Cavitation-based technologies for pretreatment and processing of food wastes: major applications and mechanisms- A review

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Abstract

Conversion of food wastes to valuable products is an important topic for sustainable development. Feedstock hydrolysis is a stage strongly affecting the anaerobic digestion process, and resistance of food waste towards hydrolysis causes a decrease in product yield. such as biomethane, biohydrogen, biohythane, VFAs, and lactic acids. Moreover, mass transfer is a serious limitation of transesterification for the production of biodiesel. Cavitation is a promising pretreatment method for the mitigation of these issues. This work presents a critical review on cavitation-assisted processing of food waste. In several studies, cavitation proved its remarkable potential.

Cavitation can also be employed in anaerobic digestion reactors and directly irradiate microorganisms, stimulating enzyme activities. Cavitation led to an increase in SCOD by up to 172%. Consequently, it caused an increase in biogas, biohydrogen, VFAs, and lactic acid converted from food waste by up to 100%, 145, 100%, and 62%, respectively. Cavitation resulted in a reduction in reaction time required for the conversion of food waste into biodiesel by up to 98% due to its potential in increasing mass transfer. In acoustic cavitation, the optimum power density for the conversion of food waste through anaerobic digestion is in ranges of 230-480 W/L and 40-50 W/L at pretreatment stage and main stage, respectively. Low frequencies in a range of 20-50 kHz are suitable for both anaerobic digestion and transesterification. However, studies on the application of high frequency are scarce and obvious “research-gap” in this field exists. In hydrodynamic cavitation, for disintegration, efficient cavitation number and pressure are in ranges of 0.07-0.15 and 2-4 bar, respectively. The maximum particle size reduction usually occurs within the initial 15 min for both types of cavitation.

Keywords: cavitation, waste management, value added products, sustainable development, fermentation, bioproducts.

Table of contents

1. Introduction

Conversion of waste to usable products leads to a reduction in waste, which is regarded as one of the principles of circular economy. The first priority of EU Waste Framework Directive ((EU (2008) Directive 2008/98/EC) on food waste is a decrease in waste at the source, and its second priority is recycling and reuse [1]. The increasing abundance of food wastes for many years is one of worldwide issues especially due to the absence of appropriate management and law regulations. The growth of population and development of economy are primary factors increasing the amount of food waste. It has been reported that food waste constitutes more than one third of total food consumed by world population [2, 3]. Food waste contains many nutritional components such as proteins, lipids, fats, polysaccharides, carbohydrates, and metal ions, which can be reused in some processes to produce value-added products (e.g., volatile fatty acids, lactic acids, carboxylic acids [2, 4]. In addition, food waste can also be converted into biogas, biohydrogen, and biodiesel, and this type of green energy can be an alternative to non-renewable fuel and reduce the dependency on fusil fuel sources [5]. The formation of biofuels from renewable sources is beneficial in environmental protection due to the employment of waste and reduction in acid rains and toxic gas emissions, which are considered major universal challenges [6]. A variety of bioproducts generated from food wastes can be observed in Fig.1.

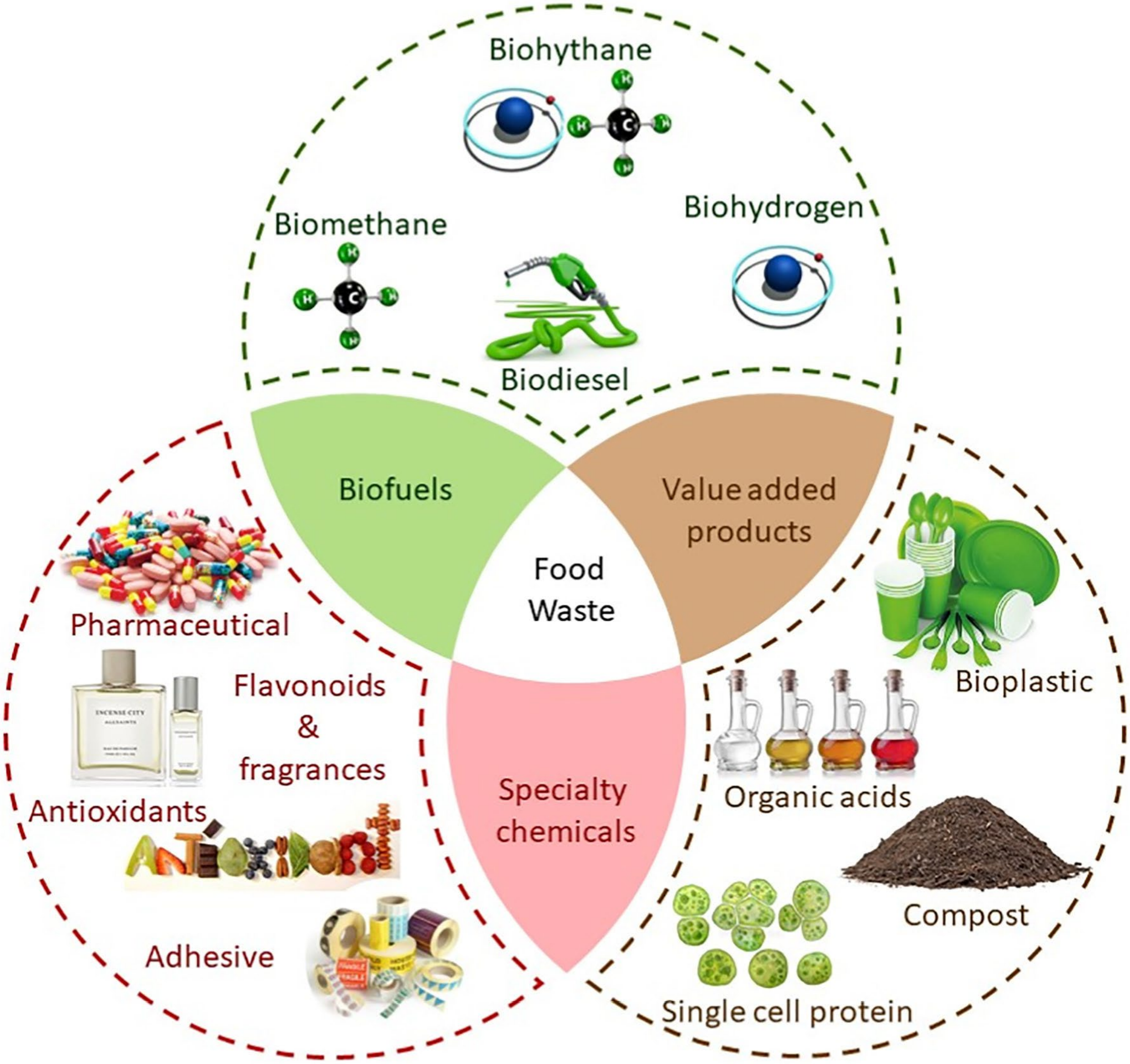

Fig.1. Bioproducts converted from food waste (Reuse from Yukesh Kannah et al. [7]).

In biological production processes from food wastes, pretreatment technologies, such as milling, acid hydrolysis, steam explosion, and nano catalyst are used to decrease particles size and increase surface area, which can subsequently enhance the efficiency of main processes [8-11]. In the production of biodiesel from food waste through transesterification, process intensification technology is required to decrease the processing time by decreasing mass transfer resistance among different reactants [12]. Hydrodynamic cavitation (HC) and acoustic cavitation (AC) can be employed as an effective pretreatment method for improving food wastes characteristics. The collapse of produced bubbles in cavitation reactors can disrupt the feedstock and result in the reduction in particles size and elimination of lignin. Moreover, cavitation can lead to significant decrease in treatment duration by biological methods through the enhancement of solubilization of organic matters [13]. High energy of collapsing gaseous bubbles can thermally decompose a wide variety of compounds existing in processing feedstocks [14]. Furthermore, the turbulence and micro circulation happening as a result of collapse of bubbles can intensify the biodiesel synthesis process through decreasing mass transfer resistance [15]. The effectiveness of cavitation treatment relies on reactor designs and process parameters [16]. Highly reactive hydroxyl ($HO^{\bullet}$) and hydroperoxyl ($HO_2^{\bullet}$) radicals formed through the subsequent collapse of bubbles can also contribute to the intensification of biological processes [16, 17]. The advantages of cavitation as a pretreatment method are low cost of processing (as there is no need for high temperature and pressure), viscosity reduction, heat generation, and high synergistic effect in combination with other chemical and physical methods [18].

In this review, the mechanisms of hydrodynamic cavitation (HC) and acoustic cavitation (AC) and parameters affecting these phenomena were explained. The role of cavitation in the pretreatment of food wastes for the production of value-added products was discussed in detail. Finally, the observed effects of cavitation on these processes and the results achieved by applying cavitation-assisted processing of food waste were mentioned.

2. Cavitation

Cavitation is the formation, growth, and implosion of bubbles in a short period [19]. The rapid changes in vapor-liquid interface leads to the development of high-speed microjets with velocities higher than 150 m s^{-1} and a corresponding water-hammer pressure of up to 200 MPa [20]. The extreme impact of microjets on the opposite side of bubble wall causes the generation of a set of shock waves with an average speed of 2000 m s^{-1}. The collapse of main torus induces even a stronger set of shock waves [21]. Furthermore, the collapse of bubbles results in a high shear wall stress of up to 3.5 kPa [22]. These extreme conditions cause a reduction in the size of processed particles such as food wastes as well as decreases the mass transfer resistance increasing the effect of chemical reactions such as oxidation or hydrolysis [23, 24]. Moreover, the compression of gas and vapor inside the bubbles causes extremely high pressure and temperature [25]. These high temperature and pressure can decompose water molecules and produce species like $HO^{\bullet}$, $HOO^{\bullet}$, and H_2O_2, which have high oxidation potential and can decompose organic compounds. Additionally, these extreme conditions can break the molecular bond of organic substances and lead to their direct decomposition [26-28]. Generally, the effect of cavitation can be observed in three main regions. Inside the bubble, the extreme temperature and pressure can provide activation energy required for the breakage of gasified solvents and solutes. The generated radicals and products may pass through the walls of bubbles and take part in the chemical reactions in the bulk of solution. In addition, in the gas-liquid interface, both pyrolysis and radical reactions can occur as the interface can be heated up due to the hot spot inside the bubbles [29].

According to the methods of generation, cavitation can be presented in four groups: HC, AC, particle cavitation, and optic cavitation. Particle cavitation and optic cavitation are used for the generation of a single bubble and do not have any application as pretreatment methods [30]. Therefore, we just studied HC and AC among these four types.

2.1. Acoustic Cavitation (AC)

Ultrasound is a sound wave which possesses a frequency higher than human audible one [31]. In AC, the formation, expansion, and collapse of microbubbles take place by acoustic irradiation [32]. Compression and expansion cycles of ultrasonic waves created by transmission of wave into the irradiated medium induce negative and positive pressures in liquid, which result in the expansion and compression of microbubbles, respectively [33]. The appropriate design of ultrasonic reactors and optimum operating conditions play key roles in specific process intensification. Hence, suitable type of transducer, appropriate frequency range and power intensity, and proper number and position of transducers in the reactor extremely enhance the effectiveness of AC [34].

2.1.1. Geometry of used systems

The consideration of device geometry is required for obtaining the highest process efficiency. The acoustic horn is the most common type of transducer directly transmitting the wave through the liquid, which can produce high magnitude of intensity near the probe; therefore, can be useful in small-scale operations [12, 34]. The diameter of this probe is normally in a range from 5 to 15 mm, and it is made of transition metals such as titanium [35]. The surface area of this type of transducer is typically in a range from $7*10^{-6}$ to 0.03 m^2 [36]. The ratio of probe diameter to vessel diameter and the immersion depth of the probe into the liquid are important factors in designing this type of reactors. An increase in the ratio of probe diameter to vessel diameter leads to an increase in cavitational activity [37] This ratio mainly influences the turbulent dissipation of energy and the intensity of acoustic streaming and is an important parameter especially where the physical effects of cavitation is significant (such as particle reduction, biodiesel production, disintegration, etc.). The immersion depth of the probe into the liquid, which impacts the reflection of acoustic waves from reactor walls or medium surface, has also an optimum value [38]. In recent study, it was found that same size of cavitation cloud size can be obtained with lower power consumption for lower depth of probe immersion. The best performance were obtained for depth below 1 cm [39, 40]. The horizontal horns usually possess higher surface area of irradiation in liquid and can lead to uniform distribution of AC and higher energy efficiency compared with conventional ones [41, 42]. Nevertheless, ultrasonic horns are not suitable for scaling up since their potential for transmission of acoustic energy into a big volume of liquid is not powerful enough, and cavitational zones are concentrated near the irradiating area (at most 2-3 cm away). Additionally, the erosion of probe is another problem for the industrial application of ultrasonic horn reactors [38]. A solution for scaling-up would be to use several closed flow-through chambers with mounted horns in parallel and a feed tank to operate process stream in a closed-loop (recirculation) system until desired rate of conversion would be obtained.

Ultrasonic bath reactor is another type in which the position of transducers is at the bottom of the reactor and the transmission of acoustic irradiation can happen either directly or indirectly [34]. Power intensity cannot be adjusted in this type of reactor. Another drawback is the reduction made in the intensity throughout the process [43]. Furthermore, it is difficult to achieve uniform distribution of acoustic energy in ultrasonic bath reactors [44].

In acoustic reactors, the extreme cavitational effects are induced near the ultrasonic transducers [45]. Hence, the utilization of several transducers, which can result in an enhancement in cavitational zones, is inevitable in industrial-scale applications. It has been also indicated that the combination of frequencies can intensify the pressure induced by collapse of bubbles compared to single frequency [46]. The exact number of these transducers is dependent on operating volume, dimensions of transducers, and power required for a specific application [47]. The position of transducers influences the direction of acoustic irradiation; therefore, the appropriate position of them can lead to an uniform distribution and maximum cavitational zone [38]. Generally, the location of transducers should be chosen by considering the reactor diameter and liquid height. The appropriate arrangement of transducers for an industrial-scale operation can be cell kind since it can provide flexibility for continuous operations. Furthermore, it is possible to locate transducers on the wall of reactors on the opposite sides, resulting in the formation of standing wave pattern which can increase the effective cavitational intensity. Rectangular cross-sections or hexagonal are reported to provide excellent distribution of cavitational activity and are preferred for large scales. In addition, an increase in the ratio of immersion transducer diameter to reactor diameter till the most favorable ratio can intensify the cavitational activity [38, 47].

2.1.2. Frequency of ultrasounds

An increase in frequency till an optimum amount can increase the efficiency of cavitation based on the desired application. Frequency inversely influences the size of bubbles and the energy generated as a result of the collapse of bubbles. Therefore, lower frequencies in a range of 20 to 50 kHz, can lead to more extreme collapse of bubbles and the intensification of physical effects of cavitation [12, 48]. This frequency range creates appropriate shock waves leading to a reduction in mass transfer resistance [49]. In addition, it generates desired shear stress which can degrade complex molecules such as complex sugars and produce simple ones, resulting in an increase in solubility and biodegradability. This frequency range has been identified to be the most efficient one for the size reduction of particles [50, 51]. Hence, in sludge pretreatment processes for the final aim of production of value-added products, in which the disintegration of organic substances is mainly performed by the physical effect, most investigations are performed at frequencies in this low range [2, 11, 52]. Since the physical effect of cavitation is required for biodiesel production, this range is the most employed one for the production of biodiesel using various transesterification processes [53-57]. However, there are few studies in which high-frequency ultrasounds were used for the production of biodiesel [58, 59]. Furthermore, low frequency range can be efficient for the degradation of polymers, textile processing, and extraction [47]. Although a frequency higher than 100 kHz causes a decrease in the size of bubbles and intensity of collapse of them, it increases the number of generated bubbles, which can produce more reactive radicals and enhance the chemical effect of cavitation [60]. The collapse of small bubbles in high frequency ultrasound can create violent turbulency [58]. High range of frequency has been reported to be effective for the decomposition of a variety of compounds in wastewater treatment and chemical synthesis combined with a variety of waste water treatment methods [47, 61]. Nevertheless, there are several drawbacks to the usage of high irradiation frequencies such as the erosion of surface of transducers through continuous operations. To mitigate this problem, multiple frequency operations can be employed instead of a single one when high cavitational intensity is required [62, 63].

2.1.3. AC Power

This parameter can influence the number, size, and lifetime of cavities in the medium as well as temperature rise affecting gas solubility and vapor pressure [47]. The acoustic power higher than a given threshold leads to cavitation. This threshold is very high for pure water, but it can remarkably decrease by the presence of impurities [52]. An increase in the intensity of irradiation up to an optimum value can lead to an increase in cavitational activity[64, 65]. Further increase in power intensity may cause cavity aggregation and cloud formation, reducing cavitation activity [66]. However, the influence of power is dependent on the end application and the geometry of reactors [47]. The diffusivity of molecules increases with an increase in power intensity, resulting in the intensification of nucleation rate in crystallization. The power density in a range from 100 to 1000 W/L has been commonly utilized for crystallization processes in different types of AC reactors [67-70]. In sludge disintegration, power density higher than 500 W/L might lead to the deactivation of sludge and a reduction in its bioactivity [52]. Furthermore, the optimum values of ultrasonic power density were observed in a range of 2000−3000 W/L for the extraction of microbial flocculant from waste activated sludge [71]. For the production of biodiesel, the optimum power is mainly in a range of 400-4000 W/L [12, 72, 73]. An optimum intensity can also result in a reduction in operating costs for a particular process [34].

2.2. Hydrodynamic Cavitation (HC)

HC can be generated by using geometrical structures like venturi tubes [74], orifice plates [75], vortex diode [76], or rotating type devices [77]. In the case of specific constructions, a stream passing through a cavitating device undergoes a substantial drop of static pressure resulting from increasing velocity according to Bernoulli’s principle. If the fluid pressure falls below the local saturated vapor pressure, cavitation phenomenon takes place [78, 79]. In addition, because of pressure fluctuations caused by turbulent flow, HC might also occur even when the pressure is still higher than vapor pressure [80].

The cavitation number, Cv, is a dimensionless number used to express the extent of cavitation [81]:

$$C_v = \frac{P_2 - P_v}{\frac{1}{2} \times \rho \times V_{th}^2} \tag{1}$$

where P_2, P_v, ρ, and V_{th} represent downstream recovered pressure, vapor pressure, density, and the velocity of stream in the throat of a cavitating device, respectively. Cavitation number implies the influences of pressure, temperature, and velocity together, and higher values indicate more resistance towards the formation of bubbles [82]. Normally, the inception of cavitation phenomenon and formation of bubbles happen at $C_V \leq 1$ [83, 84]. However, because of the existence of small amounts of dissolved gases and suspended solids, which act as nuclei needed for the initiation of cavitation, this phenomenon can happen even at C_V greater than 1 [85]. Generally, lower values of C_V result in the creation of higher number of bubbles, although it causes a decrease in the intensity of bubbles collapse. It should be mentioned that too low values of C_V lead to supercavitation leading to a reduction in collapse pressure [19]. The desired C_V resulting in efficient pretreatment of biomass and disintegration is mainly in a range from 0.07 to 0.15 [86]. For the aim of wastewater treatment, the desired value of C_V is typically between 0.1 and 0.4, especially in a range of 0.1-0.2, leading to effective degradation of pollutants. This parameter can be adjusted by controlling the downstream pressure influenced by the geometry of cavitating devices [87-90].

2.2.1. Geometry of used systems

The geometry influences the number and size of cavitation events as well as the magnitude of energy generated by collapsing bubbles [91, 92].

It has been reported that for the same flow area, a multiple-hole orifice plate can generate higher shear areas, which results in the production of higher numbers of cavities. The number, size, shape, and arrangement of holes are key factors in the design of an orifice plate [93]. A small number of holes with higher diameter is suitable for applications in which higher cavitational intensity is required, while, a large number of holes with smaller diameter is desired for applications in which lower intensities are favorable [26]. An increase in the dimension of openings results in an increase in cavitation number as a larger throat area causes a decrease in the velocity at the throat, which consequently, increases cavitation number [75, 94]. A reduction in this parameter till an optimum value can increase velocity head and generate more cavities leading to the production of higher amount of hydroxyl radicals. Nevertheless, below this value, the production of excessive bubbles can form cavity cloud which leads to the chocking of orifice plates and a drop in the intensity of cavitation phenomenon [92]. According to some studies, the area of openings is between 40 and 60 mm^2 for plates with a total surface area between 300 and 500 mm^2 [95, 96]. In addition, it has been indicated that orifice plates with conical holes are more effective, which can be attributed to the similarity of structures of holes to circular venturi tubes [97]. Researchers have also studied the effect of the arrangement of holes and reported that a cross-hole arrangement can be more effective than a radial-hole one [98]. α and β are two key parameters used to characterize the geometry of orifice plates. These two parameters are defined according to the following Eqs. [99].

$$\alpha = \frac{\text{Total perimeter of holes}}{\text{Total flow area of throat}} \tag{2}$$

$$\beta = \frac{\text{Total flow area of throat}}{\text{Cross sectional area of the pipe}} \tag{3}$$

The total perimeter of holes shows the area occupied by the shear layer and it has been proved that the turbulence in shear layer and the section occupied by it are the key factor influencing cavitation yield [83]. An increase in α can intensify turbulence and shear layer area [75]. This parameter is closely dependent on the number of holes and their diameter. The total flow area of throat determines the number of passes through the orifice plates. Although it has been reported that an increase in α increases the effectiveness of cavitation, it is not appropriate for all applications [100]. Hence, several studies in the literature have recommended optimizing this value in different applications [99, 101-103]. α values of 2 [83, 104, 105], 4 [98, 106, 107], and 1.333 [97] have been reported in the literature. However, for the lipid extraction from wet microalgae, a more smaller optimum α value of 0.05 has been reported [100]. In processes limited by mass transfer resistance, a larger value of α can remarkably enhance the processes by increasing mass transfer. For example, in biodiesel production, at the same flow area, the plate with higher number of holes and smaller diameter (larger value of α) results in higher degree of conversion [83]. Parameter β is related to the intensity of turbulence, which influences the lifetime of bubbles. Previous literature has not reported uniform results for the effect of this parameter on the degradation of pollutants. Therefore, the optimum values of β require to be found in different situations. Some studies have shown that an increase in β can continuously increase the removal of pollutants, and this trend can be attributed to the fact that the higher values of β produce a larger number of bubbles and consequently a larger number of radicals

[75, 105]. An increase in this parameter can also intensify the degree of conversion in biodiesel production [83, 108]. However, some other studies have reported the positive effect of the reduction of this parameter because the intensity of turbulence is inversely related to β [106, 109]. Higher intensity of turbulence can result in the more violent collapse of bubbles and the generation of higher energy [106, 109]. Optimum β values mainly in a range between 0.02 and 0.09 have been reported in previous studies [83, 98, 100, 104, 106, 109]. The thickness of orifice plates is the other factor affecting the cavitation. A decrease in the thickness of orifice plates can lead to a higher pressure drop resulting in the intensification of cavitation phenomenon.

The inception of cavitation normally happens when the geometry design of venturi allows a ratio of outlet to inlet pressure of 0.8, which is called liquid critical pressure factor [110-112]. Cv of venturi is lower than the Cv of orifice plate at similar operating pressures; hence, the utilization of venturi tube can lead to a higher degree of decomposition at the same operating pressure level [26, 93, 113]. Venturi tubes generate denser cavitation clouds and increase time for the expansion of bubbles and collapse of them compared to orifice plates. Generally, these conditions result in greater turbulence intensity and stronger collapse of bubbles in the downstream [81]. Typically, it has been shown that a slit venturi tube is more efficient than a circular one [88]. The maximum size of bubbles and their lifetime are dependent on the design of divergent section. The divergence angle impacts the pressure profile and pressure recovery and can be adjusted to control the collapse of bubbles [99]. An increase in the divergence angle accelerates the pressure recovery, which means a larger divergence angle results in the rapid collapse of bubbles. In contrast, a smaller divergence angle causes a smooth pressure recovery, which facilitates the growth of bubbles [93]. Generally, it has been reported that the maximum length of cavitation zone is achieved at an optimum divergence angle [99, 114]. The length of throat also influences the residence time of bubbles in the low-pressure section. When the residence time is short, bubbles are not able to grow to the desired size. Although, the longer residence time does not mean the higher intensity of cavitation because of the coalescence of bubbles. It has been reported in the literature that the optimum values of half divergence angle for circular venture, and slit venture are about 6.4 and 5.5, respectively, and the ratio of throat diameter to its length is typically 1:1 [99, 115, 116].

In rotating-type devices the shear cavitation is formed within the chamber because of the shear forces, which are the result of the relative movement of rotor, stator, and the liquid among them. The rotation of a rotor with a high speed causes a high surface velocity on the rotor surface resulting in a low-pressure area near the surface of indentions, and if the pressure drops below the vapor pressure of the liquid, cavitation phenomenon appears. An increase in the rotation speed up to an optimum value can enhance the intensity of turbulence which enhances the cavitational intensity. While, a further increase in rotation speed causes an increase in sliding between water layer and rotor, which decreases the extent of cavitation. Furthermore, higher rotational speed leads to the generation of a very large number of cavities resulting in chocked cavitation condition[26, 117]. This situation causes a decrease in the energy released as result of collapse of bubbles. Optimum speed values mainly in a range between 2000 and 3000 rpm have been reported in the literature [19, 77, 118-121]. However, there are few studies in which higher optimum speed values of 5000 rpm and 8000 rpm were reported [122, 123]. In the case of processing complex streams containing solid material – especially of natural origin (like biomass or food wastes) – this type of cavitational system provides a high ability of disintegration. The main drawback of this type of reactor is the high power consumption required to provide an appropriate rotational speed, which could be an issue in industrial scale and make the process unprofitable [124].

Vortex diode and swirling jet cavitation reactors are the two most common devices of this type, which form vortex flow without the help of any moving parts. In a swirling jet reactor, a stream circularly passes through the swirling chamber and a swirling jet is produced. If the pressure in the center is lower than the vapor pressure of the liquid, cavitation takes place [125]. In this case, bubbles are generated around the axis of rotation in the chamber where the low-pressure region is produced by highly swirling flow [126]. An advantage is that the cavitation region is not near the solid walls, which decreases the possibility of erosion [127]. Moreover, these types of reactors do not need too much operating cost and maintenance. However, some studies indicated that vortex-based reactor are effective for lab-scale and pilot scale applications, and the results achieved for larger scale are not acceptable. In fact, for the same geometry and operating condition, the performance of different scales of a device changes, which can limit the industrial applications of this type of device [128]. A significant advantage of such systems is operation under much lower pressures comparing to venture and orifice systems [129]. Additionally, it does not possess small constrictions and are not susceptible to clogging when it is used for the pretreatment of waste containing solid particles [130].

Although Venturi- and orifice-type reactors are widely used since they can produce ideal cavitation intensity for the degradation of pollutants, the pressure loss in these two types is higher compare to the other ones [26].

Table 1 indicates a comparison showing the advantages and advantages of these 4 types of HC reactors:

Table 1. Comparison of HC devices

	Advantages	Disadvantages
Orifice plate	1. Simple structure 2. Flexible design 3. Low power consumption and maintenance cost 4. Simple to operate and control	1. High possibility of being eroded and clogged when the waste includes solid particles 2. High pressure loss and energy disperse
Venturi tube	1. At a given pressure drop provide a lower Cv 2. Simple structure 3. Low power consumption and maintenance cost 4. Higher residence time	1. High possibility of being eroded and clogged when waste includes solid particles 2. High pressure loss and energy disperse 3. Approximately higher construction cost than orifice
Rotating type	1. Suitable for waste including solid particles 2. Lower pressure loss and energy disperse	1. High power consumption and maintenance cost 2. Complex structure
Vortex-based	1. Low possibility of damage to the surface of cavitation reactor and pipe 2. Lower operating and maintenance cost compared to rotating type 3. Low overpressure of the system required 4. Suitable for waste including solid particles	1. Difficult scaling -up

2.2.2. Effect of operating pressure

Inlet pressure plays an important role in the effectiveness of HC. An increase in the inlet pressure to an optimum value can enhance the cavitation effects [131]. This enhancement can be attributed to the fact that increasing inlet pressure leads to the generation of more bubbles [132]. Furthermore, an increase in the inlet pressure can lead to the intensification of collapse of bubbles and an increase in cavitation zone [131, 132]. However, beyond the optimum pressure, chocked cavitation or super cavitation phenomenon takes place, leading to filled cavitation zone and the formation of cavity cloud [132, 133]. According to the literature, in the case of venturi tubes, the recommended inlet pressure values for obtaining an appropriate Cv range between 3 and 6 bar [24, 87, 88, 90, 94, 134-137], and in the case of orifice plates this optimum value is in a range of 2-7 bar [75, 83, 97, 98, 100, 104-106, 134, 135, 138, 139].

Other factors influencing the cavitation phenomenon are summarized in Table 2.

Table 2. Parameters affecting cavitation phenomenon.

No.	Factor	Influence	Ref.
1	Temperature	A decrease in temperature can increase the cavitation threshold. Too high temperature can cause high vapor content in the bubbles, cushioning the collapse of them. Although there is an optimum temperature, it is usually preferred to employ the room temperature to avoid the use of heat exchangers.	[140, 141]
2	Liquid vapor pressure	An increase in Liquid vapor pressure enhances the number of cavities.	[91]
3	Fluid viscosity	Viscous liquids raise the critical pressure required for the inception of cavitation and slightly increase the minimum collapse pressure.	[83, 91]
4	Surface tension	High surface tension increases the pressure required for the inception of cavitation, which results in an increase in the intensity of collapsing bubbles.	[142]
5	Dissolved Gases	These types of impurities act such as nuclei accelerating the generation of bubbles.	[90, 92, 143]

Generally, the efficiency of conversion of energy in HC reactors is much higher than AC ones [144, 145]. In addition, scaling AC reactors has economic issues since the energy decays with increasing distance from transducers [91]. In contrast, HC is recognized to have a high potential of being employed in industrial scale applications [146]. The reason is that the cavitation intensity of HC reactors can remain constant or even increase by scaling up with appropriate design as the dimension of cavitation region is enlarged by the same ratio. Additionally, the manufacture of HC reactors is simple by mechanical machining as it does not contain any complex electronic parts [147]. Therefore, the best approach for the treatment and pretreatment of high volumes of industrial waste is HC, especially that of generated by orifice or venturi [91].

Designing a proper constriction with optimized operating conditions leads to a substantial reduction in the operating cost of treatment. However, in a case where the effluent includes solid materials, it is difficult to use orifice or venturi since their small throats might be blocked by particles.

3. Potential of cavitation in food waste pretreatment

Cavitation has a remarkable potential to enhance the yield of bioproducts converted from food waste. Most of bioproducts are generated through anaerobic digestion which is a biological process utilized for the generation of valuable substances through the breakage of material in food wastes in the absence of oxygen [148]. Fig. 2 demonstrates the main stages of this process and the products formed through each stage.

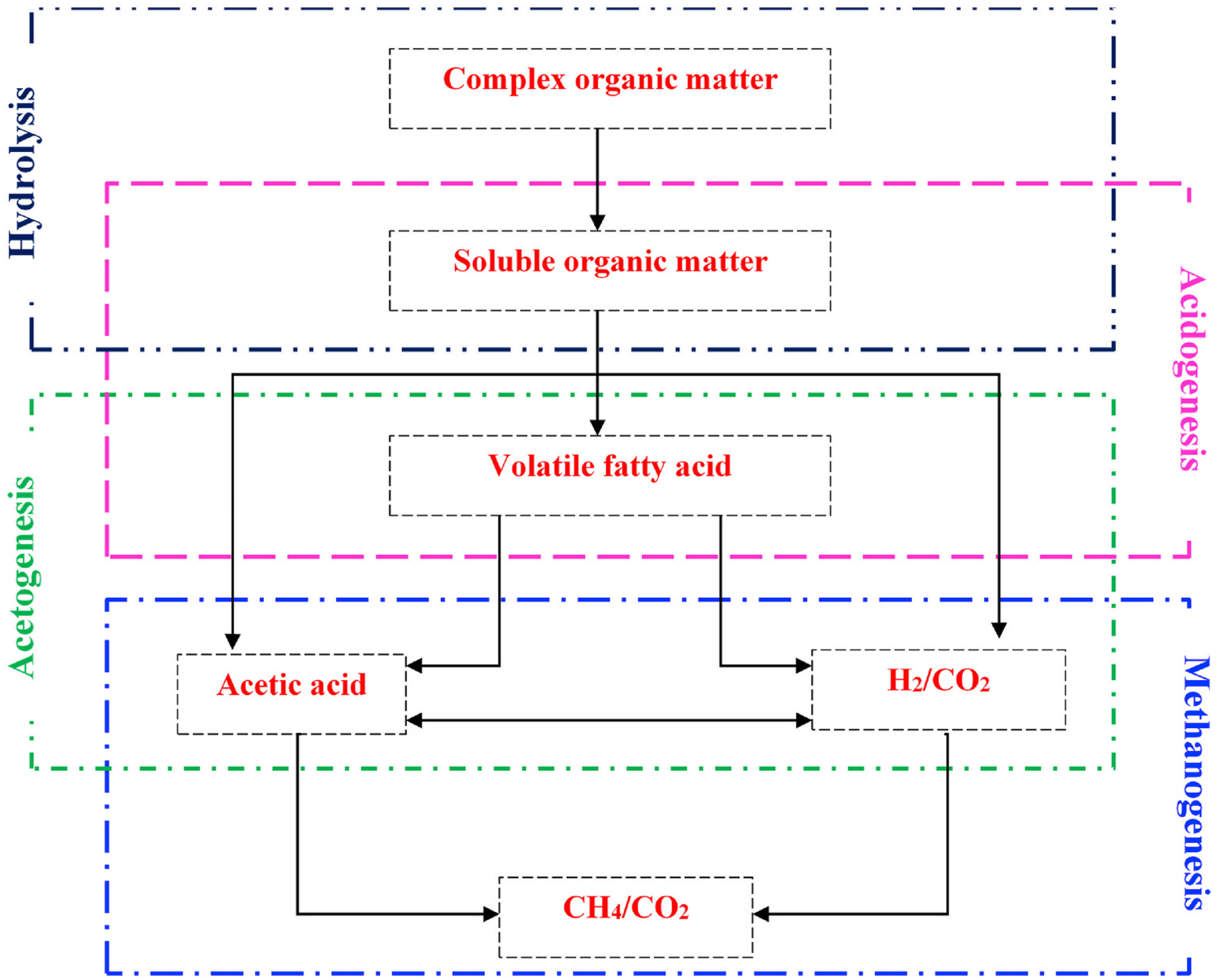

Fig.2. Stages of anaerobic digestion, including hydrolysis, acidogenesis, acetogenesis, and methanogenesis (Reuse from Yadav et al. [149]).

A normal anaerobic digestion includes 4 steps. The first step of this process is hydrolysis resulting in soluble organic matter, and the second step is acidogenesis where the monomers formed in hydrolysis step are converted to VFAs in the presence of hydrogen and carbon dioxide. In step 3 called acetogenesis, acetic acid is generated from the reduction of hydrogen and carbon dioxide assisted by homoacetogenic microorganisms. Final step is methanogenesis, where hydrogenotrophic methanogens transform carbon dioxide and acetotrophic methanogens transform acetic acid and hydrogen to methane [6, 149].

The hydrolysis of feed substrate is a key stage in the biochemical conversion of food wastes to valuable substances, and therefore, the resistance toward hydrolysis can result in a decrease in the generation of desired products [2, 150, 151]. In a hydrolysis stage, hydrolytic microbes are responsible for the production of exo-enzymes disrupting feedstock and consequently, generating simple sugars, amino acids, and fatty acids [6]. The feedstock pretreatment is a way to enhance the hydrolysis step by chemical or physical effect and provide an easy access of substrates to microbes, which leads to an increase in the growth of microbial and consequently, the generation of the desired product [6]. Cavitation can be used as an efficient pretreatment method providing improvements in feedstock, which enhance the efficacy of the main reactions [2, 6]. Fig. 3 briefly illustrates the effects of cavitation on food waste utilized for the formation of value-added products.

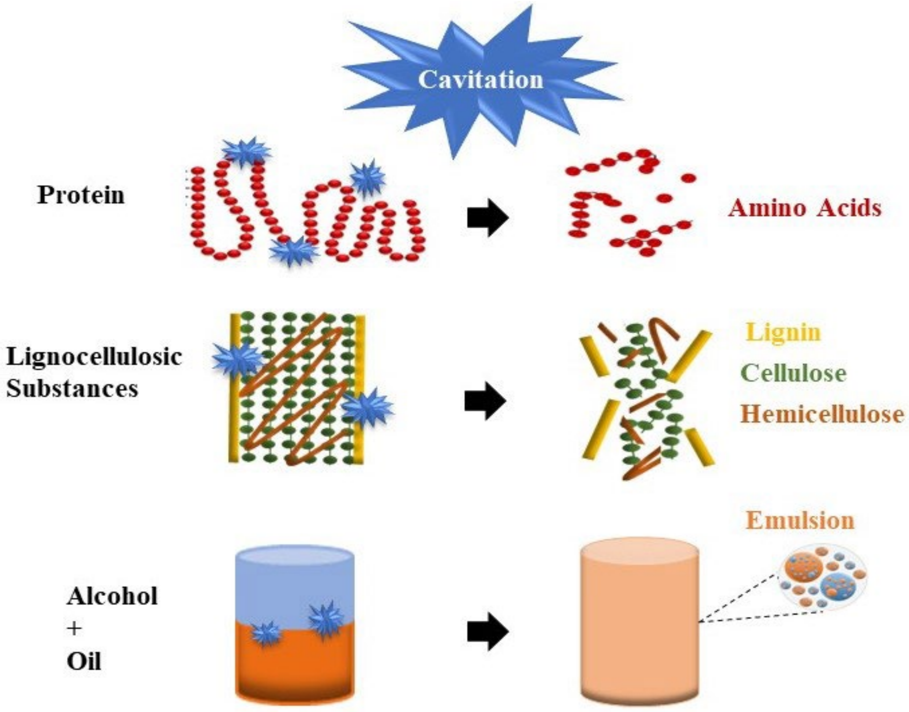

Fig. 3. The application of cavitation as a pretreatment for the processing of food waste.

A lignocellulosic food wastes are resistant to hydrolysis, since in this type of material the lignin fraction seals and protects cellulose molecules from hydrolysis [152]. The pretreatment of lignocellulosic wastes by cavitation is obtained by combination of physical and chemical effects [86]. The physical effect relates to shock waves, microjets, and shear stress causing the breakage of external structure and a decrease in particle size and degree of polymerization [153]. Cavitation can also result in a decrease in crystallinity index of cellulose [154]. However, most of researchers concluded that the effect of cavitation on the crystallinity index is negligible and may even cause an increase in this factor [155-158]. It can be due to the cavitation effects on both crystalline portion and amorphous portion of cellulose fibers [159]. Cavitation can also result in disorganized structural boundaries and loosened surface structure, leading to an increase in surface area [156, 160]. Furthermore, cavitation can cause an increase in total pore volume and total micropore volume of feedstock [86]. Therefore, cavitation as a pretreatment method can assist in the disruption of cell wall and the release of cellulose molecules into the solution, making an improvement in the solubility of organic matter [161]. Additionally, the chemical effect as a result of hot spot and hydroxyl radicals can cause the breakage of intermolecular hydrogen bond and the oxidation of lignin contents [121]. Thangavelu et al. [157] employed the combination of HC and enzyme and reported an increase in the content of cellulose by 25.3 % at an optimized pressure of 0.5 bar and reaction duration of 60 min.

The mechanical effect of cavitation has the most significant role in the disintegration of proteins which possess molecular weights higher than 20 kDa and consequently, the generation of amino acids and peptides, resulting in an enhancement to solubility of them [162]. It can cause the breakage of hydrogen bonds between large protein polymers and formation of smaller soluble protein aggregates [163]. Jang et al. [164] have investigated the influence of cavitation on the characteristics of food wastes and found that an increase in AC power till an optimum amount can increase the amount of dissolved protein. Beyond this optimum value, the percentage of protein remained constant possibly since the breakdown got saturated. They reported that AC as a pre-treatment method at a frequency of 20 kHz and a power density of 480 W/L increased the dissolved protein content of two feedstocks with TS of 40 g/L and 100 g/L by 374-424%, respectively, in 15 min. Elbeshbishy et al. [165] have reported that applying AC at a frequency of 20 kHz and a power density of 250 W/L enhanced the amount of soluble protein by approx. 20% in 24 min.

In the production of biodiesel through transesterification, the rate of reaction is dependent on the generated interfacial contact between oil and alcohol and the extent of mass transfer, which are related to the type of reactors employed for the synthesis. In the conventional reactors, usually a mechanical stirrer is utilized to form emulsion among immiscible liquid phases but cavitation reactors are reported to have a more satisfactory performance [12].

SCOD represents the soluble organic substances, and the enhanced SCOD is the result of proper hydrolysis stage. Disintegration degree (DD) is a factor demonstrating the enhancement made in feed stock, which is calculated by Eq. 4 [166].

$$DD = \frac{SCOD_f - SCOD_i}{TCOD_i - SCOD_i} \times 100 \qquad (4)$$

Where $TCOD_i$ is initial total chemical oxygen demand, and $SCOD_f$ and $SCOD_i$ represent initial and final soluble chemical oxygen demand, respectively. DD is useful for the assessment of effectiveness of pretreatment stage, nevertheless, most of papers on the application of cavitation for the pretreatment of food waste have not mentioned it, and even the data mentioned in those papers are not enough to calculate this degree. The improvements made in feedstock by cavitation are shown in Table 3. In overall, it can be concluded that both HC and AC allows to obtain disintegration of processed solid particles and solubilization as well as hydrolysis of solids resulting in increased amount of feedstock converted into liquefied state allowing its effective further processing to value-added products. Application of HC as a pretreatment method for waste activated sludge has resulted in a remarkable increase in SCOD in a range of 500%-2830%. It has caused a reduction in particle size by up to 82%. AC has led to a decrease in particle size by up to 80% and a significant enhancement to SCOD by up to 2300%. A power density of 500 W/L was employed for making this remarkable improvement in SCOD. Minimum particle sizes of 8 µm and 6 µm of waste activated sludge were obtained using HC and AC, respectively.

As the type of waste has a significant impact on the effectiveness of cavitation on the hydrolysis stage for increasing of SCOD, the range of enhanced SCOD of food waste was different comparing to waste activated sludge. Food wastes usually contain high amount of lignin and protein which are resistance to disintegration, hence, the disintegration of this type of waste might be more difficult. Up till know it was proved that cavitation can cause a considerable increase in SCOD of food wastes (table 4) by up to 172%.

On the other hand, in case of AC it is clear that only low frequency systems (19-40 kHz) were studied. According to available literature [18, 129, 167], higher frequencies (above 80 kHz) could cause a significant difference in result of food waste processing, as they offer more oxidative conditions to convert chemicals into hydrophilic derivatives. Up till know such attempts were not mode, thus in this field a big research gap is observed. Hopefully, next years should bring important understanding on the influence of high frequency aided sonocavitation on processing of food wastes.

Table 3. Several studies indicating the effect of cavitation pretreatment on feedstock

Sludge	Hydrodynamic Cavitation			Ref.
	Cavitating Device	**Pressure (bar)**	**Improved factors**	
Waste activated sludge	12-hole orifice	3.1-5.5	Reduction in average particle size from 45 to 8μm (82%). Increase in permeability.	[168]
Waste activated sludge	Single-hole orifice	4.9	Reduction in average particle size from 31 to 17 μm (45%). 2833% increase in SCOD.	[95]
Sugarcane bagasse	16-hole orifice	3	Up to 47% increase in cellulose content.	[158]
Sugarcane bagasse	27-hole orifice	3	60% decrease in lignin content.	[159]
Waste activated sludge	Swirling jet cavitation	4	Increase in SCOD from 244 to 1719 mg/L (604%).	[169]
Biomass	Stator and rotator	2	Increase in surface area from 28 to 35 m^2/kg TS (25%).	[170]
Sewage waste	Stator and rotator	-	77% reduction in particle size. 500% increase in SCOD.	[77]
Wheat straw	Stator and rotator	-	145% increase in methane yield.	[171]
Waste activated sludge	Venturi with 1.2 mm throat	12	Increase in SCOD from 100 to 1450 mg O_2/L (1350%).	[172]
Waste activated sludge	27-hole orifice	7	Disintegration degree of 23%.	[166]
1) Grass silage 2) Sugar cane bagasse	Vortex diode	3.9	1) 15% increase in methanation potential. 2) 40% increase in methanation potential.	[156]
Distillery spent wash	Vortex diode	3.9	14% increase in methanation potential.	[173]
Soya grass	Vortex diode	-	60% increase in methanation potential.	[174]

	Acoustic Cavitation			
Sludge	Power/Specific Energy	Frequency	Improved Factors	Ref.
Waste activated sludge	35000 kWs/kg TS	-	Reduction in particle size from 95 to 61 µm (35%). 394% increase in protein concentration.	[175]
Waste activated sludge	900 W/L	20	Reduction in particle size from 32 to 6 µm (80%).	[176]
Waste activated sludge	500 W/L	20	2306% increase in SCOD (from 338 to 8134 mg/L).	[177]
Sewage sludge	(a) 111 W min (b) 356 W min	16-20	(a) SCOD increase from 1509 to 1654 (10%), (b) SCOD increase from 1509 to 1755 (16%).	[178]
Mixed sludge	24 W/L	31	Reduction in particle size from 165 to 85 (48%). Increase in SCOD from 630 to 2270 mg/L (260%).	[179]
Sewage waste activated sludge	10800 kWs/L	28	Increase in SCOD/TCOD from 6% to 62%.	[180]
Sewage sludge	15500-30500 kWs/ kg TS	26	759–902% increase in soluble carbohydrate concentration. 450-659% increase in protein concentration.	[181]
Sewage sludge	21000 kWs/ kg TS	20	Increase in SCOD from 700-1200 to 4670 mg/L (567%-289%). Disintegration degree	[182]

			of 31.7%.	
Primary sludge	4000 W/L	20	Reduction in particle size from 48 to 12 µm (75%). Increase in SCOD from 1020 to 3980 mg/L (290%).	[183]

The results of some studies on the bioconversion of food wastes showing improved SCOD made by cavitation are demonstrated in Table 4.

Table 4. Improved SCOD made by cavitation.

		Acoustic Cavitation					
Frequency (kHz)	**Power Density (W/L)**	**Specific Energy (kWs/kg TS)**	**Irradiation time (min)**	**Duty Cycle%**	**TS**	**SCOD Increase%**	**Ref.**
-	837	23000	30	50%	65.5 g/L	22.1%	[184]
20	480	4320	15	100%	100 g/L	172%	[164]
		10800			40 g/L	157%	
20	400	3429	10	60%	7%	61.5%	[6]
20	232	6946	30	-	6%	159%	[152]
20	147	5000 (kWs/kg TSS)	24	50%		9%	[185]

	Hydrodynamic Cavitation				
Cavitating Device	**Cavitation Number**	**Cavitation cycle**	**TS**	**SCOD increase %**	**Ref.**
2 orifices	0.32	20	5%	48%	[186]

Particle size reduction usually happens very quickly and the maximum particle size reduction can be observed within the initial 15 mins for both AC and HC [170, 187]. However, Food wastes, which are rich in vegetables or fruit containing high amount of lignin, need more time for solubilization of organic substances [6, 157]. Re-flocculation of particles can happen and cause an increase in particle size at longer time. Although the cavitation initially decreases the size of particles, longer processing time can result in higher release of intercellular polymers. It follows from the cell lysis, which is favorable for re-flocculation. The released polymers can act as "glue" holding bioflocs together [188]. In Table 5, the characteristics of food wastes used in some studies for the production of valuable products are compiled.

Table 5. Characteristics of feedstock.

Feedstock	TS	VS	SCOD g/L	Desired Product	Ref.
Food Waste Leachate	30 g/L	23 g/L	36	CH_4	[189]
Wheat + Gram Flour + Rice + Fruit Peels + Vegetable	42±3%	65±3%	11.45	Biogas	[6]
Pulp Waste	65.5 g/L	46.1 g/L	49.9	Hydrogen	[184]
Bread + Tea Waste + Potato Peels + Rice + Banana Peels + Yard Waste	6%	-	6.5	Hydrogen	[152]
Rice + Cabbage + Pork + Tufo	40 g/L	35 g/L	34.6	VFAs	[164]
	100 g/L	99 g/L	41		
Rice + Noodles + Meat + Vegetable + Salad + Fecal Waste without urine	18.3 g/kg	17 g/kg	13	VFA	[151]

saccharified residues from food waste	26.3%	25.1%	-	Chain acids	[39]

In the case of AC, several parameters can affect the magnitude of enhanced SCOD such as AC power density, AC frequency, and AC duty cycle. The optimum values of all of these parameters are influenced by the complexity of content of food wastes. Low frequencies in a range between 20 and 50 kHz can result in the intensification of physical effects of cavitation and generation of shear stress which can lead to the breakage of complex molecules and formation of simple ones resulting in an increase in solubility and biodegradability [12, 48]. Therefore, the most investigations for the production of value added products from food waste have been performed at frequencies in this low range [165, 189]. Low power density is insufficient for the breakage of the feedstock, hence, an increase in it till an optimum amount can enhance the SCOD and generated bioproducts due to the maximum activity resulting from enhanced cell wall porosity, which enhances the transfer of nutrients from the fermented media to microorganisms [190]. Beyond this optimum amount, the SCOD remains almost constant [164]. The further increase can also cause a reduction in produced biogas because of cell disruption and deactivation of sludge leading a reduction in bioactivity of it as a result of excess AC energy input [52, 191]. Higher power density is effective when AC is employed as a feedstock pretreatment. Nevertheless, low power density is utilized when acoustic device is installed in the main anaerobic digestion reactor and irradiates to target microorganisms [192]. As a pretreatment method, AC at optimum power density values of 480 W/L [164], 400 W/L [6], and 230 W/L [152] provided a significant increase in SCOD. Low power intensity can result in an enhancement in product yield and a reduction in design time due to the stimulation of enzymatic activity of microorganisms and increase in mass transfer rate in the main stage [193, 194]. It was investigated this type of installation used power density values of 40 W/L [6] and 50 W/L [189, 195] for the conversion of food waste to bioproducts. It should be considered when acoustic device is installed in the main anaerobic digestion reactor AC power has a different influence depending on the type of microorganisms [191]. An increase in duty cycle above its optimum value can cause a decrease in amount of bioproducts since high AC irradiation can lead to excessive cavitation, which causes the degradation of solubilized contents [6]. Duty cycle values of 50% [165, 184, 185] and 60% [6] were reported in the literature as optimal. However, when AC is used in the main stage, lower duty cycle is employed since a prolonged AC period leads to the release of excess heat and mechanical shear causing adverse effects on microbial cells [6]. The optimum duty cycles vary by different microbial responses to AC, and optimum duty cycle values of 10% [6], 1.7% [185], and 1.6% [189, 195, 196] were reported. Additionally, substrate loading can also influence cavitation as it affects the density of slurry. In fact, an increase in the density of slurry can have a detrimental impact on cavitation, decreasing the solubilization of organic substances and SCOD. Substrate loading depends on the content of feedstock and is generally below 10% w/v [197]. It can be worth mentioning that the effect of input power, irradiation time, and TS can also be unified in specific energy but due to the shortage of available data reported in the literature it is still difficult to mention any general statements or optimum range for it.

In the case of HC, optimum cavitation number leading to efficient pretreatment for sludge disintegration is usually in a range from 0.07 to 0.15. The low hydrodynamic pressure is the best for waste disintegration and also the process highly depends on time [140]. Several studies using only HC made by orifice plates and venturi tubes as a pretreatment of bio sludge have indicated an optimum pressure in a range of 2-4 bar [168-170]. However, there are some other studies which reported higher pressure values [172, 198]. According to reports, higher disintegration is obtained at a higher pressure in a shorter duration. Nevertheless, if same energy supply is considered, lower pressure can also lead to the equal disintegration in a duration higher than 1 h [199]. For scale-up purposes, it is preferred to apply lower pressure for the most efficient lysis of cells [140]. Although the HC-based wastewater treatment for the removal of a variety of pollutants has been studied for years, the number of relative research on the pretreatment by HC for the formation of bioproducts from food waste is limited, which highlights the requirement for further investigation to determine the influence and range of optimum HC conditions. In HC, a main issue relates to small cross-section of the cavitating element. It causes issues for multiphase systems as well as mixtures containing large size of solid particles. There are a few studies in which HC induced by orifice [200-202] and venturi [203, 204] have been employed for the disintegration of lignocellulosic biomass but none of them have obviously explained how they coped with this problem. Alternatives are rotational cavitational devices and vortex diode systems which can induce cavitation along with effective disintegration of the particles [86, 156, 170]. In rotational devices, the intensity of cavitation is dependent on the rotational speed, and larger rotational speed can lead to higher turbulence and intensification of collapse of bubbles [205]. However, too high rotational speed is not economic and can also cause super cavitation. Hence, it is crucial to select an appropriate one [206]. In the literature, rotational speeds mainly in a range of 2000-3000 rpm have been offered for the disintegration aims [77, 121, 171, 207, 208]. The generation of bubbles in vortex-based devices involve a swirl flow and do not possess small constrictions, while forming cavities in the core of the flowing liquid. Hence, these type of systems are not susceptible to clogging when they are employed for the pretreatment of waste including solid particles [130]. More studies on this type of devices in respect to food wastes processing should be done in the near future for complete evaluation of their performance.

In case of HC, unique system configurations were studied, which makes difficult to point out general conclusions. At this stage of research, unification and further studies on most effective systems are needed. On the other hand, in case of AC it is clear that only low frequency systems (19-40 kHz) were studied. According to available literature [18, 129, 167], higher frequencies (above 80 kHz) could cause a significant difference in result of food waste processing, as they offer more oxidative conditions to convert chemicals into hydrophilic derivatives. Up till know such attempts were not studied, thus in this field a big research gap is observed. Hopefully next few years should bring important understanding on the influence of high frequency aided sonocavitation on processing of food wastes.

In the following paragraphs, the valuable products obtained from recycled food wastes by employing cavitation-assisted processes are discussed to show the effect of cavitation on the amount of final products and find out the range of optimum conditions of cavitation for obtaining the best results.

3.1. Biomethane

As mentioned before, hydrolysis is one of the severe limitations of biochemical conversion of waste in anaerobic digestion [150]. Furthermore, this method has some restrictions such as a requirement for complex reactor which is capable of providing appropriate contact, slow rate of digestion because of the complex structure of food stock, and the stability of microbiological culture [148]. Recently, researchers focused on enhancement in bioactivity of anaerobic cultures, which results in the intensification of application capacity, by the use of a variety of procedures like feedstock pretreatment. Cavitation as a pretreatment method is able to intensify the hydrolysis stage in anaerobic digestion by increasing the interaction between substrate and microbes through the reduction in particle size [8]. Moreover, low-intensity AC can enhance product yield and decrease digestion time by stimulating enzymes activities and decreasing mass transfer resistance [193]. Since cavitation can decrease crystallinity and the degree of polymerization of cellulose, it can result in the generation of lesser furfural and hydroxymethyl furfural inhibiting anaerobic digestion [13].

The improvements made in anaerobic digestion by cavitation were reported by investigating a variety of parameters. Xie et al. [194] investigated dehydrogenate activity (DHA) and the content of coenzyme F_{420} and reported a remarkable enhancement in the biological activity was achieved by using AC at a power intensity of 0.2 W/cm^2 and a frequency of 35 kHz, while a further increase in power intensity caused a drastic decrease in the activity. Cho et al. reported that the production of methane increased by 39% and 19% using AC at a power density of 2.5 W/L and frequency of 20 kHz for 2 s on time per 30 s (6.6% duty cycle) in ambient and mesophilic conditions, respectively [196]. Joshi and Gogate [6] have observed a 62.8% increase in SCOD and approximately 100% increase in biogas production employing AC at an optimum power density of 400 W/L and a frequency of 20 kHz in 10 min. However, further increases in power density to 1000 W/L just resulted in a 55.5% increase in SCOD compared to initial SCOD without using AC. Cho et al. [189] employed low-intensity AC for the production of methane and have reported a 213% enhancement in enzyme activity. Cho et al. [192] also performed a morphological study of cells applying low-intensity AC and indicated an increase in permeability by 37% and a rise in specific area by 230%. Tran et al. [186] have studied the application of HC with a cavitation number of 0.32 as a pretreatment method for the production of biomethane from food waste and indicated that HC enhanced the methane yield by 13% and kinetic constant by 60% as a result of a reduction in particle size and an increase in biomass solubilization. One cavitation cycle represents the required time for the whole sample volume to pass through the system and they reported a reduction in the consumption of energy by increasing the number of cavitation cycle. Larger particles require more energy to pass through cavitating devices and this decrease in the consumption of energy can indicate particle size reduction over time resulting from HC.

3.2. Biohydrogen

Nutrients and organic acids found in food wastes can be reused for the production of renewable biohydrogen by fermentation processes. Fermentation is one of the simplest biological procedures for the generation of hydrogen through the batch, semi-batch, and continues processes, and the hydrogen produced by fermentation process has high stability and efficiency. In a fermentation process, the feedstock is required to be hydrolyzed for being transformed to suitable substrate [2]. In a biochemical recycle of biomass, the hydrogen-producing enzymes are synthetized to generate hydrogen from complex molecules [209]. Dark fermentation is an anaerobic fermentative process in which both inorganic and organic substrates are transformed into biohydrogen in the absence of light. In this process, the complex sugars or polysaccharides are converted into biohydrogen, acetate butyrate, etc.

Intermediates such as lactate, acetate, butyrate, and ethanol are characteristic for this type of fermentation. Many researchers have reported the remarkable generation of biohydrogen by utilizing food wastes from restaurants and food processing industries [2]. During fermentation, fermentable sugars containing a high level of organic acids are extracted from food wastes and employed for the production of biohydrogen. In this case, complex polysugars structures are firstly converted to monosugars. Nevertheless, this method of generation of hydrogen has some limitations such as requirement for energy to separate organic acid and the cost of liquefaction to form soluble fermentable sugars [210]. Another disadvantage of this method is the slow kinetics of hydrogen generation [211]. Cavitation has attracted a lot of attention as a means of improving the efficacy of fermentation process by stimulating the growth of microorganisms, enhancing enzyme activities, and metabolic performance [212]. AC-assisted fermentation can intensify the generation of this renewable fuel due to the physical and chemical influences provided by cavitation in the medium. By using cavitation, the hydrolysis of substrate can be performed at a lower temperature [2]. Cavitation can enhance the kinetics of fermentation process as it increases cellular transport and stimulates changes in the structure of enzymes [11]. An improvement in cell membrane permeability caused by cavitation can induce the acceleration of microbial proliferation. AC at a low power results in repairable damages to microorganisms, while a high power can cause permanent damages [213]. Additionally, reactive radicals produced by the collapse of bubbles can make a contribution to the thermochemical and biochemical reactions and disrupt the complex sugars in the food wastes and produce the simple ones. The holes which appear in the cells are the result of synergistic effect of mechanical effects and highly reactive radicals induced by cavitation. These free radicals have primary responsibility for the movement of lipid bilayer and can disrupt the cell membrane due to lipid peroxidation [214]. An increase in the permeability of membrane results in the acceleration of substances transfer and therefore, the intensification of growth of microorganisms [215]. Cavitation can increase the number of viable cells due to the de-agglomeration of microbial clusters, which can increase the consumption of nutrients by microorganisms [213]. However, using AC at a power higher than 100 W/L in an experiment time greater than 90 min can remarkably reduce the number of these viable cells. Hence, AC can have both positive and negative influences on microbial proliferation, depending on power and the duration of fermentation process [214]. Similarly, AC can also have both inhibition and promotion effects on enzymes activities. It has been reported that the impact of AC on the activity of endoenzymes is much more extreme than on exoenzymes. The enhanced enzyme activities can be attributed to the intensified release of endoenzymes into substrates through the altered permeability of cell membranes. AC can also promote enzyme activities by reducing thermodynamic parameters such as activation energy [216]. Nevertheless, the denaturation of enzymes may also occur when AC is applied at excessively high power. The duration of AC also has the same effect on the activity of enzymes [217]. Cavitation can also decrease the growth of microorganisms which inhibit the generation of hydrogen in the feed waste [2]. Acoustic irradiations can help to eliminate some of the restrictions happening in fermentation stage done for the generation of hydrogen through the disruption of complex intermediates and bioconversion of substances into desired compounds by selective biometabolic pathways. Cavitation can also enhance the possibility of breakage of hydrogen bonds from the substrate. This process can be used combined with heat-shock, alkaline, and acid pretreatments [152].

Elbeshbishy et al. [184] have compared hydrogen production with and without AC, and reported an increase in hydrogen production by 77% and a rise in hydrogen production rate by 127% when using AC at a 23000 kWs/ kg TS as a pre-treatment of pulp waste followed by anaerobic hydrogen production. Moreover, they have indicated an increase of 70% in VFAs using AC in irradiation time of 30 mins. Dinesh et al. [2] have investigated the influence of AC on the generation of biohydrogen and indicated more than an 80% increase in hydrogen production. Elbeshbishy et al. [165] have compared the production of biohydrogen in three systems: A) A continuously-stirred tank reactor (CSTR) consuming raw food waste, B) a continuously-stirred tank reactor consuming sonicated food waste, and C) an AC biological hydrogen reactor (SBHR) including a CSTR connected with an ultrasonic probe at the bottom of the reactor, and reported the increase in hydrogen production by 27% and 90% using systems B and C compared with that of system A, respectively. Furthermore, systems B and C exhibited an enhanced hydrogen yield by 23% and 62%, respectively. It clearly confirmed advantageous application of sonocavitation for biohydrogen production processes.

3.3. Volatile Fatty Acids (VFAs)

Volatile fatty acids (VFAs), such as acetic acid, propanoic acid, butyric acid, can be produced through the conversion of complex sugars or polysaccharides in anaerobic fermentation by acetogenic bacteria through following reactions:

$$C_6H_{12}O_2 + H_2O_2 \rightarrow 4H_2 + 2CH_3COOH + CO_2 \quad (5)$$

$$C_6H_{12}O_2 + 2\ H_2 \rightarrow 4H_2 + 2CH3CH_2COOH + CO_2 \quad (6)$$

$$C_6H_{12}O_2 + H_2O_2 \rightarrow 2H_2 + 2CH_3CH_2CH_2COOH + CO_2 \quad (7)$$

VFAs are a valuable product which can be employed to enhance the biosynthesis value of polyhydroxyalkanoates and utilized as raw material for the production of biodegradable thermoplastics [218, 219]. However, the low efficiency of formation of VFAs is a limitation for being used industrially [164]. Rajagopal et al. [151] have reported that an 86% of total VFAs generated from an adjusted feedstock with alkaline pH was acetic acid, since the formation of short-chain fatty acids with lower molecular weight from short-chain fatty acids with higher molecular weight was efficient at alkaline pH [220]. Similar to other products, the first stage related to solubilization and hydrolysis is the main restriction of VFAs production. The degree and products of hydrolysis stage directly influence the fermentation stage since microorganisms just access dissolved organic matters for biological degradation [221, 222]. The key objectives of pretreatment methods are the enhancement in biodegradability of substrate, and reduction in mass transfer resistance which lead to the full consumption of sugar and protein by microorganisms and as a result, promotion of formation of VFAs [223]. Due to the physical and chemical effects provided by cavitation, a considerable contribution can be made to the production of these valuable acids by softening the content of food wastes and breakage of the structure of substance for providing appropriate substrates and as a result, enhancing the VFAs production rate [224]. Jiang et al. [164] have studied the formation of VFAs from food wastes through anaerobic digestion fermentation and reported the concentration of VFAs based on COD equivalent. They indicated that by using AC at optimum conditions (a frequency of 20 kHz, a power density of 480 W/L, and an irradiation time of 15 min) significantly increased the VFAs produced from food wastes. Elbeshbishy and Nakhla [185] have reported that by applying AC as a pretreatment at a frequency of 20 kHz under specific energy of 5000 kWs/kg TSS increased by 7% the concentration of VFAs. While using AC in the main stage resulted in 18% increase in VFAs concentration. The observed increase in VFAs formation was related to the enhancement made in the amounts of SCOD, protein, and reducing sugars, that started to be available (soluble) from the processed waste for bioconversion. Elbeshbishy et al. [184] have reported an increase in the production of VFAs by 70% from food waste at 23000 kWs/kg TS. In another study [165], this team has indicated that the concentration of VFAs increased by approx. 7% using AC at 5000 kWs/kg TS.

3.4. Lactic Acid

Lactic acid ($C_3H_6O_3$) is a valuable substance which is widely employed in a variety of industries such as food, textile, chemical, pharmaceutical [225, 226]. It is mainly used as an acidulant, flavor, or component for the formation of polymers utilized for food packaging, grafts, etc. [225]. It is expected that the production of lactic acid will increase by approximately 60% because of the growth of demand for this acid [227]. This acid can be produced chemically or by fermentation, however, fermentative production is regarded as a more environment-friendly method because of the less use of harsh chemicals and fewer by-products [228]. Lactic acid is generated through the hydrolysis and acidogenesis processes, which are the first two stages of anaerobic digestion [229]. These two stages are often promoted at pH in the range of 4-5, resulting in an increase in the formation of lactic acid by utilizing food waste as the substrate [230]. In the literature, food wastes like potato peels, mango peels, and vegetable and fruit residue were utilized as low cost and economically viable substrates for the microbial fermentation of lactic acid [231]. The production of lactic acid is not efficient by using the conventional method, and cavitation can enhance its production as a result of enhanced homogenization, leading to an increase in availability of sugars and proteins for the consumption by microorganisms [225]. Ma et al. [39] employed AC at a frequency of 28 kHz and a power of 1600 Was a pre-treatment method of saccharified residues and reported a significant (162%) enhancement of lactic acid production. Cavitation can enhance mass transfer performance between the substrate and inoculated sludges and as a result, increase the production of the acid. Đukić-Vuković et al. [225] applied AC at a frequency of 20 kHz as a pre-treatment method and indicated an increase in lactic acid concentration from wasted bread by 15%. At early stage of research on cavitation based processes in this application it is hard to form general conclusions, as beside the configuration of sonocavitation system, obtained results are fundamentally affected by characteristics of food wastes as well as bacteria strains used in final bioconversion. It is clear that more studies followed by serious standardization of research conditions are a must.

3.5. Biodiesel

Food waste oil can be recycled for the production of biodiesel, which refers to fatty acid alkyl esters present in vegetable oils and animal fats. Fig. 4 illustrates the reaction mechanism of biodiesel production on a surface of a heterogeneous catalyst.

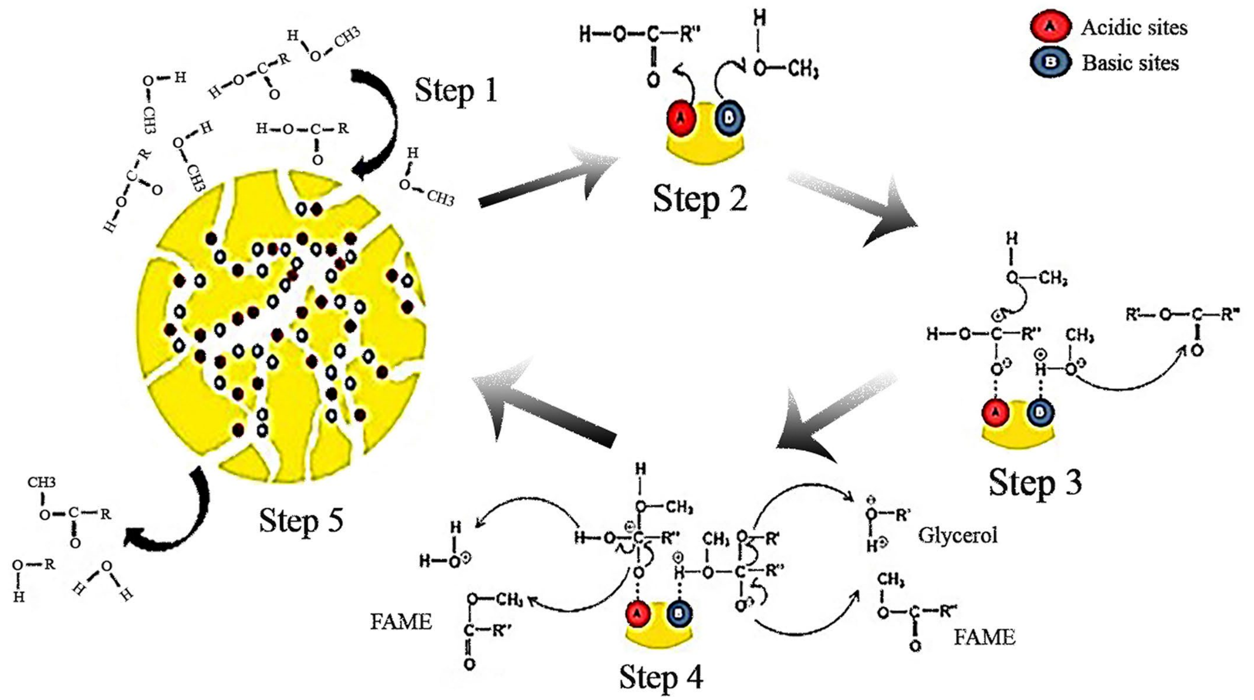

Fig. 4. The mechanism of biodiesel production on a heterogeneous catalyst (Reuse from Esmaeili [232]).

The key reaction in biodiesel production is transesterification, a chemical reaction which requires a catalyst to take place and generate biodiesel (i.e., fatty acids methyl esters, FAME). During transesterification triglycerides found in the raw substances react with simple alcohol such as methanol or ethanol [233, 234]. Non-edible oils are rich in free acids, which are considered a limitation for transesterification because of the potential of soap formation from the reaction between free acid and alkali (the catalyst). Biodiesel generation from non-edible oils requires acid-catalyzed synthesis method or a two-step approach of esterification followed by transesterification to reduce the amount of acid. Both of these approaches consume a lot of energy and time, hence, it is crucial to develop process intensification technology resulting in more efficient approaches [12]. Conventional stirring methods used for biodiesel production normally require temperature in the range of 70-200 ℃, pressure in the range of 6-10 atm, and reaction time up to 70 h to obtain conversion in the range of 90%-95% depending on the type of raw substance, type, and concentration of catalyst, and the percentage of excess alcohol [235]. A variety of pretreatment methods have been investigated for the intensification of transesterification and among them, cavitation has been selected as the most effective one [236]. Cavitation can decrease mass transfer resistance, which is a serious limitation of transesterification because of the immiscible nature of fatty acids and alcohol as the reactants of this reaction. The collapse of bubbles can disrupt the phase boundary of this liquid-liquid heterogeneous system and provide close contact between reagents due to the formation of emulsion, and as a result, enhance the transesterification reaction [15, 237]. It has been indicated that conventional stirring methods are approximately 10 times slower than HC-assisted and AC-assisted methods [235]. Since in the case of biodiesel, which physical effect of cavitation is beneficial, a frequency in the range of 20-50 kHz is recommended. In addition, the utilization of multiple-frequency operations can lead to more intense and uniformly distributed cavitation [12, 63]. Enzymatic procedure for biodiesel synthesis has been regarded as the most viable green choice, and it has been indicated that the application of low-frequency AC can have advantageous for biological operations like microbial cell disruption [13]. An increase in power up to an optimum value results in a decrease in the entire mixing time. However, a further increase can reduce the yield of FAMEs, which can be attributed to the fact that gasification caused by higher power can produce a mass of bubbles and decrease the methanol content in the liquid phase and interface zone [73]. Cavitation can remarkably reduce the time of reaction compared to conventional transesterification [238]. Sáez-Bastante et al. [234] have compared the production of biodiesel from chicken grease and beef-lamb grease using an AC-assisted method (at a frequency of 20 kHz and a power of 500 W) with that of the conventional one, and reported that AC resulted in an increase in conversion and a decrease in reaction time. Teixeira et al. [238] have studied the production of biodiesel using animal fat by AC-assisted transesterification at a frequency of 24 kHz and a power of 400 W and indicated a reduction in reaction time from 1 h for conventional method to 70 s by AC-assisted process. Fayyazi et al. [239] have employed chicken fat oil for the production of biodiesel using AC at 24 kHz and reported a reduction in reaction time by 87%. Deshmane et al. [240] have reported that AC aided process resulted in 98.5% conversion comparing to 90% for classic system along with 4-time shortening of reaction time. This advancement was confirmed also by studies of Mootabadi et al. [53]. Yu et al. [241] have investigated the AC-assisted production of biodiesel at a frequency of 40 kHz and a power of 400 W/L in the presence of lipase enzyme (Novozym 435) and indicated a significant improvement in efficiency from 62 to 93%.. Moreover, cavitation can lead to an energy-saving transesterification in comparison with the conventional one as the same effect can be achieved at lower reaction temperature [12, 234]. The usefulness of AC reactors and cavitational influence for biodiesel production is determined by oil properties. When there are two phases in the reaction system, it is better to have AC irradiation in the alcohol phase [12]. It has been reported that HC is more efficient in comparison to acoustic cavitation, however, the energy produced in

HC reactors depends on the type of cavitating device [73, 235]. Kelkar et al. [235] confirmed that comparable results can be obtained for HC-assisted esterification at an operating temperature of 30 °C comparing to conventional system operated at 65°C. Furthermore, HC resulted in a 3-5-time decrease in required excess of methanol to fatty acid. HC and AC were compared based on cavitational yield representing the yield of product per unit supplied energy to the system. It was indicated that the HC- cavitational yield was in the range of $1*10^{-4}$ - $2*10^{-4}$ g/J (on the basis of supplied energy) and the AC-cavitational yield was in the range of $5*10^{-6}$-$2*10^{-}5$ g/J. Additionally, HC has more potential for being industrially applied since it is not sensitive to scale-up [73]. Wang et al. [73] have studied biodiesel production by applying AC and HC and reported that AC-assisted transesterification at a frequency of 19.7 kHz and a power of 150 W and HC-assisted transesterification at an operating pressure of 7 bar with a single orifice as cavitating device led to 100% conversion in 10 min and 30 min, respectively. The energy consumption values for AC- and HC-assisted processes were 250 Wh/kg and 183 Wh/Kg, respectively.

3.6. Other Products

Caproic acid is a medium-chain carboxylic acid gaining more attention because of its wide range of applications. This acid can be utilized in food and paint industries as additives as well as in pharmaceutical industry. In addition, it can be employed as an antimicrobial material and a plant growth promoter [242]. Caproic acid is a suitable intermediate in bioproduct formation processes because of its high caloric value and hydrophobicity and can be formed from an electron donor such as lactic acid or ethanol and an electron acceptor such as VFAs [243, 244]. Ma et al. [39] have investigated the effect of AC on the production of this acid and reported a 113%

enhancement comparing to classic process using a 28 kHz frequency system with power density of 1600 W.

Sophorolipid is a type of biosurfactant possessing skin moisturizing, antibacterial, skin healing, and anticancer properties, which can be generated by microbial conversion of vegetable oils [245-247]. In addition, it can be employed as a capping agent to synthetize cobalt nanoparticles, and enhance oil recovery [248, 249]. The ability of sophorolipid to stimulate the metabolism of skin fibroblast cells has made it attractive to be utilized in therapeutic cosmetic applications [250]. Maddikeri et al. [249] have used AC at a frequency of 40 kHz and a power of 600 W for pretreatment of waste cooking oil as feedstock to fermentation process revealing usefulness of cavitation for this process - a 14% increase in sophorolipid yield was reported. This enhancement can be attributed to the alteration of permeability and mass transfer as a result of cavitation phenomenon. In table 6, the valuable products converted from food wastes by cavitation-aided processes are compared to demonstrate the impact of cavitation on the amount of final products and find out the optimum range of parameters for achieving the best results.

Table 6. Role of cavitation-based processes and optimum conditions depending on target product.

Reported Products	Food waste details/type	Optimum conditions	Temp./ pH	Cavitation-aided stage	Obtained modification	Ref.
Biodiesel	Palm oil	20 kHz, 400 W/L, Irradiation time:60 min, Catalyst: BaO, SrO, CaO Methanol:Oil=12:1 3%w/w catalyst	65 °C	Main stage	50%-75% reduction in reaction time, 42%, 97.5, 1300% increase in biodiesel yield.	[53]
Biodiesel	Waste cooking oil	20 kHz, 34 W/L, 50% duty cycle, 1 wt.% H_2SO_4 Methanol:Oil=10:1	28 °C	Main stage	96% reduction in reaction time, 54% reduction in operating temperature, 65% reduction in required excess methanol.	[235]
Biodiesel	Beef tallow	24 kHz, 400 W, Irradiation time: 70 s, 0.5% wt/wt KOH, Methanol:Oil=6:1	60 °C	Main stage	98% reduction in reaction time.	[238]
Biodiesel	Chicken fat	24 kHz, Irradiation time=9	45 °C	Main stage	87.5% reduction in reaction	[239]

		min, 1% w/w KOH, Methanol:Oil=7:1,			time.	
Biodiesel	Soybean	19.7 kHz, 150 W, Irradiation time: 10 min, Methanol:Oil=6:1 1 wt.% KOH	45 °C	Main stage	Higher than 85% reduction in reaction time.	[73]
Biodiesel	Soybean	Single orifice, 0.7 MPa, Reaction time: 30 min, Methanol:Oil= 6:1, 1 wt.% KOH	45 °C	Main stage	50% reduction in reaction time.	[73]
Biodiesel	Waste cooking oil	Orifice plate, 1 wt.% H_2SO_4 Methanol:Oil=10:1	28 °C	Main stage	96% reduction in reaction time, 54% reduction in operating temperature, 65% reduction in required excess methanol.	[235]
Biogas	Food waste containing wheat, gram flour and rice with some	20 kHz, 400 W/L, 60% duty cycle,	6.2	Pretreatment	61.5% increase in SCOD.	[6]

	content of fruit peels and vegetable waste	Irradiation time: 10 min, Substrate loading: 7%w/v				
Biogas	Food waste containing wheat, gram flour and rice with some content of fruit peels and vegetable waste; SCOD:18 g/L	25 kHz, 40 W/L, 10% duty cycle, Irradiation time: 5 min	7.5	Main stage	100% increase in biogas production, 67% increase in SCOD removal.	[6]
Caproic acid, Lactic acid	TS:26% VS:25%	28 kHz, 1600 W, Irradiation time: 30 min	25 °C, 6.3	Pretreatment	113% increase in caproic acid production, 62% increase in lactic acid production.	[39]
Lactic acid	Stillage after bioethanol production on wasted bread	20 kHz, Irradiation time: 10 min	6.5	Pretreatment	15% increase in lactic acid production.	[225]
Hydrogen	Bread (28%), tea wastes (25%), potato peels (23%), rice (14%), banana peels (10%): TS:6%, SCOD:6.5 g/L	20 kHz, 232 W/L, 6946 kWs/kg TS	-	Pretreatment	159% increase in SCOD, negligible effect on biohydrogen yield.	[152]

Hydrogen, VFAs	Pulp waste from Dufferin Organics Processing Facility (DOPF); TS:65.5 g/L, VS:46 g/L, SCOD:45 g/L	23000 kWs/kg TS, 837 W/L, 50% duty cycle, Irradiation time: 30 min	30 °C	Pretreatment	30% increase in soluble carbohydrate, 13.6% increase in soluble protein, 145% increase in hydrogen production, 70% increase in VFAs.	[184]
Hydrogen, VFAs	DOPF TSS:42.5 g/L, VSS:29 g/L, SCOD:44 g/L	20 kHz, 5000 kWs/kg TSS, 50% duty cycle, Irradiation time: 24 min	-	Pretreatment	27% increase in hydrogen production, 7% increase in VFAs.	[165]
Hydrogen, VFAs	DOPF; TSS:42.5 g/L, VSS:29 g/L, SCOD:44 g/L	20 kHz, 250 W/L, 1.6 % duty cycle, Irradiation time: 24 min/d	-	Main stage	90% increase in hydrogen production, 48% increase in VFAs.	[165]
Hydrogen, Methane	Food waste from DOPF;TSS:42 g/L, VSS:29 g/L, SCOD:44 g/L	20 kHz, 250 W/L, 1.7% duty cycle, Irradiation time: 24 min/d	37 °C, 5-6	Main stage	85% increase in hydrogen production, 40% increase in methane production.	[185]
Methane	Food waste from DOPF ; TSS:42 g/L, VSS:29 g/L,	5000 kWs/kg TSS, 147 W/L, 50% duty cycle,	30 °C, 7	Pretreatment	9% increase in SCOD, 20% increase in soluble protein,	[185]

	SCOD:44 g/L	Irradiation time: 24 min			17% increase in soluble carbohydrate, 31% increase in methane production.	
Methane	Food waste leachate; TS:30 g/L VS:23 g/L, SCOD:36 g/L	20 kHz, 50 W/L, 1.6 % duty cycle	37 °C, 7	Main stage	213% increase in hydrolytic enzyme activities, 18% increase in methane production, 8.5% increase in SCOD removal.	[189]
Methane	Food waste from student canteen in the campus of university; TS:211 g/L, VS:174 g/L, SCOD:148 g/L	50 W/L, 1.6% duty cycle	25 °C, 7	Main stage	38% increase in methane production.	[196]
Methane	Food waste from biogas plant; TS:5%, Particle size < 4 mm	Two orifices with diameter in a range of 1-3 mm, 20 cavitation cycles	-	Pretreatment	48% increase in SCOD, 13% increase in methane yield.	[186]
Sophorolipid	Waste cooking oil	of 40 kHz, 600 W, 20% duty cycle, Irradiation	-	Main stage	14% increase in sophorolipid yield.	[249]

		time:10 min				
VFAs	Rice(35%), Cabbage(45%), Pork(16%), Tufo(4%); 1. TS:40 g/L, VS:36 g/L, SCOD:35 g/L 2. TS :100g/L, VS:99 g/L SCOD:40 g/L	20 kHz, 480 W/L, Irradiation time: 15 min	4.6-5	Pretreatment	1. 172% increase in SCOD, 374% increase in protein content, 100% increase in VFAs. 2. 157% increase in SCOD, 424% increase in protein content, 58% increase in VFAs.	[164]

It is clear that cavitation was employed in main process of biodiesel production, while for other types of processes its usefulness was confirmed both for pretreatment stage of the feedstock as well as to aid the main process. In case of biodiesel production, it is known that feedstocks also demand pretreatment, for example to firstly remove or esterify the free fatty acids, which lowers the consumption of catalyst. It seems that due to advantages of cavitation phenomenon to enhance mass transfer, it should be studied also to assist the pretreatment of biodiesel feedstocks [129].

Depending on the stage of processing, different strategies of cavitation employment are observed. According to the comparison made in table 6, when using AC as a pretreatment, higher power density is employed comparing to the cases in which AC is applied in the main stage and directly irritates on the microorganisms. Accordingly, lower duty cycle is used when acoustic devices are installed in the main reactor. The reported effect of HC on the biogas production is weaker than for AC system, which can be attributed to the lack of appropriate design of HC reactors. In the case of biodiesel production, the application of both AC and HC results in a considerable reduction in reaction time. Cavitation can also lead to a decrease in required operating temperature and excess alcohol.

Conclusion

Cavitation phenomenon causes changes in food waste feedstock on microscale and even on molecular level. Detailed studies on this aspects, including interactions of formed cavitational bubbles, formed micro-jets with solid structures of food waste particles are needed to fully explain observed macroscale changes in the processed streams. On the other hand, applicational value is evaluated based on macroscale observations relating to changes of the size of solid particles as well as increase of bioavalability of food waste components caused by cracking, hydrolysis and oxidation which make some part of the feedstock soluble. These effects can be related to process parameters affecting the rate and intensity of cavitation. Such analysis of the already developed processes should allow to form general conclusions useful for other researchers working on applications of cavitation and food waste conversion to value-added products. This review was performed on the latter point of view.

Cavitation has been revealed to be effective to remarkably facilitate the conversion of food wastes to value-added products such as biogas, biodiesel, VFAs, biohydrogen as well as lactic acids. It can be employed both in the pretreatment stage of the feedstocks as well as in the main bioproduction stage. In first case, much more destructive abilities of cavitation are utilized using high power density. It follows from the need of disintegration of solids in food wastes and intensification of chemical transformations leading to increased bioavailability of primary material (increased SCOD) of post-treated feedstock. According to reviewed studies, the optimum power density is in a range from 230 W/L to 480 W/L for the disintegration aims, and a power density of minimum 230 W/L of processed mixture is needed to obtain a significant increase in SCOD. In case of aiding the main bioprocess less intensive cavitation is used, mainly to increase mass transfer and to minimize negative effects of cavitation on microorganisms. In this type of installation, low intensity AC is employed and the optimal density values are in a range of 40-50 W/L. However, it should be noted that for cases in which the acoustic device is installed in the main anaerobic digestion reactor, the optimum range of the power density depends on the type of microorganisms. The optimum duty cycle values in a range of 50%-60%

and 1.6%-10% were employed for the pretreatment and for main process, respectively. Substrate loading is affected by the content of feedstock and is generally below 10% w/v.

It is crucial to investigate the geometry of cavitation reactor and properly design it to achieve the maximum chemical and especially mechanical effects. Future researchers should follow already published system configuration that seems to be the most effective to unify the instrumentation used in cavitation-aided processing and allow to compare data between different projects.

A variety of other factors can influence the effectiveness of cavitation and yield of bioproducts. In the case of AC, low frequencies in a range of 20-50 kHz are suitable for the desired production of bioproducts through anaerobic digestion and transesterification. However, studies on application of high frequency ultrasounds in AC for pretreatment of feedstocks are scarce and clear "research-gap" in this field exists. In near future, more studies in this field should be performed.

In the case of HC based on orifice plates and venturi tubes, optimum cavitation number and pressure resulting in efficient pretreatment for sludge disintegration is mainly in a range of 0.07-0.15 and 2-4 bar, respectively. Rotational speeds mainly in a range of 2000-3000 rpm have been offered for the disintegration by rotational type HC reactors. Vortex diode systems have been rarely investigated for the conversion of waste to bioproducts and should be considered in future studies as these types of devices are desirable for pretreatment of food waste since they do not possess small constrictions and are energy efficient as they do not need high pressures to be operated, any moving parts and require low maintenance cost. Particle size reduction usually occurs rapidly and the maximum particle size reduction can be obtained within the initial 15 mins for both AC and HC. According to the reviewed literature, for food waste, cavitation can result in an increase in SCOD in a range from 9% to 172%, stimulation of enzyme activities, and reduction in mass transfer resistance. Cavitation pretreatment of food waste has led to an increase in biogas production in a range of 13-100%. It has also increased biohydrogen generated from food waste in a range from 27% to 145%. The enhancements in VFAs and lactic acid produced from food waste were reported to be in a range of 7-100% and 15-62%, respectively. Furthermore, Cavitation-assisted conversion of food waste into biodiesel has resulted in a reduction in reaction time in a range of 50-98%.

Observed strong differences in results obtained by different research groups on the role of cavitation phenomenon in percent enhancement of overall effectiveness of bioconversion of food wastes, confirm the need of standardization of systems (reactors) used in the studies. On the other hand, research community should develop commonly acceptable reference (model) food waste materials used in the future studies to confirm the effectiveness of used system, allowing easy comparison of results between published papers. As first recommendation, it is believed that such a model food waste could be based on boiled potatoes or rice, as their elementary composition and structure are relatively comparable worldwide. Effectiveness evaluation of the pretreatment process should be done based on standardized parameters. SCOD increase is useful parameter. However, to relate obtained effect to primary content of food waste solid fraction in the feedstock a disintegration degree (DD) parameter should be also provided. Up till know in studies of cavitation based processes this parameter was omitted by researchers in results reporting.

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References

1. Grillo, G., et al., *Cocoa bean shell waste valorisation; extraction from lab to pilot-scale cavitational reactors.* Food Research International, 2019. **115**: p. 200-208.
2. Dinesh, G.K., R. Chauhan, and S. Chakma, *Influence and strategies for enhanced biohydrogen production from food waste.* Renewable and Sustainable Energy Reviews, 2018. **92**: p. 807-822.
3. Kumar, P., A. Hussain, and S.K. Dubey, *Methane formation from food waste by anaerobic digestion.* Biomass conversion and biorefinery, 2016. **6**(3): p. 271-280.
4. Kim, D.-H., et al., *Sewage sludge addition to food waste synergistically enhances hydrogen fermentation performance.* Bioresource Technology, 2011. **102**(18): p. 8501-8506.
5. Sawatdeenarunat, C., et al., *Anaerobic digestion of lignocellulosic biomass: challenges and opportunities.* Bioresource technology, 2015. **178**: p. 178-186.
6. Joshi, S.M. and P.R. Gogate, *Intensifying the biogas production from food waste using ultrasound: Understanding into effect of operating parameters.* Ultrasonics sonochemistry, 2019. **59**: p. 104755.
7. Kannah, R.Y., et al., *Food waste valorization: Biofuels and value added product recovery.* Bioresource Technology Reports, 2020. **11**: p. 100524.
8. Zhang, C., et al., *The anaerobic co-digestion of food waste and cattle manure.* Bioresource technology, 2013. **129**: p. 170-176.
9. Joshi, S.M. and P.R. Gogate, *Intensified Synthesis of Bioethanol from Sustainable Biomass*, in *Waste Biomass Management–A Holistic Approach*. 2017, Springer. p. 251-287.
10. Mullai, P., M. Yogeswari, and K. Sridevi, *Optimisation and enhancement of biohydrogen production using nickel nanoparticles–A novel approach.* Bioresource technology, 2013. **141**: p. 212-219.
11. Sarma, S., et al., *Metabolic flux network analysis of hydrogen production from crude glycerol by Clostridium pasteurianum.* Bioresource technology, 2017. **242**: p. 169-177.
12. Gole, V.L. and P.R. Gogate, *A review on intensification of synthesis of biodiesel from sustainable feed stock using sonochemical reactors.* Chemical Engineering and Processing: Process Intensification, 2012. **53**: p. 1-9.
13. Gogate, P.R. and A.M. Kabadi, *A review of applications of cavitation in biochemical engineering/biotechnology.* Biochemical Engineering Journal, 2009. **44**(1): p. 60-72.
14. Gągol, M., et al., *Hydrodynamic cavitation based advanced oxidation processes: Studies on specific effects of inorganic acids on the degradation effectiveness of organic pollutants.* Journal of Molecular Liquids, 2020. **307**: p. 113002.
15. Qiu, Z., L. Zhao, and L. Weatherley, *Process intensification technologies in continuous biodiesel production.* Chemical Engineering and Processing: Process Intensification, 2010. **49**(4): p. 323-330.

16. Gągol, M., A. Przyjazny, and G. Boczkaj, *Highly effective degradation of selected groups of organic compounds by cavitation based AOPs under basic pH conditions.* Ultrasonics sonochemistry, 2018. **45**: p. 257-266.
17. De-Nasri, S.J., et al., *Quantification of hydroxyl radicals in photocatalysis and acoustic cavitation: Utility of coumarin as a chemical probe.* Chemical Engineering Journal, 2020: p. 127560.
18. Fedorov, K., et al., *Synergistic effects of hybrid advanced oxidation processes (AOPs) based on hydrodynamic cavitation phenomenon–a review.* Chemical Engineering Journal, 2021: p. 134191.
19. Badve, M., et al., *Hydrodynamic cavitation as a novel approach for wastewater treatment in wood finishing industry.* Separation and purification technology, 2013. **106**: p. 15-21.
20. Philipp, A. and W. Lauterborn, *Cavitation erosion by single laser-produced bubbles.* Journal of fluid mechanics, 1998. **361**: p. 75-116.
21. Supponen, O., et al., *The inner world of a collapsing bubble.* Physics of Fluids, 2015. **27**(9): p. 091113.
22. Dijkink, R. and C.-D. Ohl, *Measurement of cavitation induced wall shear stress.* Applied physics letters, 2008. **93**(25): p. 254107.
23. Xuan, X., et al., *Nanoarchitectonics of low-dimensional metal-organic frameworks toward photo/electrochemical CO2 reduction reactions.* Journal of CO2 Utilization, 2022. **57**: p. 101883.
24. Musmarra, D., et al., *Degradation of ibuprofen by hydrodynamic cavitation: Reaction pathways and effect of operational parameters.* Ultrasonics Sonochemistry, 2016. **29**: p. 76-83.
25. Suslick, K.S., *Sonochemistry.* science, 1990. **247**(4949): p. 1439-1445.
26. Wang, B., H. Su, and B. Zhang, *Hydrodynamic cavitation as a promising route for wastewater treatment–A review.* Chemical Engineering Journal, 2021. **412**: p. 128685.
27. Cako, E., et al., *Ultrafast degradation of brilliant cresyl blue under hydrodynamic cavitation based advanced oxidation processes (AOPs).* Water Resources and Industry, 2020. **24**: p. 100134.
28. Askarniya, Z., M. Sadeghi, and S. Baradaran, *Removal of Naphthalene from Wastewater Using Hydrodynamic Cavitation.* 2020.
29. Suslick, K.S., D.A. Hammerton, and R.E. Cline, *Sonochemical hot spot.* Journal of the American Chemical Society, 1986. **108**(18): p. 5641-5642.
30. Gogate, P.R., *Hydrodynamic Cavitation for Food and Water Processing.* Food and Bioprocess Technology, 2011. **4**(6): p. 996-1011.
31. Pang, Y.L., A.Z. Abdullah, and S. Bhatia, *Review on sonochemical methods in the presence of catalysts and chemical additives for treatment of organic pollutants in wastewater.* Desalination, 2011. **277**(1-3): p. 1-14.
32. Gogate, P.R., *Cavitational reactors for process intensification of chemical processing applications: A critical review.* Chemical Engineering and Processing: Process Intensification, 2008. **47**(4): p. 515-527.
33. Ritesh, P. and V.C. Srivastava, *Understanding of ultrasound enhanced electrochemical oxidation of persistent organic pollutants.* Journal of Water Process Engineering, 2020. **37**: p. 101378.
34. Asgharzadehahmadi, S., et al., *Sonochemical reactors: Review on features, advantages and limitations.* Renewable and Sustainable Energy Reviews, 2016. **63**: p. 302-314.
35. Goyat, M., S. Ray, and P. Ghosh, *Innovative application of ultrasonic mixing to produce homogeneously mixed nanoparticulate-epoxy composite of improved physical properties.* Composites Part A: Applied Science and Manufacturing, 2011. **42**(10): p. 1421-1431.
36. Li, W., et al., *Ultrasound–The Physical and Chemical Effects Integral to Food Processing, Ref. Modul.* Food Sci, 2019.
37. Kumar, A., et al., *Characterization of flow phenomena induced by ultrasonic horn.* Chemical engineering science, 2006. **61**(22): p. 7410-7420.

38. Sutkar, V.S. and P.R. Gogate, *Design aspects of sonochemical reactors: techniques for understanding cavitational activity distribution and effect of operating parameters.* Chemical Engineering Journal, 2009. **155**(1-2): p. 26-36.
39. Ma, H., et al., *Effect of ultrasonic pretreatment on chain elongation of saccharified residue from food waste by anaerobic fermentation.* Environmental Pollution, 2021. **268**: p. 115936.
40. Kozmus, G., et al., *Characterization of cavitation under ultrasonic horn tip–Proposition of an acoustic cavitation parameter.* Ultrasonics sonochemistry, 2022: p. 106159.
41. Csoka, L., S.N. Katekhaye, and P.R. Gogate, *Comparison of cavitational activity in different configurations of sonochemical reactors using model reaction supported with theoretical simulations.* Chemical Engineering Journal, 2011. **178**: p. 384-390.
42. Kumar, A., P.R. Gogate, and A.B. Pandit, *Mapping the efficacy of new designs for large scale sonochemical reactors.* Ultrasonics sonochemistry, 2007. **14**(5): p. 538-544.
43. Priego-Capote, F. and M.L. De Castro, *Analytical uses of ultrasound I. Sample preparation.* TrAC Trends in Analytical Chemistry, 2004. **23**(9): p. 644-653.
44. Pugin, B., *Qualitative characterization of ultrasound reactors for heterogeneous sonochemistry.* Ultrasonics, 1987. **25**(1): p. 49-55.
45. Gogate, P.R. and A.B. Pandit, *Sonochemical reactors: scale up aspects.* Ultrasonics Sonochemistry, 2004. **11**(3-4): p. 105-117.
46. Sivakumar, M., P.A. Tatake, and A.B. Pandit, *Kinetics of p-nitrophenol degradation: effect of reaction conditions and cavitational parameters for a multiple frequency system.* Chemical Engineering Journal, 2002. **85**(2-3): p. 327-338.
47. Gogate, P.R., V.S. Sutkar, and A.B. Pandit, *Sonochemical reactors: important design and scale up considerations with a special emphasis on heterogeneous systems.* Chemical Engineering Journal, 2011. **166**(3): p. 1066-1082.
48. Gogate, P.R. and A.B. Pandit, *Sonophotocatalytic reactors for wastewater treatment: a critical review.* AIChE journal, 2004. **50**(5): p. 1051-1079.
49. Thokchom, B., et al., *A review on sonoelectrochemical technology as an upcoming alternative for pollutant degradation.* Ultrasonics Sonochemistry, 2015. **27**: p. 210-234.
50. Sabnis, S.S., R. Raikar, and P.R. Gogate, *Evaluation of different cavitational reactors for size reduction of DADPS.* Ultrasonics Sonochemistry, 2020. **69**: p. 105276.
51. Hielscher, K., *Ultrasonic milling and dispersing technology for nano-particles.* MRS Online Proceedings Library (OPL), 2012. **1479**: p. 21-26.
52. Zhang, G., et al., *Using acoustic cavitation to improve the bio-activity of activated sludge.* Bioresource Technology, 2008. **99**(5): p. 1497-1502.
53. Mootabadi, H., et al., *Ultrasonic-assisted biodiesel production process from palm oil using alkaline earth metal oxides as the heterogeneous catalysts.* Fuel, 2010. **89**(8): p. 1818-1825.
54. Salamatinia, B., A.Z. Abdullah, and S. Bhatia, *Quality evaluation of biodiesel produced through ultrasound-assisted heterogeneous catalytic system.* Fuel Processing Technology, 2012. **97**: p. 1-8.
55. Badday, A.S., A.Z. Abdullah, and K.-T. Lee, *Optimization of biodiesel production process from Jatropha oil using supported heteropolyacid catalyst and assisted by ultrasonic energy.* Renewable energy, 2013. **50**: p. 427-432.
56. Choudhury, H.A., et al., *Ultrasonic biodiesel synthesis from crude Jatropha curcas oil with heterogeneous base catalyst: mechanistic insight and statistical optimization.* Ultrasonics sonochemistry, 2014. **21**(3): p. 1050-1064.

57. Gupta, A.R., S.V. Yadav, and V.K. Rathod, *Enhancement in biodiesel production using waste cooking oil and calcium diglyceroxide as a heterogeneous catalyst in presence of ultrasound.* Fuel, 2015. **158**: p. 800-806.
58. Mahamuni, N.N. and Y.G. Adewuyi, *Optimization of the synthesis of biodiesel via ultrasound-enhanced base-catalyzed transesterification of soybean oil using a multifrequency ultrasonic reactor.* Energy & fuels, 2009. **23**(5): p. 2757-2766.
59. Aghbashlo, M., et al., *Multi-objective exergetic and technical optimization of a piezoelectric ultrasonic reactor applied to synthesize biodiesel from waste cooking oil (WCO) using soft computing techniques.* Fuel, 2019. **235**: p. 100-112.
60. Crum, L.A., *Comments on the evolving field of sonochemistry by a cavitation physicist.* Ultrasonics Sonochemistry, 1995. **2**(2): p. S147-S152.
61. Shestakova, M., et al., *Sonoelectrocatalytic decomposition of methylene blue using Ti/Ta2O5–SnO2 electrodes.* Ultrasonics Sonochemistry, 2015. **23**: p. 135-141.
62. Feng, R., et al., *Enhancement of ultrasonic cavitation yield by multi-frequency sonication.* Ultrasonics sonochemistry, 2002. **9**(5): p. 231-236.
63. Yasui, K., T. Tuziuti, and Y. Iida, *Dependence of the characteristics of bubbles on types of sonochemical reactors.* Ultrasonics Sonochemistry, 2005. **12**(1-2): p. 43-51.
64. Nanzai, B., et al., *Effect of reaction vessel diameter on sonochemical efficiency and cavitation dynamics.* Ultrasonics sonochemistry, 2009. **16**(1): p. 163-168.
65. Hodnett, M., M.J. Choi, and B. Zeqiri, *Towards a reference ultrasonic cavitation vessel. Part 1: Preliminary investigation of the acoustic field distribution in a 25 kHz cylindrical cell.* Ultrasonics sonochemistry, 2007. **14**(1): p. 29-40.
66. Contamine, R.F., et al., *Power measurement in sonochemistry.* Ultrasonics Sonochemistry, 1995. **2**(1): p. S43-S47.
67. Bund, R. and A. Pandit, *Sonocrystallization: effect on lactose recovery and crystal habit.* Ultrasonics sonochemistry, 2007. **14**(2): p. 143-152.
68. Khaire, R.A. and P.R. Gogate, *Understanding the role of different operating modes and ultrasonic reactor configurations for improved sonocrystallization of lactose.* Chemical Engineering and Processing-Process Intensification, 2021. **159**: p. 108212.
69. Khaire, R.A. and P.R. Gogate, *Intensified recovery of lactose from whey using thermal, ultrasonic and thermosonication pretreatments.* Journal of Food Engineering, 2018. **237**: p. 240-248.
70. Patil, G.K., et al., *Effect of process parameters on the recovery of lactose in an antisolvent acetone/acetone-ethanol mixture: A comparative study based on sonication medium.* Ultrasonics Sonochemistry, 2020. **67**: p. 105128.
71. Zhang, Z., et al., *Ultrasound-promoted extraction of cheap microbial flocculant from waste activated sludge.* Environmental technology, 2013. **34**(10): p. 1219-1224.
72. Singh, A.K. and S.D. Fernando. *Base catalyzed fast-transesterification of soybean oil using ultrasonication*. in *2006 ASAE Annual Meeting*. 2006. American Society of Agricultural and Biological Engineers.
73. Ji, J., et al., *Preparation of biodiesel with the help of ultrasonic and hydrodynamic cavitation.* Ultrasonics, 2006. **44**: p. e411-e414.
74. Ge, M., et al., *Combined suppression effects on hydrodynamic cavitation performance in Venturi-type reactor for process intensification.* Ultrasonics Sonochemistry, 2022: p. 106035.
75. Rajoriya, S., S. Bargole, and V.K. Saharan, *Degradation of reactive blue 13 using hydrodynamic cavitation: Effect of geometrical parameters and different oxidizing additives.* Ultrasonics sonochemistry, 2017. **37**: p. 192-202.

76. Jain, P., et al., *Hydrodynamic cavitation using vortex diode: An efficient approach for elimination of pathogenic bacteria from water.* Journal of environmental management, 2019. **242**: p. 210-219.
77. Kim, H., et al., *Investigation of sludge disintegration using rotor-stator type hydrodynamic cavitation reactor.* Separation and Purification Technology, 2020. **240**: p. 116636.
78. Askarniya, Z., M.-T. Sadeghi, and S. Baradaran, *Decolorization of Congo red via hydrodynamic cavitation in combination with Fenton's reagent.* Chemical Engineering and Processing-Process Intensification, 2020. **150**: p. 107874.
79. Doltade, S.B., et al., *Hydrodynamic cavitation as an imperative technology for the treatment of petroleum refinery effluent.* Journal of Water Process Engineering, 2019. **29**: p. 100768.
80. Liu, C., et al., *Cavitation onset caused by a dynamic pressure wave in liquid pipelines.* Ultrasonics Sonochemistry, 2020. **68**: p. 105225.
81. Bhat, A.P. and P.R. Gogate, *Cavitation-based pre-treatment of wastewater and waste sludge for improvement in the performance of biological processes: A review.* Journal of Environmental Chemical Engineering, 2020: p. 104743.
82. Mukherjee, A., et al., *Surfactant degradation using hydrodynamic cavitation based hybrid advanced oxidation technology: A techno economic feasibility study.* Chemical Engineering Journal, 2020. **398**: p. 125599.
83. Kumar, P.S., M.S. Kumar, and A. Pandit, *Experimental quantification of chemical effects of hydrodynamic cavitation.* Chemical Engineering Science, 2000. **55**(9): p. 1633-1639.
84. Çalışkan, Y., H.C. Yatmaz, and N. Bektaş, *Photocatalytic oxidation of high concentrated dye solutions enhanced by hydrodynamic cavitation in a pilot reactor.* Process Safety and Environmental Protection, 2017. **111**: p. 428-438.
85. Choi, J., et al., *Hydrodynamic cavitation and activated persulfate oxidation for degradation of bisphenol A: Kinetics and mechanism.* Chemical Engineering Journal, 2018. **338**: p. 323-332.
86. Sun, X., et al., *Recent advances in hydrodynamic cavitation-based pretreatments of lignocellulosic biomass for valorization.* Bioresource Technology, 2021: p. 126251.
87. Barik, A.J. and P.R. Gogate, *Hybrid treatment strategies for 2, 4, 6-trichlorophenol degradation based on combination of hydrodynamic cavitation and AOPs.* Ultrasonics sonochemistry, 2018. **40**: p. 383-394.
88. Saharan, V.K., et al., *Effect of geometry of hydrodynamically cavitating device on degradation of orange-G.* Ultrasonics sonochemistry, 2013. **20**(1): p. 345-353.
89. Albanese, L., et al., *Beer-brewing powered by controlled hydrodynamic cavitation: Theory and real-scale experiments.* Journal of Cleaner Production, 2017. **142**: p. 1457-1470.
90. Rajoriya, S., S. Bargole, and V.K. Saharan, *Degradation of a cationic dye (Rhodamine 6G) using hydrodynamic cavitation coupled with other oxidative agents: Reaction mechanism and pathway.* Ultrasonics sonochemistry, 2017. **34**: p. 183-194.
91. Gągol, M., A. Przyjazny, and G. Boczkaj, *Wastewater treatment by means of advanced oxidation processes based on cavitation–a review.* Chemical Engineering Journal, 2018. **338**: p. 599-627.
92. Mukherjee, A., et al., *Performance and energetic analysis of hydrodynamic cavitation and potential integration with existing advanced oxidation processes: A case study for real life greywater treatment.* Ultrasonics Sonochemistry, 2020. **66**: p. 105116.
93. Rajoriya, S., et al., *Hydrodynamic cavitation: an advanced oxidation process for the degradation of bio-refractory pollutants.* Reviews in Chemical Engineering, 2016. **32**(4): p. 379-411.
94. Saharan, V.K., M.P. Badve, and A.B. Pandit, *Degradation of Reactive Red 120 dye using hydrodynamic cavitation.* Chemical Engineering Journal, 2011. **178**: p. 100-107.

95. Jung, K.-W., et al., *Development of a novel electric field-assisted modified hydrodynamic cavitation system for disintegration of waste activated sludge.* Ultrasonics sonochemistry, 2014. **21**(5): p. 1635-1640.
96. Bagal, M.V. and P.R. Gogate, *Degradation of 2, 4-dinitrophenol using a combination of hydrodynamic cavitation, chemical and advanced oxidation processes.* Ultrasonics sonochemistry, 2013. **20**(5): p. 1226-1235.
97. Bis, M., et al., *Application of hydrodynamic cavitation to improve the biodegradability of mature landfill leachate.* Ultrasonics sonochemistry, 2015. **26**: p. 378-387.
98. Lu, G., et al., *Effect of cavitation hydrodynamic parameters on bisphenol A removal.* Environmental Engineering Science, 2019. **36**(8): p. 873-882.
99. Abbas-Shiroodi, Z., M.-T. Sadeghi, and S. Baradaran, *Design and optimization of a cavitating device for Congo red decolorization: Experimental investigation and CFD simulation.* Ultrasonics Sonochemistry, 2021. **71**: p. 105386.
100. Lee, I., Y.-K. Oh, and J.-I. Han, *Design optimization of hydrodynamic cavitation for effectual lipid extraction from wet microalgae.* Journal of Environmental Chemical Engineering, 2019. **7**(2): p. 102942.
101. Huang, Y., et al., *Degradation of chitosan by hydrodynamic cavitation.* Polymer Degradation and Stability, 2013. **98**(1): p. 37-43.
102. Balasundaram, B. and S. Harrison, *Optimising orifice geometry for selective release of periplasmic products during cell disruption by hydrodynamic cavitation.* Biochemical engineering journal, 2011. **54**(3): p. 207-209.
103. Ghayal, D., A.B. Pandit, and V.K. Rathod, *Optimization of biodiesel production in a hydrodynamic cavitation reactor using used frying oil.* Ultrasonics sonochemistry, 2013. **20**(1): p. 322-328.
104. Wang, Y., et al., *Disinfection of bore well water with chlorine dioxide/sodium hypochlorite and hydrodynamic cavitation.* Environmental technology, 2015. **36**(4): p. 479-486.
105. Malade, L.V. and U.B. Deshannavar, *Decolorisation of Reactive Red 120 by hydrodynamic cavitation.* Materials Today: Proceedings, 2018. **5**(9): p. 18400-18409.
106. Vichare, N.P., P.R. Gogate, and A.B. Pandit, *Optimization of hydrodynamic cavitation using a model reaction.* Chemical Engineering & Technology: Industrial Chemistry ‐ Plant Equipment ‐ Process Engineering ‐ Biotechnology, 2000. **23**(8): p. 683-690.
107. Entezari, M.H. and P. Kruus, *Effect of frequency on sonochemical reactions II. Temperature and intensity effects.* Ultrasonics Sonochemistry, 1996. **3**(1): p. 19-24.
108. Braeutigam, P., et al., *Role of different parameters in the optimization of hydrodynamic cavitation.* Chemical Engineering & Technology: Industrial Chemistry ‐ Plant Equipment ‐ Process Engineering ‐ Biotechnology, 2010. **33**(6): p. 932-940.
109. Sivakumar, M. and A.B. Pandit, *Wastewater treatment: a novel energy efficient hydrodynamic cavitational technique.* Ultrasonics sonochemistry, 2002. **9**(3): p. 123-131.
110. Ashrafizadeh, S.M. and H. Ghassemi, *Experimental and numerical investigation on the performance of small-sized cavitating venturis.* Flow measurement and Instrumentation, 2015. **42**: p. 6-15.
111. Xiong, Y. and F. Peng, *Optimization of cavitation venturi tube design for pico and nano bubbles generation.* International journal of mining science and technology, 2015. **25**(4): p. 523-529.
112. Jain, T., J. Carpenter, and V.K. Saharan, *CFD analysis and optimization of circular and slit venturi for cavitational activity.* J Mater Sci Mech Eng, 2014. **1**(1): p. 28-33p.
113. Mishra, K.P. and P.R. Gogate, *Intensification of degradation of Rhodamine B using hydrodynamic cavitation in the presence of additives.* Separation and Purification Technology, 2010. **75**(3): p. 385-391.

114. Kuldeep and V.K. Saharan, *Computational study of different venturi and orifice type hydrodynamic cavitating devices.* Journal of Hydrodynamics, Ser. B, 2016. **28**(2): p. 293-305.
115. Saharan, V.K., *Computational study of different venturi and orifice type hydrodynamic cavitating devices.* Journal of Hydrodynamics, Ser. B, 2016. **28**(2): p. 293-305.
116. Bashir, T.A., et al., *The CFD driven optimisation of a modified venturi for cavitational activity.* The Canadian Journal of Chemical Engineering, 2011. **89**(6): p. 1366-1375.
117. Sun, X., et al., *Effect of the cavitation generation unit structure on the performance of an advanced hydrodynamic cavitation reactor for process intensifications.* Chemical Engineering Journal, 2021. **412**: p. 128600.
118. Sežun, M., et al., *Cavitation as a potential technology for wastewater management: an example of enhanced nutrient release from secondary pulp and paper mill sludge.* Strojniški vestnik, 2019. **65**(11/12): p. 641-649.
119. Petkovšek, M., et al., *Rotation generator of hydrodynamic cavitation for water treatment.* Separation and purification technology, 2013. **118**: p. 415-423.
120. Badve, M.P., et al., *Modeling the shear rate and pressure drop in a hydrodynamic cavitation reactor with experimental validation based on KI decomposition studies.* Ultrasonics sonochemistry, 2015. **22**: p. 272-277.
121. Badve, M.P., et al., *Hydrodynamic cavitation as a novel approach for delignification of wheat straw for paper manufacturing.* Ultrasonics Sonochemistry, 2014. **21**(1): p. 162-168.
122. Jyoti, K. and A.B. Pandit, *Water disinfection by acoustic and hydrodynamic cavitation.* Biochemical Engineering Journal, 2001. **7**(3): p. 201-212.
123. Maršálek, B., et al., *Synergistic effects of trace concentrations of hydrogen peroxide used in a novel hydrodynamic cavitation device allows for selective removal of cyanobacteria.* Chemical Engineering Journal, 2020. **382**: p. 122383.
124. Zupanc, M., et al., *Shear-induced hydrodynamic cavitation as a tool for pharmaceutical micropollutants removal from urban wastewater.* Ultrasonics sonochemistry, 2014. **21**(3): p. 1213-1221.
125. Wang, X. and Y. Zhang, *Degradation of alachlor in aqueous solution by using hydrodynamic cavitation.* Journal of hazardous materials, 2009. **161**(1): p. 202-207.
126. Kulkarni, A.A., et al., *Pressure drop across vortex diodes: Experiments and design guidelines.* Chemical Engineering Science, 2009. **64**(6): p. 1285-1292.
127. Sarvothaman, V.P., A.T. Simpson, and V.V. Ranade, *Modelling of vortex based hydrodynamic cavitation reactors.* Chemical Engineering Journal, 2019. **377**: p. 119639.
128. Ranade, V.V., et al., *Scale-up of vortex based hydrodynamic cavitation devices: A case of degradation of di-chloro aniline in water.* Ultrasonics sonochemistry, 2021. **70**: p. 105295.
129. Cako, E., et al., *Cavitation based cleaner technologies for biodiesel production and processing of hydrocarbon streams: A perspective on key fundamentals, missing process data and economic feasibility–A review.* Ultrasonics sonochemistry, 2022. **88**: p. 106081.
130. Simpson, A. and V.V. Ranade, *110th Anniversary: comparison of cavitation devices based on linear and swirling flows: hydrodynamic characteristics.* Industrial & Engineering Chemistry Research, 2019. **58**(31): p. 14488-14509.
131. Thanekar, P. and P.R. Gogate, *Combined hydrodynamic cavitation based processes as an efficient treatment option for real industrial effluent.* Ultrasonics sonochemistry, 2019. **53**: p. 202-213.
132. Baradaran, S. and M.T. Sadeghi, *Coomassie Brilliant Blue (CBB) degradation using hydrodynamic cavitation, hydrogen peroxide and activated persulfate (HC-H2O2-KPS) combined process.* Chemical Engineering and Processing-Process Intensification, 2019. **145**: p. 107674.

133. Saxena, S., V.K. Saharan, and S. George, *Enhanced synergistic degradation efficiency using hybrid hydrodynamic cavitation for treatment of tannery waste effluent.* Journal of Cleaner Production, 2018. **198**: p. 1406-1421.
134. Kumar, M.S., S. Sonawane, and A.B. Pandit, *Degradation of methylene blue dye in aqueous solution using hydrodynamic cavitation based hybrid advanced oxidation processes.* Chemical Engineering and Processing: Process Intensification, 2017. **122**: p. 288-295.
135. Patil, P.N., S.D. Bote, and P.R. Gogate, *Degradation of imidacloprid using combined advanced oxidation processes based on hydrodynamic cavitation.* Ultrasonics sonochemistry, 2014. **21**(5): p. 1770-1777.
136. Prajapat, A.L. and P.R. Gogate, *Intensified depolymerization of aqueous polyacrylamide solution using combined processes based on hydrodynamic cavitation, ozone, ultraviolet light and hydrogen peroxide.* Ultrasonics Sonochemistry, 2016. **31**: p. 371-382.
137. Gore, M.M., et al., *Degradation of reactive orange 4 dye using hydrodynamic cavitation based hybrid techniques.* Ultrasonics sonochemistry, 2014. **21**(3): p. 1075-1082.
138. Kumar, M.S., et al., *Treatment of ternary dye wastewater by hydrodynamic cavitation combined with other advanced oxidation processes (AOP's).* Journal of Water Process Engineering, 2018. **23**: p. 250-256.
139. Patil, P.N. and P.R. Gogate, *Degradation of methyl parathion using hydrodynamic cavitation: effect of operating parameters and intensification using additives.* Separation and purification technology, 2012. **95**: p. 172-179.
140. Bhat, A.P. and P.R. Gogate, *Cavitation-based pre-treatment of wastewater and waste sludge for improvement in the performance of biological processes: A review.* Journal of Environmental Chemical Engineering, 2021. **9**(2): p. 104743.
141. Moholkar, V., I. Shirgaonkar, and A. Pandit, *Cavitation and sonochemistry in the eyes of a chemical engineer.* INDIAN CHEMICAL ENGINEER SECTION B INDUSTRY AND NEWS, 1996. **38**: p. 81-93.
142. Gogate, P.R., *Cavitation: an auxiliary technique in wastewater treatment schemes.* Advances in Environmental Research, 2002. **6**(3): p. 335-358.
143. Mason, T.J. and J.P. Lorimer, *Applied sonochemistry: the uses of power ultrasound in chemistry and processing*. Vol. 10. 2002: Wiley-Vch Weinheim.
144. Xu, L., W. Chu, and N. Graham, *Degradation of di-n-butyl phthalate by a homogeneous sono–photo–Fenton process with in situ generated hydrogen peroxide.* Chemical Engineering Journal, 2014. **240**: p. 541-547.
145. Wu, Z., et al., *Harnessing cavitational effects for green process intensification.* Ultrasonics Sonochemistry, 2019. **52**: p. 530-546.
146. Sun, X., et al., *Hydrodynamic cavitation: A promising technology for industrial-scale synthesis of nanomaterials.* Frontiers in Chemistry, 2020. **8**: p. 259.
147. Sun, X., et al., *A review on hydrodynamic cavitation disinfection: The current state of knowledge.* Science of the Total Environment, 2020. **737**: p. 139606.
148. Kadam, R. and N. Panwar, *Recent advancement in biogas enrichment and its applications.* Renewable and Sustainable Energy Reviews, 2017. **73**: p. 892-903.
149. Yadav, M., et al., *Reprint of: Organic waste conversion through anaerobic digestion: A critical insight into the metabolic pathways and microbial interactions.* Metabolic Engineering, 2022.
150. Menzel, T., P. Neubauer, and S. Junne, *Role of microbial hydrolysis in anaerobic digestion.* Energies, 2020. **13**(21): p. 5555.

151. Rajagopal, R., A. Ahamed, and J.-Y. Wang, *Hydrolytic and acidogenic fermentation potential of food waste with source segregated feces-without-urine as co-substrate.* Bioresource technology, 2014. **167**: p. 564-568.
152. Bundhoo, Z.M., *Effects of microwave and ultrasound irradiations on dark fermentative bio-hydrogen production from food and yard wastes.* International Journal of Hydrogen Energy, 2017. **42**(7): p. 4040-4050.
153. Bundhoo, Z.M. and R. Mohee, *Ultrasound-assisted biological conversion of biomass and waste materials to biofuels: A review.* Ultrasonics sonochemistry, 2018. **40**: p. 298-313.
154. Pinjari, D.V. and A.B. Pandit, *Cavitation milling of natural cellulose to nanofibrils.* Ultrasonics sonochemistry, 2010. **17**(5): p. 845-852.
155. Madison, M.J., et al., *Mechanical pretreatment of biomass–Part I: Acoustic and hydrodynamic cavitation.* Biomass and Bioenergy, 2017. **98**: p. 135-141.
156. Nagarajan, S. and V.V. Ranade, *Pretreatment of lignocellulosic biomass using vortex-based devices for cavitation: influence on biomethane potential.* Industrial & Engineering Chemistry Research, 2019. **58**(35): p. 15975-15988.
157. Thangavelu, K., et al., *Delignification of corncob via combined hydrodynamic cavitation and enzymatic pretreatment: process optimization by response surface methodology.* Biotechnology for biofuels, 2018. **11**(1): p. 1-13.
158. Hilares, R.T., et al., *Hydrodynamic cavitation as an efficient pretreatment method for lignocellulosic biomass: a parametric study.* Bioresource technology, 2017. **235**: p. 301-308.
159. Hilares, R.T., et al., *Hydrodynamic cavitation-assisted alkaline pretreatment as a new approach for sugarcane bagasse biorefineries.* Bioresource technology, 2016. **214**: p. 609-614.
160. Hilares, R.T., et al., *A new approach for bioethanol production from sugarcane bagasse using hydrodynamic cavitation assisted-pretreatment and column reactors.* Ultrasonics sonochemistry, 2018. **43**: p. 219-226.
161. Sun, Y. and J. Cheng, *Hydrolysis of lignocellulosic materials for ethanol production: a review.* Bioresource technology, 2002. **83**(1): p. 1-11.
162. Jayasooriya, S., et al., *Effect of high power ultrasound waves on properties of meat: a review.* International Journal of Food Properties, 2004. **7**(2): p. 301-319.
163. Zhang, Y., et al., *Effects of ultrasound pretreatment on the enzymolysis and structural characterization of wheat gluten.* Food Biophysics, 2015. **10**(4): p. 385-395.
164. Jiang, J., et al., *Effects of ultrasound pre-treatment on the amount of dissolved organic matter extracted from food waste.* Bioresource technology, 2014. **155**: p. 266-271.
165. Elbeshbishy, E., H. Hafez, and G. Nakhla, *Ultrasonication for biohydrogen production from food waste.* International Journal of Hydrogen Energy, 2011. **36**(4): p. 2896-2903.
166. Lee, I. and J.-I. Han, *The effects of waste-activated sludge pretreatment using hydrodynamic cavitation for methane production.* Ultrasonics Sonochemistry, 2013. **20**(6): p. 1450-1455.
167. Cako, E., et al., *Desulfurization of raw naphtha cuts using hybrid systems based on acoustic cavitation and advanced oxidation processes (AOPs).* Chemical Engineering Journal, 2022. **439**: p. 135354.
168. Cai, M., et al., *Synergetic pretreatment of waste activated sludge by hydrodynamic cavitation combined with Fenton reaction for enhanced dewatering.* Ultrasonics sonochemistry, 2018. **42**: p. 609-618.
169. Mancuso, G., M. Langone, and G. Andreottola, *A swirling jet-induced cavitation to increase activated sludge solubilisation and aerobic sludge biodegradability.* Ultrasonics Sonochemistry, 2017. **35**: p. 489-501.

170. Garuti, M., et al., *Monitoring of full-scale hydrodynamic cavitation pretreatment in agricultural biogas plant.* Bioresource technology, 2018. **247**: p. 599-609.
171. Patil, P.N., et al., *Intensification of biogas production using pretreatment based on hydrodynamic cavitation.* Ultrasonics sonochemistry, 2016. **30**: p. 79-86.
172. Grübel, K. and J. Suschka, *Hybrid alkali-hydrodynamic disintegration of waste-activated sludge before two-stage anaerobic digestion process.* Environmental Science and Pollution Research, 2015. **22**(10): p. 7258-7270.
173. Nagarajan, S. and V.V. Ranade, *Pre-treatment of distillery spent wash (vinasse) with vortex based cavitation and its influence on biogas generation.* Bioresource Technology Reports, 2020. **11**: p. 100480.
174. Nagarajan, S. and V.V. Ranade, *Valorizing Waste Biomass via Hydrodynamic Cavitation and Anaerobic Digestion.* Industrial & Engineering Chemistry Research, 2021. **60**(46): p. 16577-16598.
175. Feng, X., et al., *Dewaterability of waste activated sludge with ultrasound conditioning.* Bioresource technology, 2009. **100**(3): p. 1074-1081.
176. Nguyen, D.D., et al., *Enhanced efficiency for better wastewater sludge hydrolysis conversion through ultrasonic hydrolytic pretreatment.* Journal of the Taiwan Institute of Chemical Engineers, 2017. **71**: p. 244-252.
177. Li, X., et al., *Anaerobic digestion using ultrasound as pretreatment approach: Changes in waste activated sludge, anaerobic digestion performances and digestive microbial populations.* Biochemical Engineering Journal, 2018. **139**: p. 139-145.
178. Quarmby, J., et al., *The application of ultrasound as a pre-treatment for anaerobic digestion.* Environmental technology, 1999. **20**(11): p. 1155-1161.
179. Tiehm, A., K. Nickel, and U. Neis, *The use of ultrasound to accelerate the anaerobic digestion of sewage sludge.* Water science and technology, 1997. **36**(11): p. 121-128.
180. Na, S., Y.-U. Kim, and J. Khim, *Physiochemical properties of digested sewage sludge with ultrasonic treatment.* Ultrasonics sonochemistry, 2007. **14**(3): p. 281-285.
181. Neumann, P., Z. González, and G. Vidal, *Sequential ultrasound and low-temperature thermal pretreatment: process optimization and influence on sewage sludge solubilization, enzyme activity and anaerobic digestion.* Bioresource technology, 2017. **234**: p. 178-187.
182. Tian, X., W.J. Ng, and A.P. Trzcinski, *Optimizing the synergistic effect of sodium hydroxide/ultrasound pre-treatment of sludge.* Ultrasonics Sonochemistry, 2018. **48**: p. 432-440.
183. Mao, T., et al., *A comparison of ultrasound treatment on primary and secondary sludges.* Water Science and Technology, 2004. **50**(9): p. 91-97.
184. Elbeshbishy, E., H. Hafez, and G. Nakhla, *Viability of ultrasonication of food waste for hydrogen production.* International journal of hydrogen energy, 2012. **37**(3): p. 2960-2964.
185. Elbeshbishy, E. and G. Nakhla, *Comparative study of the effect of ultrasonication on the anaerobic biodegradability of food waste in single and two-stage systems.* Bioresource Technology, 2011. **102**(11): p. 6449-6457.
186. Tran, D., *Hydrodynamic cavitation applied to food waste anaerobic digestion*. 2016.
187. Zhao, Y.-H., et al. *Optimization of Energy Consumption of the Ultrasonic Pretreatment on Sludge Disintegration*. in *IOP Conference Series: Materials Science and Engineering*. 2019. IOP Publishing.
188. Pilli, S., et al., *Ultrasonic pretreatment of sludge: a review.* Ultrasonics sonochemistry, 2011. **18**(1): p. 1-18.

189. Cho, S.-K., Y.-M. Yun, and S.G. Shin, *Low-strength ultrasonication positively affects methanogenic granules toward higher AD performance: Hydrolytic enzyme excretions.* Ultrasonics Sonochemistry, 2017. **36**: p. 168-172.
190. Subhedar, P.B. and P.R. Gogate, *Ultrasound-assisted bioethanol production from waste newspaper.* Ultrasonics Sonochemistry, 2015. **27**: p. 37-45.
191. Zhao, Y., et al., *Applications of ultrasound to enhance mycophenolic acid production.* Ultrasound in medicine & biology, 2012. **38**(9): p. 1582-1588.
192. Cho, S.-K., et al., *Low strength ultrasonication positively affects the methanogenic granules toward higher AD performance. Part I: Physico-chemical characteristics.* Bioresource technology, 2013. **136**: p. 66-72.
193. Mata-Alvarez, J., S. Macé, and P. Llabres, *Anaerobic digestion of organic solid wastes. An overview of research achievements and perspectives.* Bioresource technology, 2000. **74**(1): p. 3-16.
194. Xie, B., H. Liu, and Y. Yan, *Improvement of the activity of anaerobic sludge by low-intensity ultrasound.* Journal of Environmental Management, 2009. **90**(1): p. 260-264.
195. Cho, S.-K., et al., *Enhanced activity of methanogenic granules by low-strength ultrasonication.* Bioresource Technology, 2012. **120**: p. 84-88.
196. Cho, S.-K., et al., *Application of low-strength ultrasonication to the continuous anaerobic digestion processes: UASBr and dry digester.* Bioresource technology, 2013. **141**: p. 167-173.
197. Cesaro, A., et al., *Enhanced biogas production from anaerobic codigestion of solid waste by sonolysis.* Ultrasonics sonochemistry, 2012. **19**(3): p. 596-600.
198. Habashi, N., et al., *Hydrodynamic cavitation as a novel approach for pretreatment of oily wastewater for anaerobic co-digestion with waste activated sludge.* Ultrasonics sonochemistry, 2016. **31**: p. 362-370.
199. Mancuso, G., et al., *Effects of hydrodynamic cavitation, low-level thermal and low-level alkaline pre-treatments on sludge solubilisation.* Ultrasonics Sonochemistry, 2019. **59**: p. 104750.
200. Kim, I., et al., *Hydrodynamic cavitation as a novel pretreatment approach for bioethanol production from reed.* Bioresource Technology, 2015. **192**: p. 335-339.
201. Hilares, R.T., et al., *Ethanol production in a simultaneous saccharification and fermentation process with interconnected reactors employing hydrodynamic cavitation-pretreated sugarcane bagasse as raw material.* Bioresource Technology, 2017. **243**: p. 652-659.
202. Hilares, R.T., et al., *Hydrodynamic cavitation-assisted continuous pre-treatment of sugarcane bagasse for ethanol production: effects of geometric parameters of the cavitation device.* Ultrasonics sonochemistry, 2020. **63**: p. 104931.
203. Nakashima, K., et al., *Hydrodynamic cavitation reactor for efficient pretreatment of lignocellulosic biomass.* Industrial & Engineering Chemistry Research, 2016. **55**(7): p. 1866-1871.
204. Baxi, P.B. and A.B. Pandit, *Using cavitation for delignification of wood.* Bioresource Technology, 2012. **110**: p. 697-700.
205. Sun, X., et al., *Experimental investigation of the thermal and disinfection performances of a novel hydrodynamic cavitation reactor.* Ultrasonics sonochemistry, 2018. **49**: p. 13-23.
206. Mancuso, G., et al., *Decolourization of Rhodamine B: A swirling jet-induced cavitation combined with NaOCl.* Ultrasonics Sonochemistry, 2016. **32**: p. 18-30.
207. Tsalagkas, D., et al., *Assessment of the papermaking potential of processed Miscanthus× giganteus stalks using alkaline pre-treatment and hydrodynamic cavitation for delignification.* Ultrasonics sonochemistry, 2021. **72**: p. 105462.

208. Lauberte, L., et al., *Lignin–Derived antioxidants as value-added products obtained under cavitation treatments of the wheat straw processing for sugar production.* Journal of Cleaner Production, 2021. **303**: p. 126369.
209. Hallenbeck, P., *Fundamentals of the fermentative production of hydrogen.* Water Science and Technology, 2005. **52**(1-2): p. 21-29.
210. Redwood, M.D., et al., *An integrated biohydrogen refinery: synergy of photofermentation, extractive fermentation and hydrothermal hydrolysis of food wastes.* Bioresource technology, 2012. **119**: p. 384-392.
211. Das, D. and T.N. Veziroǧlu, *Hydrogen production by biological processes: a survey of literature.* International journal of hydrogen energy, 2001. **26**(1): p. 13-28.
212. Dong, Z.Y., et al., *Accelerated aging of grape pomace vinegar by using additives combined with physical methods.* Journal of Food Process Engineering, 2020. **43**(6): p. e13398.
213. Yeo, S.-K. and M.-T. Liong, *Effect of ultrasound on the growth of probiotics and bioconversion of isoflavones in prebiotic-supplemented soymilk.* Journal of agricultural and food chemistry, 2011. **59**(3): p. 885-897.
214. Abesinghe, A., et al., *Effects of ultrasound on the fermentation profile of fermented milk products incorporated with lactic acid bacteria.* International Dairy Journal, 2019. **90**: p. 1-14.
215. Yu, Z., et al., *Potential use of ultrasound to promote fermentation, maturation, and properties of fermented foods: A review.* Food Chemistry, 2021: p. 129805.
216. Delgado-Povedano, M. and M.L. De Castro, *A review on enzyme and ultrasound: A controversial but fruitful relationship.* Analytica Chimica Acta, 2015. **889**: p. 1-21.
217. Huang, G., et al., *Effects of ultrasound on microbial growth and enzyme activity.* Ultrasonics Sonochemistry, 2017. **37**: p. 144-149.
218. Chen, H., et al., *Polyhydroxyalkanoate production from fermented volatile fatty acids: effect of pH and feeding regimes.* Bioresource technology, 2013. **128**: p. 533-538.
219. Petkewich, R., *Technology Solutions: Microbes manufacture plastic from food waste*. 2003, ACS Publications.
220. Luo, K., et al., *Hydrolysis and acidification of waste-activated sludge in the presence of biosurfactant rhamnolipid: effect of pH.* Applied microbiology and biotechnology, 2013. **97**(12): p. 5597-5604.
221. He, M., et al., *Influence of temperature on hydrolysis acidification of food waste.* Procedia Environmental Sciences, 2012. **16**: p. 85-94.
222. Wang, X. and Y.-c. Zhao, *A bench scale study of fermentative hydrogen and methane production from food waste in integrated two-stage process.* International Journal of Hydrogen Energy, 2009. **34**(1): p. 245-254.
223. Cesaro, A. and V. Belgiorno, *Pretreatment methods to improve anaerobic biodegradability of organic municipal solid waste fractions.* Chemical Engineering Journal, 2014. **240**: p. 24-37.
224. Xu, S.Y., et al., *Effect of inoculum to substrate ratio on the hydrolysis and acidification of food waste in leach bed reactor.* Bioresource technology, 2012. **126**: p. 425-430.
225. Đukić-Vuković, A., et al., *Ultrasound as a physical treatment of stillage for lactic acid fermentation.* Journal on Processing and Energy in Agriculture, 2016. **20**(1): p. 13-16.
226. Rodrigues, C., et al., *Production and application of lactic acid*, in *Current developments in biotechnology and bioengineering*. 2017, Elsevier. p. 543-556.
227. de Oliveira, R.A., et al., *Challenges and opportunities in lactic acid bioprocess design—From economic to production aspects.* Biochemical Engineering Journal, 2018. **133**: p. 219-239.

228. Abdel-Rahman, M.A., Y. Tashiro, and K. Sonomoto, *Lactic acid production from lignocellulose-derived sugars using lactic acid bacteria: overview and limits.* Journal of biotechnology, 2011. **156**(4): p. 286-301.
229. Tang, J., et al., *Effect of pH on lactic acid production from acidogenic fermentation of food waste with different types of inocula.* Bioresource technology, 2017. **224**: p. 544-552.
230. Wu, Y., et al., *Lactic acid production from acidogenic fermentation of fruit and vegetable wastes.* Bioresource technology, 2015. **191**: p. 53-58.
231. Jawad, A.H., et al., *Production of the lactic acid from mango peel waste–Factorial experiment.* Journal of King Saud University-Science, 2013. **25**(1): p. 39-45.
232. Esmaeili, H., *A critical review on the economic aspects and life cycle assessment of biodiesel production using heterogeneous nanocatalysts.* Fuel Processing Technology, 2022. **230**: p. 107224.
233. Ahmad, T., et al., *Optimization of process variables for biodiesel production by transesterification of flaxseed oil and produced biodiesel characterizations.* Renewable Energy, 2019. **139**: p. 1272-1280.
234. Sáez-Bastante, J., et al., *Recycling of kebab restoration grease for bioenergy production through acoustic cavitation.* Renewable Energy, 2020. **155**: p. 1147-1155.
235. Kelkar, M.A., P.R. Gogate, and A.B. Pandit, *Intensification of esterification of acids for synthesis of biodiesel using acoustic and hydrodynamic cavitation.* Ultrasonics Sonochemistry, 2008. **15**(3): p. 188-194.
236. Günay, M.E., L. Türker, and N.A. Tapan, *Significant parameters and technological advancements in biodiesel production systems.* Fuel, 2019. **250**: p. 27-41.
237. Arrojo, S. and Y. Benito, *A theoretical study of hydrodynamic cavitation.* Ultrasonics Sonochemistry, 2008. **15**(3): p. 203-211.
238. Teixeira, L.S., et al., *Comparison between conventional and ultrasonic preparation of beef tallow biodiesel.* Fuel Processing Technology, 2009. **90**(9): p. 1164-1166.
239. Fayyazi, E., et al., *An ultrasound-assisted system for the optimization of biodiesel production from chicken fat oil using a genetic algorithm and response surface methodology.* Ultrasonics sonochemistry, 2015. **26**: p. 312-320.
240. Deshmane, V.G., P.R. Gogate, and A.B. Pandit, *Process intensification of synthesis process for medium chain glycerides using cavitation.* Chemical Engineering Journal, 2008. **145**(2): p. 351-354.
241. Yu, D., et al., *Ultrasonic irradiation with vibration for biodiesel production from soybean oil by Novozym 435.* Process Biochemistry, 2010. **45**(4): p. 519-525.
242. Duber, A., et al., *Exploiting the real wastewater potential for resource recovery–n-caproate production from acid whey.* Green Chemistry, 2018. **20**(16): p. 3790-3803.
243. Andersen, S.J., et al., *Electrolytic extraction drives volatile fatty acid chain elongation through lactic acid and replaces chemical pH control in thin stillage fermentation.* Biotechnology for biofuels, 2015. **8**(1): p. 1-14.
244. Roghair, M., et al., *Development of an effective chain elongation process from acidified food waste and ethanol into n-caproate.* Frontiers in bioengineering and biotechnology, 2018. **6**: p. 50.
245. Asmer, H.-J., et al., *Microbial production, structure elucidation and bioconversion of sophorose lipids.* Journal of the American Oil Chemists' Society, 1988. **65**(9): p. 1460-1466.
246. Shah, V., D. Badia, and P. Ratsep, *Sophorolipids having enhanced antibacterial activity.* Antimicrobial Agents and Chemotherapy, 2007. **51**(1): p. 397-400.

247. Fu, S.L., et al., *Sophorolipids and their derivatives are lethal against human pancreatic cancer cells.* Journal of surgical research, 2008. **148**(1): p. 77-82.
248. Kasture, M., et al., *Synthesis of silver nanoparticles by sophorolipids: Effect of temperature and sophorolipid structure on the size of particles.* Journal of Chemical Sciences, 2008. **120**(6): p. 515-520.
249. Maddikeri, G.L., P.R. Gogate, and A.B. Pandit, *Improved synthesis of sophorolipids from waste cooking oil using fed batch approach in the presence of ultrasound.* Chemical Engineering Journal, 2015. **263**: p. 479-487.
250. Maingault, M., *Utilization of sophorolipids as therapeutically active substances or cosmetic products, in particular for the treatment of the skin*. 1999, Google Patents.