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Review

Microwave and Ultrasound Based Methods in Sludge Treatment: A Review

Zoltán Jákói [1], Balázs Lemmer [2], Cecilia Hodúr [1] and Sándor Beszédes [1,*]

[1] Department of Biosystems Engineering, University of Szeged, 6725 Szeged, Hungary; jakoiz@mk.u-szeged.hu (Z.J.); hodur@mk.u-szeged.hu (C.H.)
[2] Department of Mechanical Engineering, University of Szeged, 6725 Szeged, Hungary; lemmer@mk.u-szeged.hu
* Correspondence: beszedes@mk.u-szeged.hu

Abstract: The amount of waste activated sludge (WAS) is increasing annually, and since it presents potential environmental and health-related risks, an appropriate treatment and stabilization process is needed. It has been shown in numerous studies in the past few decades that amongst the advanced treatment methods of sludge, microwave and ultrasound-based processes offer promising and effective alternatives. The main advantage of these physical methods is that they are energy-efficient, easy to implement and can be combined with other types of treatment procedures without major difficulties. In this review article we would like to present the recent scientific results of the microwave, ultrasound and combined (microwave-alkaline, microwave-H_2O_2, ultrasound-alkaline and ultrasound-H_2O_2) treatment of wastewater sludge, in terms of different process-efficiency indicators. Although the obtained results somewhat vary between the different scientific papers, it can be undoubtedly stated that both MW and US—either individually or in combination with chemical treatments—can enhance several aspects of sludge processing, like increasing the SCOD/TCOD rate, disintegration degree (DD), or the anaerobic digestibility (AD), but the extent of these increments clearly depends on the treatment conditions or parameters.

Keywords: sludge; sludge treatment; microwave; ultrasound

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1. Introduction—General Aspects of Sludge

The waste residue which is generated during a variety of processes in a wastewater treatment plant is called sludge. Since it contains residual (mostly organic) pollutants, pathogenic microorganisms and other toxic compounds that originated from the treated wastewater, sludge is potentially harmful to both the environment and health. Moreover, it has been shown that during the conventional activated sludge process, the extent of waste activated sludge (WAS)—which is the by-product of the microbial organic pollutant removal subprocess—have been continuously increasing annually in the last few decades, and definitely will further in the near future [1]. Therefore, the proper treatment and stabilization of it are inevitable, however, the most significant problem is that these processes have high energy demands and costs. During a conventional activated sludge process, the expense for WAS treatment is costly, and the cost of its treatment can cover 50–60% of the total cost of a wastewater treatment plant [2,3].

The main objective of the activated sludge process is to generate a mixture of primary sludge (PS) and WAS which can be used for fertilization or can be stabilized and utilized afterwards via anaerobic digestion (AD). Anaerobic digestion or fermentation uses specific microorganism which converts organic substances to methane and carbon dioxide through different biochemical processes, which involves the hydrolysis of proteins, lipids and carbohydrates; fermentation of amino acids and sugars to acids (acidogenesis); oxidation of fatty acids and alcohols into acetic acid, CO_2 and hydrogen, and the conversion of acetic acid and hydrogen to methane [4].

Due to the relatively high time and cost demand of the AD process, it has been shown in several studies that pre-treatment methods should be implemented to accelerate the process and/or increase its effectiveness. Primarily, these pre-treatment methods aim to increase the disintegration degree (DD) of the sludge by bursting microbial cell structures and disintegrating microbial flocks [5]. There are many different kinds of pre-treatment processes, e.g., biological (enzymatic hydrolysis), physical (microwave, ultrasound, thermal, gamma-radiation), chemical (alkaline, H_2O_2, ozone), but it has been shown that these methods regardless of their type can disrupt the structure of the sludge, which leads to—among others higher solubilized organic matter content (and thus increasing the soluble chemical oxygen demand, SCOD), and therefore accelerating the following anaerobic digestion step [6,7]. In this literature review article, we would like to primarily focus on the standalone and combined pre-treatment processes based on microwave and ultrasonic irradiation; two advanced physical treatment methods that have been widely investigated in the last few decades, and which have been already found to be effectively applied in certain environmental and biotechnological procedures, such as sludge treatment [8,9].

2. Efficiency Indicators

It is evidently clear that to characterize a treatment or pre-treatment process in terms of its effectiveness, a specific indicator (or indicators) should be determined which allows the comparison of the different methods. In sludge (pre-) treatment methods, depending on the approach, several of these indicators can be defined, however, the scientific literature and research articles do not always use them consequentially, and thus the comparison of the different processes has its limitations.

In environmental sciences, chemical oxygen demand (COD) is an indicative measure of the amount of oxygen that is needed to oxidize the organic matter content of a given sample. Typically, COD is given in mgO_2/L. COD measurement and the determination of COD level is widely used in wastewater and sludge treatment, for the reason that the measurement is rather quick (especially when compared to the biochemical oxygen demand, BOD determination), and gives accurate information about the organic content of a wastewater or sludge sample [10]. When comparing different processes in terms of organic matter elimination, the reduction rate of COD can give a precise insight about how efficient a given method is, i.e., the more it can reduce the COD level, the more effective it is. "Pure" COD, however, is usually too general and sometimes does not provide enough information about the applied treatment method. Therefore it is favourable to split it into two different variants, the soluble chemical oxygen demand (SCOD) and the total chemical oxygen demand (TCOD). SCOD, as its name suggest, contains only those organic materials that can be found in the soluble phase, whilst TCOD contains all organic content (as well as in the soluble and in the solid phase). The ratio of these two (SCOD/TCOD) can accurately indicate what proportion of the total COD can be found in the soluble phase, and as its extent correlates with anaerobic digestibility [11], this ratio is commonly used in the scientific literature when comparing different methods or processes in sludge treatment.

Biochemical oxygen demand (BOD) determination serves a similar purpose as COD, however, both the method and its value differ from that of chemical oxygen demand. BOD also measures the amount of oxygen needed to break down organic compounds, although the determination process is based on microbial activity, i.e., how much oxygen do specific aerobic microorganisms need to oxidize the organic matter of the sample [12]. In contrast to COD measurement, the applied bacteria cannot essentially utilize every type of organic molecule in a wastewater or sludge sample, therefore BOD provides information about the organic load of wastewater, applicable wastewater purification technologies and the organic matter removal efficiency of biological wastewater treatment, for instance. BOD is also used as a key pollutant indicator in wastewater discharge standards and limits in many countries. Contrary to chemical oxygen demand (COD), BOD is a sensitive parameter for the presence of toxic components, therefore can provide information about the bioavailability/biodegradability of substrates in water and wastewater. Considering the high variability of industrial wastewater, the determination of the change of BOD influenced by the wastewater characteristics, and the operational parameters of wastewater treatment technologies—can provide useful information for the practice, as well. BOD is usually used as an efficiency indicator when the goal is to determine how a certain process can affect the biological usability of a given sludge sample.

Disintegration degree (DD) is one of the most common indicators in sludge treatment. DD is calculated as the ratio of SCOD increase caused by the analysed disintegration method in relation to the SCOD increase caused by the chemical disintegration [13]. As its definition suggests, a given process can be evaluated in terms of its effectiveness by calculating DD; the more increment the process can cause in DD, the more it disintegrates the structure of the sludge, hence increasing the SCOD, and ultimately, the anaerobic digestibility. The estimation of WAS disintegration degree is generally based upon the values of SCOD, STOC and STN, as suggested by Ren et al. [14]. From an experimental point of view, there are some novel methods for the assessment of sludge DD, for example, differential centrifugal sedimentation [15].

Total solid (TS) and volatile solid (VS) percentages are also rather important in terms of sludge characterization, and for that commonly used as indicators as well.

During the treatment of wastewater in a wastewater treatment plant, an excessive amount of wastewater sludge is produced. The resulting sludge can be and is used for either fertilization purposes [16,17] or anaerobic digestion (AD), i.e., biogas production. The product of the AD, as discussed in the Introduction, is mainly methane and carbon dioxide. It can be stated that the more methane is being produced during AD, the more effective the process is (but of course there is a limitation in CH_4 extent). For these considerations, scientific literature often uses methane yield as an indicator, and when comparing different treatment or pre-treatment processes to each other in terms of effectivity, it is usually calculated how they can increase the overall methane yield in the following AD process. A slightly simpler method is to determine the exact biogas yield; however, it carries less information about the usable content of the biogas itself.

Since several of the applicable pre-treatment methods means external energy investment, it is very common to determine specified indicators based upon the amount of transmitted energy to be able to objectively compare different types of treatment methods. There are numerous variations of these specified indicators, non-exhaustively kJ/kg TS, kJ/kg VS, ΔSCOD/kJ, ΔBOD/kJ, ΔCH_4/kg, etc. On the other hand, it can be observed that many scientific research papers use quite a unique unit of measurements to describe certain processes due to various reasons (e.g., the experimental design or setup, uniqueness of the applied equipment or method, etc.), which makes it difficult or sometimes impossible to compare different experimental results in research articles.

3. Principles of Chemical Treatments: Alkaline and H_2O_2

Alkaline compounds have been frequently used as a method in wastewater and sludge treatment to enhance several factors, such as anaerobic digestibility, disintegration or solubilisation. The addition of alkali increases the amount of hydroxyl ions in the material, and, therefore, its pH level. This means that the environment becomes hypotonic, which causes the turgor pressure in the microbial cells to increase to an extent the cell can no longer sustain, and, therefore, its cell wall breaks down [14]. By using an alkaline treatment, the biodegradability of the sludge can be significantly increased, as it induces the swelling of particulate organics, making them more accessible to enzymes [15]. Alkaline treatment can also enhance the solubilisation of COD; Kim et al. determined that by adding NaOH in a dosage of 5–21 g/L, approximately 40% of COD solubilisation of sludge can be achieved [18]. As shown in several studies, the addition of alkaline can affect the degree of disintegration and anaerobic biodegradability as well—in a recent 2021 study, Ayesha et al. have shown that standalone alkaline treatment (via 0.8% NaOH) of dewatered WAS resulted in an 11.3 disintegration degree and 32.6% higher methane yield, compared to the control samples [19]. Erkan et al. showed that during the electrochemical treatment of

WAS, the initial pH of the sludge sample plays a role in terms of DD–higher pH values obtained via the addition of NaOH resulted in the increase of DD (from 3.8% to 7.33%) [20].

Naturally, the concentration or the dosage of the applied alkaline also plays a key role in terms of effectiveness. Sahinkaya and Sevimli showed that 0.05 N was the optimal concentration of NaOH [21], while Penaud et al. in 1999 concluded that 0.125 N was the most favourable, and resulted in a 40% increment in biodegradability [22].

However, standalone alkaline treatments have numerous disadvantages. The addition of various chemicals on one hand increases the overall cost requirements of the process [23], and on the other hand, can inhibit the anaerobic digestion during some conditions—it was reported that too high concentrations of K or Na-ions can inhibit the AD process [24].

Hydrogen peroxide (H_2O_2) is a highly reactive chemical compound, mainly used as an oxidizer; a low-cost strong oxidant, which produces clean oxidation product-water [25]. Numerous studies have shown that in wastewater and wastewater sludge treatment H_2O_2 can be implemented in various ways, mostly in Fenton's/Fenton-like reactions or in a combination with physical treatments, such as microwave irradiation or ultrasonication [26,27].

4. Microwave Irradiation

In the electromagnetic spectrum, microwave (MW) irradiation occurs in a frequency range of 300 MHz to 300 GHz with a corresponding wavelength of 1 mm–1 m. MW irradiation is considered a promising alternative to conventional heating methods. In wastewater and wastewater sludge treatment, during microwave irradiation, the destruction of microorganisms and other molecules may occur in two ways: thermal and athermal (non-thermal) effects. Thermal effects are generated via ionic conduction (in shorter frequencies) and dipole rotation (in higher frequencies)—the former means the electrophoretic (conductive) migration of dissolved ions in the electromagnetic field [28], while the latter is generated through the rotation of dipole molecules (like water) due to the constant and repeated changes in the polarity of the field [29]. Athermal effects are induced by the change in dipole orientation of certain polar molecules, which increase the possibility of breaking down the hydrogen bonds of biopolymers (polysaccharides, proteins, DNA, RNA) [30,31]. In industrial use, a frequency of 915 MHz is the most favourable, since shorter frequencies have higher penetration depth [32], thus increasing the extent of thermal and athermal effects.

It was concluded that the SCOD/TCOD ratio increased from 2% to 22% of sludge after MW irradiation (630 kJ total irradiated energy) [33]. SCOD/TCOD ratios were also increased in waste activated sludge from 8% to 18% after microwave-based heating to 72.5 °C [34] and from 6% to 18% after MW heating to 96 °C [35]. Gil et al. reported that depending on the applied total energy and power ratings, a 43% to 66% of increment occurred in the solubility (COD/TVS ratio) of floated sewage sludge [36].

Standalone microwave irradiation can also increase the extent of biogas production from sludge. Waste activated sludge (WAS) heated to different temperatures through microwave treatment resulted in a higher rate and extent of biogas production [37]. Alqaralleh et al. showed that the microwave heating of thickened waste activated sludge up to 175 °C resulted in a 135% higher biogas yield compared to the control samples [38]. Applying a total of 14.000 kJ/kgTS microwave energy resulted in a +570% biogas yield, as reported by Ebenezer et al. in 2015 [39]. In another experiment, the effects of microwave irradiation on the removal of COD were investigated: Park et al. reported that the treatment of WAS by MW to 91 °C, 64% of COD decrement could be achieved [40]. Combination of microwave irradiation with ultrasonication can also be a promising method in wastewater and wastewater sludge treatment: Mesfin Yeneneh et al. applied ultrasonic irradiation (0.4 W/mL, 6 min) after MW treatment (2450 MHz, 3 min), which resulted in a higher cumulative biogas production compared to the control samples [41].

4.1. Microwave-Alkaline Combined Treatment

Although microwave irradiation can be used for several purposes on its own in wastewater and sludge treatment, numerous studies have shown that to increase its efficiency, MW technology should be combined with chemical co-treatments, such as the use of alkalies. It was concluded in several papers that the effects of microwave and alkaline treatment are additive [42–44]; Chang et al. for example found that MW-alkaline combination in the treatment of sludge resulted in the increase of solubilization rate by 20% in contrast to the standalone treatments. Yang et al. found that by the combined alkaline-MW treatment of sludge, the disintegration degree (DD) reached 65.9% (at 38,400 kJ/kg TS and pH 11) and the anaerobic batch experiment showed that the combined pre-treatment significantly improved volatile fatty acids accumulation and shortened its time requirement [45]. Chi et al. concluded that the maximum solubilization ratio (85.1%) of volatile suspended solids in sludge could be achieved at MW heating to 210 °C with 0.2 g NaOH/g SS [46]. They also investigated the cumulative methane production (CMP) during thermophilic anaerobic digestion and found that the optimal settings of combined pre-treatments in terms of CMP were MW heating to 170 °C and 0.05 g NaOH/g SS, with 1 min of holding time. In a study by Jang and Ahn, it was shown that with the combination of MW and alkalic treatment, the overall increase in biogas production exceeded 228% [47]. Dogan and Sanin found that the SCOD/TCOD ratio could be increased by combining microwave irradiation with alkaline treatment up to 0.37, however, the level of pH plays a key role in the entire process, with pH 12.5 being the optimal one [43]. Beszédes et al. also investigated the effects of different pH (ranging from pH 2–12) on the change in SCOD/TCOD ratio and found that at any given total irradiated microwave energy level (70 kJ/L, 150 kJ/L, 230 kJ/L) a pH of 12.0 resulted in the highest SCOD/TCOD ratio (0.33) [48]. Lemmer et al. came to a similar conclusion; when combining microwave treatment with alkaline, increasing the alkaline dosage and microwave energy intensity, DD could be enhanced up to a certain point (about 50%) [49].

Although several types of alkalic compounds can be used in wastewater and sludge treatment (such as NaOH, KOH, $Ca(OH)_2$), their effects on the efficiency of the whole process can be different. In 2012 Tyagi and Lo concluded that in terms of the rate of sludge solubilization, by using NaOH 52.5% solubilization could be achieved, while with KOH this rate was shown to be 4% less, 48.5% [50].

4.2. Microwave—H_2O_2 Combined Treatment

It was observed that in WAS the combined MW/H_2O_2 treatment could effectively solubilize several intra- and extracellular compounds, for instance, proteins and sugars [51]. The reason behind the combinability of these two treatments is that H_2O_2 is a very heat-sensitive compound and undergoes thermal decomposition, which results in nascent OH· radicals, and so increasing the effect of oxidization [52].

It was shown that in the temperature range of 60–120 °C achieved by MW irradiation, the addition of H_2O_2 could increase the solubility of ammonia in sludge [53]. In the study of Yin et al. it was shown that the extent of soluble COD in sludge was significantly higher (around 10,000 mgL^{-1}) when using MW/H_2O_2 treatment than that obtained for the standalone MW or H_2O_2 (approx. 5000 mgL^{-1} and 2500 mgL^{-1}, respectively) [54]. Ambrose et al. concluded that the application of hybrid MW-H_2O_2 pre-treatment in a WAS and fruit-waste mixture increased the solubilization of sludge by 33%, and enhanced the biogas yield as well [55]. Eswari et al. shown that combining H_2O_2 with microwave irradiation resulted in a significant increment in solubilization from 30 to 50%, when the specific energy investment was 18.600 kJ/kg TS. When acidic conditions were applied during the H_2O_2-assisted MW treatment of the sludge samples, the methane production reached 323 mL/gVS [56].

Table 1 summarizes the results of these studies in regards to different efficiency indicators while applying microwave irradiation alone or combined.

Table 1. Summary of results of microwave and combined treatment in terms of efficiency.

Type of Treatment	Efficiency Indicator	Results	Reference
MW	SCOD/TCOD	2% to 22% increment	Ahn et al., 2009
MW	SCOD/TCOD	8% to 18% increment	Hong et al., 2006
MW	COD/TVS	up to 43–66% increment	Gil et al., 2019
MW + Alkaline	DD	65.9% at 38,400 kJ/TS, pH = 11	Yang et al., 2013
MW + Alkaline	SCOD/TCOD	0.38 at pH = 12	Dogan and Sanin, 2009
MW + Alkaline	SCOD/TCOD	0.33 at pH = 12, 230 kJ/L	Beszédes et al., 2018
MW + H_2O_2	SCOD	from 5000 mg/L to 10,000 mg/L	Yin et al., 2007
MW + H_2O_2	solubilization rate	from 30% to 50%	Parvathy et al., 2016

5. Ultrasound Treatment

Ultrasounds are longitudinal acoustic waves in the frequency range of 20 kHz and 10 MHz. Just like other acoustic waves, ultrasounds act differently depending on the material they are going through. To express to which extent the ultrasound can be absorbed in the irradiated material, the following expression can be used [57]:

$$A = A_0 e^{-\alpha x} \quad (1)$$

In the equation, A_0 represents the initial amplitude of the ultrasonic wave, x means the length of path and α is the attenuation coefficient.

The effects of ultrasonic treatments are mostly due to the cavitation process in the treated material. During this process, alternating high-pressure (compression) and low-pressure (rarefaction) cycles occur, and the rate is frequency-dependent. The so-called transient cavitation bubbles usually last for only a few cycles [58], their size can significantly increase, and when these bubbles reach a volume at which they can no longer absorb any more energy, they viciously collapse during a high-pressure cycle. During this collapse, extremely high pressure and temperature can be reached locally [59]. According to Ashokkumar, the theoretical temperature can be calculated via the following expression [60]:

$$T = T_0 \left(\frac{P_m(\gamma - 1)}{P_v} \right) \quad (2)$$

In the expression, T_0 is the ambient solution temperature, P_m demonstrates the sum of the hydrostatic and acoustic pressures, γ is the specific heat ratio of the gas/vapour mixture and P_v is the pressure inside the cavitation bubble when it reaches its maximum volume.

These cavitation effects can undoubtedly cause severe structural, physical and chemical changes in the exposed material, such as wastewater or wastewater sludge. The use of sonication in wastewater treatment goes back to the late 1990s and early 2000s, and since then the various effects of the process have been heavily studied. It was shown that the hydromechanical shear force is the dominant effect when treating wastewater and sludge with ultrasonication [61], however other factors like locally high temperature and pressure or the formation of free radicals (H and OH; due to the extreme local temperatures) can also play a significant role in various mechanisms (e.g., sludge disintegration or solubilization).

Ultrasound treatment of sludge mainly results in the solubilization of organic particles and less in mineral particles, as shown by Bougrier et al. [62]. They reported that at a specific energy input of 15,000 kJ/kg TS, 29% of the organic particles were solubilized, whereas only 3% of mineral particles were solubilized. Solubilization of COD is mostly due to the disintegration of extracellular polymeric substances (EPS) [63]. These substances are high molecular weight polymers, which play a key role in floc size, stability and bioflocculation. When WAS is exposed to ultrasonication and the various effects caused by it, these EPS are shattered along with microorganism flocs and the key components of EPS (proteins, carbohydrates) and the intracellular substances of microbial cells (enzymes, DNA, carbohydrates) enter the soluble phase [64]. This will lead to an increased SCOD/TCOD ratio, which was shown to be beneficial in terms of biogas production [65]. In the study of Tian et al., it was also reported that the ultrasound irradiation of sludge resulted in a significant increase in loosely bound polysaccharide (PS) contents, and also in carbonyl, hydroxyl and amine functional group contents [66]. Several studies prove that ultrasonic pre-treatment of sludge can cause a significant increase in biogas production and volatile solid destruction [67,68]. Daukyns et al. stated that by disintegrating sludge with ultrasonic treatment, the methane content in the produced biogas was almost 72%, whereas in the case of non-disintegrated sludge, only 54% [69].

5.1. Ultrasound-Alkaline Combined Treatment

As mentioned earlier, ultrasonic irradiation, more specifically the extreme local temperatures caused by ultrasonic cavitation can lead to the production of H and OH radicals. These oxidative radicals can play a significant role in sludge disintegration and solubilization, as well as in anaerobic digestion. However, it is worth noting that the formation of these free radicals depends on the pH of the medium and can be controlled or enhanced by using alkalis.

This and other phenomena caused by the combined effects of ultrasound and alkaline treatment of wastewater and sludge have been shown in several studies. Wang et al. described that COD solubilization caused by ultrasonication was higher when using it with an alkaline combination [70]. The solubilization of COD may be caused by three different processes: solubilization by alkali, ultrasound or by the synergistic effect of these two. Kim et al. in 2010 have proved that the efficiency of the combined ultrasound/alkaline treatment exceeded the effectiveness of the alkali and ultrasound treatment individually, thus proving that the effects of the two are additive [71]. Liu et al. found that the solubilization of proteins that originated from microbial cells were significant (around 67%) when applying ultrasound and NaOH treatment in a combination [72]. Combined ultrasound/alkaline treatment can also be used for enhancing the anaerobic fermentation of sludge. In the study of Tian et al., it was shown that using 0.05 mol/L alkaline treatment in a combination of 21 kJ/g TS ultrasound irradiation, the biodegradability increased by almost 21%, compared to the control sample [73]. Seng et al. also concluded that ultrasound/alkaline pre-treated sludge resulted in 42.1% higher methane production (with a solids retention time of 10 days) than that obtained for the untreated sludge [74]. Bao et al. showed that methane productivity can be enhanced via US-alkaline combined treatment; methane production rate was enhanced to 0.15 m^3 CH_4/m^3 reactor/d, which means a 3 times improvement compared to the control [75].

5.2. Ultrasound—H_2O_2 Combined Treatment

Several studies have shown that the oxidizing effects of H_2O_2 can be further increased when combined with physical treatments, such as microwave or ultrasonic irradiation. Rahdar et al. have shown that the combination of US and hydrogen peroxide can be applied for effective aniline degradation, and the effects were stronger than those obtained for the standalone US or H_2O_2 treatments [76]. It was also reported that with this combined treatment method, pesticides in an aqueous solution can be reduced [77], as well as bisphenol A [78]. In a recent 2021 study, Yuan et al. investigated the effects of US-H_2O_2 treatment on excess sludge destruction. They found that with an initial pH level of 11.0, 0.5 mmol/L H_2O_2 concentration, 17 g/L sludge concentration and 15 min US treatment (40 kHz), ΔSCOD reached 3662.78 mg/L, with a DD of 28.61% and a sludge reduction rate of 19.47%. [79].

Table 2 summarizes the results of these studies in regards to different efficiency indicators while applying ultrasonication alone or combined with chemical treatments.

Table 2. Summary of results of ultrasound and combined treatment in terms of efficiency.

Type of Treatment	Efficiency Indicator	Results	Reference
US	solubilization of organic matter	29% at 15.000 kJ/kg TS	Bougrier et al., 2005
US	CH_4 content in biogas	from 54% to 72%	Dauknys et al., 2020
US + Alkaline	SCOD	~2200 mg/L, pH = 12	Wang et al., 2005
US + Alkaline	solubilization of proteins	67% with NaOH	Liu et al., 2008
US + Alkaline	rate of biodegradability	21% increment, 21 kJ/kg TS, 0.05 mol/L alkaline	Tian et al., 2015
US + Alkaline	CH_4 production rate	0.15 m^3 CH_4/m^3 reactor/day	Bao et al., 2020
US + H_2O_2	ΔSCOD DD	3662.78 mg/L 28.61%	Yuan et al., 2021

6. Conclusions

Microwave and ultrasound-based treatment processes of sludge have been widely investigated in the past few decades. Amongst the advanced treatment methods, these physical procedures present promising and effective alternatives when applying them to different kinds of sludge. Studies report that standalone microwave irradiation can increase the organic content of the soluble phase (i.e., SCOD) due to certain thermal and athermal effects, which lead to better anaerobic digestibility. The amount of increment somewhat oscillates between the different scientific studies, however, all of them show an average result of around 10–20%. AD can also be enhanced via microwave irradiation, studies show that the level of increase can reach up to 135%.

The effects of microwave-alkaline combined were found to be additive according to numerous studies. In regards to the SCOD/TCOD ratio, combining microwaves with alkali, the growth can reach 30% or more, while the disintegration degree can be increased up to 66%. Biogas yield can be significantly improved as well, a study concludes that the overall increase exceeded 228%. Application of microwave-H_2O_2 treatment to sludge also show promising results, studies report that the extent of soluble COD can be doubled when using this type of combination (from 5000 mg/L to 10,000 mg/L).

Ultrasonic treatment of sludge also results in the solubilization of organic particles, which is beneficial for the following anaerobic digestion. In the case of US treatment, the solubilization of COD is mostly due to the disintegration of extracellular polymeric substances. A study reports that by using standalone ultrasonic treatment, the methane content in the produced biogas almost reached 72%. However it has been shown that the individual use of ultrasound in terms of energy efficiency is usually inadequate, and therefore it should be combined with other mostly chemical treatments. Combining ultrasound with alkaline treatment, the solubilization of certain organic molecules can be significantly enhanced, up to 67% in the case of proteins. It can be also used for increasing the efficiency of AD, a study shows that the ultrasound—NaOH combination improved the biogas yield by 21%, and in automatized reactors, the daily methane production rate can reach 0.15 m^3 CH_4/m^3 reactor. Combining US with H_2O_2 can be applied to increase sludge reduction rate, as well as improving SCOD, and DD—the difference in SCOD reached 3662.78 mg/L when applying 15 min of US treatment with an initial pH of 11, and DD exceeded almost 29% during the same conditions.

Although microwave and ultrasonic treatments have verified advantageous effect on biodegradability and improve the biogas yield from sludge, further researches are needed to investigate their applicability in technologies focusing on the non-energetic utilization of sludge. According to the circular economy concepts another important area of research is the microwave and ultrasound-assisted processes to extract the valuable non-organic compounds of municipal and industrial sludge. Detailed analysis of dielectric properties of different originated sludge can help to achieve higher heating efficiency of microwave-assisted processes. Development of industry scale microwave or ultrasonic sludge processing equipment and technologies necessitates labs-scale and pilot-scale experiments using continuous flow microwave/ultrasonic reactors, respectively.

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