established as the BOD_5/COD ratio. The cavitation number was calculated using the Equation (1):

$$Cv = (p2 - pv)/(0.5\varrho v_o{}^2), \quad (1)$$

where p2 is the fully recovered downstream pressure, pv is the vapor pressure of the liquid, ϱ is the liquid density, and v_o is the orifice velocity. The applied orifice plate was characterized by a total area of holes of 7.0686 mm^2. The piezoelectric pressure gauges (Keller

PR–33X, resolution of 1 mbar) were used to measure the fully recovered down-stream pressure (p2). This sensor was located in the expansion zone of the cavitation inducer.

3. Results and Discussion

3.1. Characteristic of Mixtures Applied in HC

In the present study, four mixtures with differing properties were used in HC. The results are presented in Tables 1 and 3, as well as in Figure 3. MW and MLL were used as sole waste streams. The MW sample presented a typical composition for municipal wastewater after mechanical treatment. Compared with the other mixtures in the study, it was characterised by a high BI index as well as low contents of COD, SCOD, TS, VS and VFA. In turn, MLL had a composition as expected for a mature leachate characterised by high alkalinity and a low BI (<0.1) [25]. Moreover, this side stream showed high VFA, COD and N-NH_4^+ contents, typically observed for earlier stage of decomposition of landfill [26]. The high concentrations of VFA and N-NH_4^+ might be especially problematic for AD of this substrate [27,28]. An additional factor that might limit the further use of this substrate in biological processes is a significant content of recalcitrant organic matter, which is also confirmed by the low BI (Table 1).

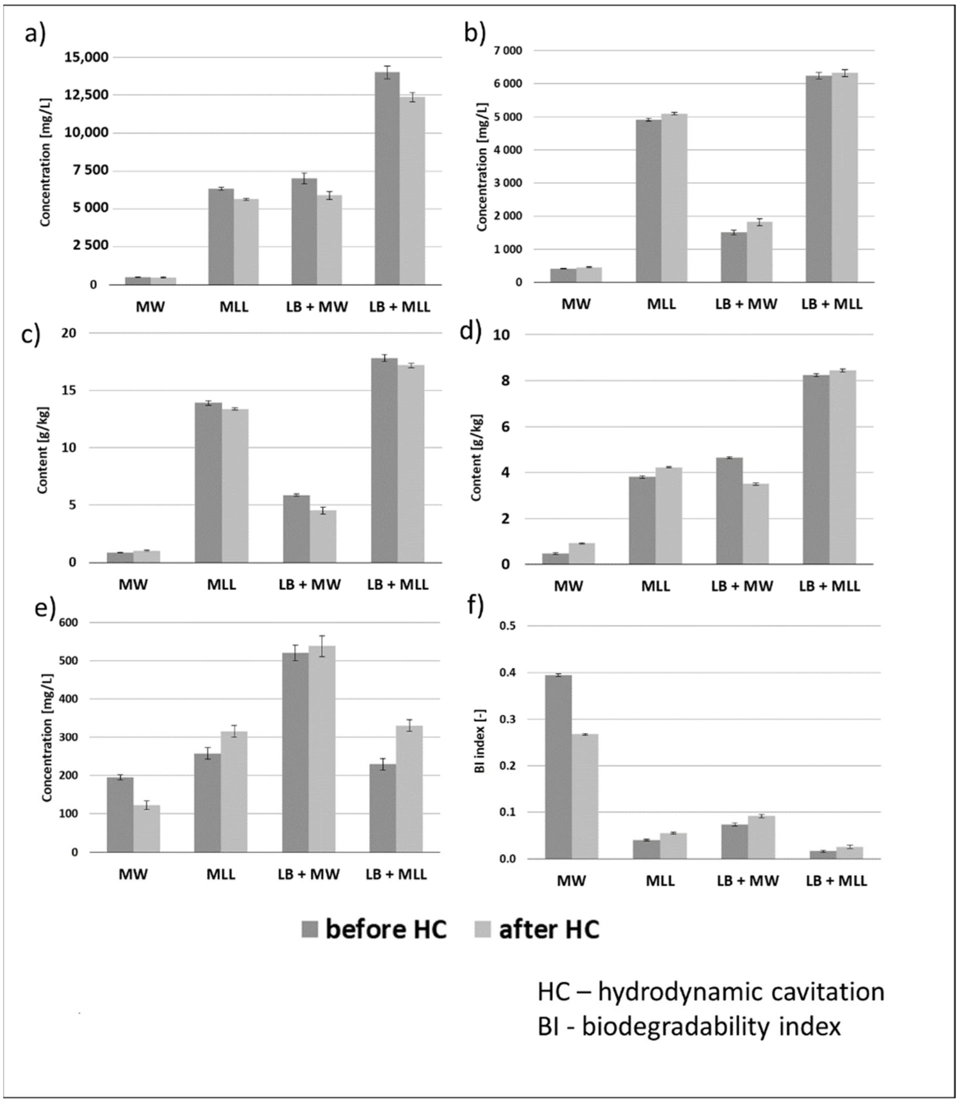


Figure 3. Mixture composition before and after cavitation: (**a**) COD; (**b**) SCOD; (**c**) TS; (**d**) VS; (**e**) BOD5; and (**f**) BI (average values and standard deviations are given).

Table 3. Mixture composition in terms of AD application before and after cavitation (average values and standard deviations are given).

Parameter	Unit		MW	MLL	LB + MW	LB + MLL
ALK	mg/L	Before HC	580 ± 35	13,444 ± 327	551 ± 20	12,767 ± 346
		After HC	574 ± 14	12,694 ± 308	631 ± 39	14,369 ± 290
pH	-	Before HC	7.30 ± 0.03	8.12 ± 0.05	7.34 ± 0.07	8.22 ± 0.08
		After HC	8.01 ± 0.02	8.65 ± 0.05	7.21 ± 0.07	8.51 ± 0.08
VFA	mg/L	Before HC	140 ± 14	1213 ± 124	595 ± 38	1865 ± 211
		After HC	136 ± 6.8	1198 ± 132	740 ± 45	1909 ± 261
$N\text{-}NH_4^+$	mg/L	Before HC	68 ± 0.5	1710 ± 260	65 ± 1.5	1729 ± 285
		After HC	63.5 ± 0.5	1902 ± 300	64.3 ± 0.7	2810 ± 310

As shown in Figure 3, the addition of LB to MW and MLL led to increases in COD, SCOD, TS, and VS in the raw mixtures. This fact is related to the LB characteristic of being a substrate rich in organic compounds (Table 1). A different trend occurred only in the case of LB diluted in MLL with regard to BOD_5. In this case, a decrease of 12% was observed compared with sole MLL. Importantly, the implementation of LB to both carriers, MW and MLL, led to the deterioration of BI. The significant declines of 81 and 60% were observed for the mixtures of LB and MW as well as LB and MLL, respectively. This was related to the application of the substrate characterised by a high content of refractory compounds (Figure 1). This fact is also highly unfavourable from the point of view their subsequent application in biological processes.

It should be noted that especially anaerobic processes are highly sensitive to various environmental factors, including the pH values, ALK, VFA as well as $N\text{-}NH_4^+$ contents, which might inhibit or accelerate the activity of methanogens [29,30]. Therefore, these parameters were also analysed in the present study (Table 3).

Importantly, compared with sole MW and MLL, an enhanced VFA content was observed in the presence of LB. Its concentration increased by over 325% and 54% in LB + MW and LM + MLL, respectively. Previous studies indicate that VFA inhibition is the most frequent factor contributing to process instability and even leading to AD failure [31,32]. Its accumulation in the digester resulted in a decrease in the pH value and the subsequent reduction of methane production. On the other hand, regarding the pH values as well as the $N\text{-}NH_4^+$ content, there were no noticeable effects of LB application on MW and MLL compositions. Apart from the previously mentioned parameters, ALK is considered as a crucial monitoring parameter within AD [29]. It should be noted that the optimum pH range for methanogens is relatively narrow and should be in the range 6.8 to 7.8. Therefore, the application of substrates with high ALK might ensure the adequate buffering capacity within the digester, which is particularly recommended. Moreover, previous studied indicate that high ALK allows for better process performance, increased methane yields, and reduced retention time [33]. Additionally, this fact might play a key role in conducting the multicomponent AD of various agro-industrial wastes, as well as organic fraction of municipal waste [34]. It should be noted that in the present study, the application of LB led to minor decreases in this parameter, compared with sole waste streams.

3.2. *Influence of HC on the Properties of the Applied Mixtures*

The results in terms of organic compounds are presented in Figure 3. Compared with the raw mixtures, HC resulted in minor declines in the COD content in all mixtures (Figure 3a). Major changes were observed for both mixtures with LB. Reductions of 15.7% and 11.8% were observed for LB suspended in MLL and MW, respectively. A similar observation was made for the TS content (Figure 3c). The exception was the series with MW; in this case, comparable results were achieved before and after HC. The observed changes resulted from the destruction of organic compounds that occurred within HC [9]. However, considering the VS content, there was no clear tendency in terms of the HC influence on the compositions of mixtures. In the case of MLL, as well as LB and MLL, comparable results were found before and after HC. The major change, as previously, was found for LB suspended in MW: a drop of 24% in the cavitated mixture was observed, indicating decomposition of LB.

Previous studies indicate the great potential of this method for degradation of organic molecules [16,35,36]. It has been applied as a pre-treatment method for wheat straw, corncob, corn stover, grass silage, sugar cane bagasse, reed, and miscanthus grass [8,35].

The changes within HC of various wastes are related to the physical and chemical effects that occur, as well as their combination. The physical effects include shockwaves, microcurrents, shear stress and increased temperature. These effects tend to break down the external structure, decrease the particle size, enhance the surface area, and finally lead to improvement in the accessibility and/or solubility of LB [8,35,36]. In turn, the chemical effects are related to the generation of hydroxyl radicals, which are highly reactive and are able to oxidise organic matter. In particular, the hydrogen peroxide (H_2O_2) produced from hydroxyl radicals has a proven effectiveness in reducing the organic and inorganic matter presented in substrates [9]. The crucial factors the process are the type of cavitation inductor, the characteristics of the treated material and the adopted operational parameters [35].

In the present study an orifice plate with one concentric hole was used as an HC inductor. It is known that orifice plate is one of the most effective HC devices allowing for the generation of the intense cavitation conditions, mainly due to the extended intensity of the formation of hydroxyl radicals [37]. This device is preferred in order to achieve intense chemical reactions [38]. Previous studies indicate that multiple-hole orifice plates result in enhanced cavitation effects compared with single-hole orifice plates [37,39–41]. Generally, smaller size holes and a greater number of holes result in higher removal rate of various pollutants [42,43]. However, such a HC design is not suitable for all applications. Regarding the LB pre-treatment, a single concentric hole seems to be a more advantageous design. Such a design promotes the oxidation of volatile hydrophobic substances in the gas phase, but limits the diffusion of hydroxyl radicals outside of the bubbles [44].

A different trend was observed with regard to SCOD; in this case, increases in all cavitated mixtures were achieved (Figure 3b). The greatest enhancements in this concentration were recorded for both mixtures with MW. For sole MW, it was 11%, while for the mixture of LB and MW, it reached over 20%. This was related to the solubilisation effect, a release of organic substances into the liquid phase within HC [8]. HC might also contribute to changes in organic compound structures and conversion of recalcitrant compounds in pre-treated materials to more biodegradable forms, which was confirmed by previous studies [35,37].

It should be noted that in almost all cases, an increase in BOD_5 concentrations was found after HC. The exception was the series with MW; in this case, the parameter was reduced by approximately 40%. Importantly, for sole MLL and for a mixture of LB and MLL, enhancements of 23% and 24% were observed, respectively. The results obtained for BOD_5 corresponded with the BI. As previously, in almost all experimental series, an improvement of the BI in cavitated mixtures occurred. Only for MW was the BI deterioration observed. In turn, for the cavitated mixture of LB and MW, BI improved by 24%. It should be noted that the HC of LB suspended in MLL resulted in an improvement by 56% in the BI, compared with the mixture before HC. For sole MLL, a minor enhancement of 36% was found. The observed improvements in BI were related to high temperature and pressure, and to a lesser extent, with the activity of highly oxidizing radicals generated within HC [45]. It should be noted that increased temperature is especially recommended for LB. The studies conducted by Baxi and Pandit [46] and Teran Hilares et al. [47] indicate enhanced removal rates of hemicellulose and lignin. However, the optimal temperature largely depends on the boiling point as well as vapor pressure of the applied medium [48].

Importantly, the results obtained for BI are consistent with previous studies. The improvement in BI within HC of various types of side streams, such as distillery by-products [49], pigments [50] and cork [51] as well as municipal wastewaters [7,52] has been reported. Moreover, such beneficial outcomes have been also found within HC of landfill leachate [9]. The achieved results for BI are particularly important because the effective treatment of the analysed substrates still constitutes a serious technological and environmental issue. The management of lignocellulosic biomass is an especially urgent topic [18]. The results obtained also confirm that HC could be applied as an effective pre-treatment of these substrates.

Moreover, these results indicate the importance of optimisation studies in HC to determine the most suitable inlet pressure and cavitation time [14]. Especially the first parameter is considered as a crucial factor in the cavitation intensity. For orifice plates, it should be in the range from 2 to 8 bar; however, the optimal value depends on shape, size and number of holes [39]. Generally, with the enhancement of this parameter, the amount of liquid passing in a given treatment time increases, which extends the residence time of the pollutants in the cavitation zone and results in an improved degradation rate of specific pollutants. However, exceeding the pressure to a certain level may lead to supercavitation, which can yield poor HC results. Moreover, it should be noted that high pressure is not beneficial for every pollutant [35,37]. This was confirmed in the present study. As previously mentioned, a decreasing trend in terms of BI was obtained only for MW. Importantly, the prior research conducted by Lebiocka [52] indicates that the optimal effects for this medium were obtained with a lower inlet pressure of 5 bar using the same orifice plate as HC inductor as in the present study. Regarding the lignocellulose biomass, for reed, the best results were found with an inlet pressure of 5 bar and 41.1 min [53]. In turn, for sugarcane bagasse, the HC was conducted under the following conditions: inlet pressure of 3 bar and total time of 10 min [54]. However, in both cases, the HC processes were combined with alkali pre-treatment.

However, due to the complexity of HC, additional indicators should be considered before the implementation of this method on a technical scale. Often, a key concern in its successful application is the possible generation of toxic by-products leading to secondary pollution of the treated medium, thus excluding its subsequent application. This problem was previously reported in literature during the application of the lignocellulosic biomass using this technology [16,17,55,56]. Therefore, it is crucial to select an appropriate carrier for suspension of LB, especially when waste streams are used as carriers. Frequently, the HC of sole liquids and their mixtures with LB present divergent results, mainly due to additional interactions occurring during the process [45]. Therefore, more thorough evaluation of the composition of the treated material is required. Despite the beneficial effect observed within the HC of LB and MLL, previous research indicates that HC favours the formation of aromatic compounds that might inhibit the AD process, thus preventing MLL from being used as a carrier for lignocellulosic biomass [57]. On the other hand, the application of different operational parameters could lead to different results. Therefore, optimisation studies play a crucial role in successful HC; such evaluation should include temperature, pressure, duration as well as the type of the HC inductor.

The pH value is a crucial factor within the HC process; it has a significant influence on the degradation of specific pollutants. The acidic pH values promote the formation of hydroxyl radicals, thus ensuring a higher oxidation potential and a lower rate of their recombination [37,58]. As shown in Table 3, a decrease in the pH value occurred only for the mixture of LB and MW, which could be related to a transformation of some organic compounds into low-molecular-weight acids [59]. In the remaining cases, HC led to an increase in the pH value in cavitated mixtures. The observed growth in the pH values within the HC of MLL and LB + MLL resulted from the decomposition of acid groups [45]. Compared with the raw mixtures, a growth in the VFA content by 24% was observed, indicating a deposition of lipids within HC was found only for the cavitated mixture of LB and MW. In the remaining cases, comparable values were observed before and after HC. Regarding the $N\text{-}NH_4^+$ content resulting from HC, only for sole MLL and the mixture LB + MLL led to an increase in its concentration compared with the raw mixtures. This was related to the destruction of proteins. As was previously mentioned, the ammonia nitrogen is recognised as a major AD inhibitor that could lead to process failure [29]. This observation also excluded the application of MLL as a carrier for LB. Considering the ALK within HC, sole MW and MLL resulted in minor reductions. In the series with LB, an enhancement in the ALK content occurred. Importantly, this beneficial effect was found for LB and MW, thus improving the properties of the mixture. The results obtained in terms of AD parameters are consistent with the previous studies, which indicated that HC favours a lower production of inhibitors [60].

Another crucial factor that should be considered before implementation of this technology on a technical scale are the operational costs related to energy consumption and reagent dosing. These costs are particularly important during the HC of lignocellulose biomass. It should be pointed out that previous studies related to application of this technology for LB treatment included an additional alkali pre-treatment which contributed to the unprofitability of this solution [8,18]. Additionally, despite the favourable results in terms of hemicelulose and lignin removal and increasing accessible surface area, the real scale application is limited [36,61]. This is mainly due to the necessity of providing a high volume of the alkaline solution to recirculate through the pre-treated medium in HC devices [35]. Importantly, this cost is not considered in the present study because LB is suspended in waste streams. Compared with other pre-treatment methods, HC is characterized by low operational costs [4]. A sole HC required up to 75% less energy consumption, compared with ultrasound cavitation that operated between 1000 and 16,000 kJ/kg TS [62,63]. In turn, the application of thermo-alkaline methods results in energy consumption of up to 130,000 kJ/kg TS [64]. The HC process can result in energy consumption varying between 470 and 50,000 kJ/kg TS [65,66]. However, the exact values depend mainly on the applied cavitation time.

The application of hydrodynamic cavitation as a pre-treatment method faces various problems and challenges. Several factors should be considered, and as demonstrated in the present study, each waste should be treated individually. Table 4 presents a set of experiences in the field of HC application.

Table 4. Challenges of hydrodynamic cavitation of organic wastes.

No	Steps to Successful HC	Factors to Consider
1.	Goal to achieve	– BI improvement, – Organic compounds removal.
2.	Selection of HC inductor	The type of inductor influenced the transformations within HC: – For BI improvement, the Venturi, rotational and orifice with one concentric hole are recommended (the predominance of physical processes, e.g., high temperature and pressure), – For organic compounds removal, a multiple-hole orifice plate is recommended (the predominance of chemical processes related to the formation of hydroxyl radicals), – The adopted configuration influences the device geometry, velocity through the inductor and cavitation number.
3.	Purchase or construction of the device/choosing the size and shape of cavitation inducer	– There are industrial HC devices available on the market, – A device can be chosen specifically for a given type of waste and the goal to achieve by cavitation.
4.	Consideration of dry matter content	– If a cavitation device dedicated to the high total solids (up to 30%) is not available, a sustainable carrier must be used for high dry matter waste, e.g., lignocellulose biomass (waste streams are preferred), – For sole liquids, e.g., industrial wastewater, a carrier is not needed.
5.	Selection of operational parameters and multi-criteria optimization	The following parameters have a decisive influence: inlet pressure, number of cavitation cycles (passes of the stream through the cavitation zone) and the corresponding duration, dry matter content or pollutant concentration in the cavitated medium, temperature of the medium.

Table 4. *Cont.*

No	Steps to Successful HC	Factors to Consider
6.	Evaluation of the effects	– Success, e.g., BI improvement or high pollutant removal, lack of toxic by-products, energy efficiency, – Partial success, – Failure, In the case of HC utilization, there is a necessity to evaluate the possible generation of toxic by-products leading to secondary pollution of treated waste.
7.	Alternatively, another attempt to select the cavitation inducer and operational parameters	In case of failure or partial success, it is recommended to change the operational conditions: inlet pressure, duration, dry matter content or pollutant concentration, temperature of the medium and type of HC inductor.
8.	Final	Assess the profitability of the technology

4. Conclusions

The results obtained indicate that HC can be applied as a pre-treatment method for selected organic wastes and also for materials which are difficult to biodegrade, such as lignocellulosic wastes. During HC, in almost all the analysed materials, solubilisation and decomposition of complex organic matter were observed. Importantly, the improvement of biodegradability was found in almost all cases, confirmed by enhanced BI, as well as SCOD content. The exception was the series with MW; in this case, BI was reduced by approximately 40%, indicating the improperly selected operational conditions for this medium.

The achieved results also showed that a key factor in successful HC of LB is the selection of an adequate carrier for LB. Regarding the type of carrier for LB, more beneficial results were found for MW, as confirmed by improved BI, alkalinity as well as SCOD content accompanied by low concentrations of ammonia nitrogen in the cavitated mixtures. The application of this method might be considered as a cost effective and environmentally friendly technology that may allow for further energy utilization of pre-treated organic wastes in the AD process.

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