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Evaluation of thickening and dewatering of the digested sewage sludge preconditioned by sonication

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ABSTRACT

This study aimed to determine whether, and to what extent, preconditioning of excess sludge subjected to digestion can improve the final thickening and dewatering of sewage sludge. The substrate used in the study was excess sewage sludge. Sonication was conducted under static conditions in five test cycles for selected values of vibration amplitude: 7.88 μm (1.6 W/cm^2), 15.77 μm (2.2 W/cm^2), 23.65 μm (2.7 W/cm^2), 31.54 μm (3.2 W/cm^2), and 39.42 μm (3.8 W/cm^2). Sonication time ranged from 0 to 600 s. After sonication, the sludge was subjected to digestion, and capillary suction time, final water content, specific resistance, thickening curves, and thickening velocities were determined. The application of ultrasonic field in sewage sludge conditioning led to an increase in capillary suction time in proportion to increases in wavelength and operating time. Stabilization of sewage sludge preconditioned by sonication improved the filtration capacity of the sludge by reducing the capillary suction time. The final water content on each day of the digestion process also decreased. Sonication had a very positive effect on sludge thickening. Single, fragmented flocs were better packed and released free water.

Keywords: Sewage sludge; Sonication; Digestion; Dewatering

1. Introduction

The primary objective of sewage sludge treatment is to mineralize organic compounds, leading to sludge stabilization and volume reduction [1]. The choice of a conditioning method to support the above processes depends on many factors, for example, susceptibility to dewatering, the content of hazardous substances, and a method of sludge management.

Research in the field of waste management is aimed at reducing the volume of sludge produced and thus increasing the economic efficiency of the processes. Popular alternative conditioning methods and approaches include the use of chemical conditioning [2,3], mechanical disintegration, UV radiation, magnetic and electric fields, sludge preparation using acids and bases [4], Fenton's reagents [5,6], ultrasonic sludge conditioning [7–10], thermal conditioning, microwave sludge conditioning [11,12], and the addition of ash, coal, or diatomaceous earth as structure-building substances.

The use of ultrasound in sludge conditioning involves significant electrical power consumption [13,14]. Breaking up the structure of a sludge floc requires energy in excess of 330 kWh/m^3 of sludge [15]. If the floc structure is not to be completely broken up, 110 kWh/m^3 of sludge is consumed [16]. Extensive research in this area has been conducted by Bień and Zielewicz for many years, although other studies on this area can also be found in the literature [17–19].

The coagulating effect of sonication plays an important role in liquid systems. It affects the specific resistance value and accelerates the gravitational thickening process. A study by Na et al. [20] showed that the effectiveness of sonication depends on three factors: input power supplied,

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sample volume, and exposure time. These factors can be unified as an average of the energy supplied. In his study, Na used the energy of 7,200 kJ/dm^3, resulting in an 80% reduction in the volume of the sludge cake. The dispersion of sonicated sludge flocs was 5 times higher compared to the sludge not treated with ultrasound exposure. Similar relationships were also found by Gonze [21].

The efficiency of the sonication process is strongly influenced by ultrasound frequency and the temperature rise induced by the ultrasound exposure [22]. However, an increase in temperature does not significantly affect the rate of reactions occurring in the medium and thus the disintegration process [23].

Analysis of the results of Pilla et al. [24] showed that ultrasound exposure not only improves dewatering efficiency but also has a significant effect on sludge biodegradation during anaerobic stabilization. Studies have found that ultrasonic conditioning of sludge can have both positive and negative effects on dewatering. According to Yin [25], exposure to ultrasound has a positive effect on reducing the water content in the sludge from petrochemical wastewater treatment. His study reported a decrease in water content from 99% to 80%. The negative effect of ultrasound by increasing capillary suction time and specific resistance was demonstrated by Dewil et al. [26] and Wang et al. [27]. In a study by Wang, the CST for raw sludge was 32 s, specific resistance was 1.67×10^{12} m/kg, while after ultrasound application, these values were 344 s and 1.33×10^{14} m/kg, respectively. The values characterizing the dewatering efficiency (CST, sludge specific resistance) are strongly influenced by the amount of energy supplied. According to various researchers, the use of ultrasonic energy of 800 and 2,200 kJ/kg d.m. improves the efficiency of sewage sludge dewatering [28], whereas the use of ultrasonic energy above 4,400 kJ/kg d.m. deteriorates the process [29].

An extensive study of the effect of a conditioning agent on stabilization was conducted by Saha et al [30]. In their study, the microwave (2,450 MHz, 1,250 W) and ultrasonic (20 kHz, 400 W) exposure and chemical–mechanical conditioning with NaOH were used for pre-modification before stabilization. Four variables were tested: temperature (range 50°C–175°C), sonication time (15–90 min), sludge type (primary, secondary), and digester temperature. Following a 21-d mesophilic anaerobic stabilization, the application of the microwave field proved to be the most effective conditioning agent, reaching a 90% increase in methane production compared to the control sample.

The boundary between disintegration and classical conditioning methods is difficult to define [31]. Ultrasonic exposure is considered a method of sludge disintegration with a direct effect on accelerating the hydrolysis process. At the same time, ultrasound is one of the methods of sludge conditioning before sludge thickening or dewatering. The efficiency of anaerobic stabilization depends on the disintegration processes used. A study conducted by Zawieja et al. [32] confirmed the effect of sonication of excess sludge on the intensification of methane fermentation, expressed as an increase in chemical oxygen demand (COD) and volatile fatty acids (VFA).

Also, Nickel and Neis [33] conditioned sewage sludge using ultrasound exposure and obtained a solids degradation of 30% by 20% fragmentation. Chu et al. [34] found that the capillary suction time of sewage sludge increased 2.5 times after 60-min ultrasound exposure. Consequently, the filtration capacity deteriorated significantly, which is due to the fact that the water molecules were connected with the increased surface area caused by dispersion.

Based on the studies by Kopp and Wolski [35,36], the dispersion of the sludge floc under the ultrasound exposure can adversely affect the parameters of dewatering efficiency. Fragmented flocs can deteriorate the filtration and sedimentation process and have a direct effect on dewatering [37]. The increase in solutes and colloidal substances in the water may indirectly affect the increase in polyelectrolyte consumption and directly influence dewatering efficiency [38].

Sonication of sludge leads to the fragmentation of the floc structure. Some of the dispersed particles pass into the liquid phase, contributing to a change in its physicochemical parameters. According to Qian and Prasad [39,40], a noticeable dispersion of flocs of the sludge can be observed only in the first minutes. The structure of the sludge further exposed to ultrasound is only slightly fragmented. Therefore, a longer sonication time leads to the destruction of the cohesiveness of the flock structure, thus causing an increase in the amount of bound water [41].

The problem of waste management is still relevant. The increasing number of wastewater treatment plants and the use of new technological solutions cause the formation of more and more waste, requiring final treatment and the costs associated with their processing [42,43].

2. Substrate and methodology

The substrate of the study was excess sewage sludge from a mechanical–biological wastewater treatment plant with a capacity of about 90,000 m^3/d. The sludge studied was characterized by a dry matter of 11.0 ± 2.4 g/dm^3, organic dry matter of 7.3 ± 2.4 g/dm^3, capillary suction time of 24 ± 2 s, the initial water content of 98.9%, the final water content of 84.8 %, and sludge specific resistance of 2.96×10^{12} m/kg.

After preconditioning with ultrasound exposure and the addition of inoculation (10% digested sludge), excess sludge was subjected to anaerobic digestion.

Before anaerobic stabilization, the time and wavelength used in ultrasound conditioning were selected. Amplitude values were assumed based on the available literature. The entire range of capabilities of the ultrasound device was used. Sonication was conducted under static conditions in five test cycles for selected values of vibration amplitude: 7.88 μm (20% amplitude); 15.77 μm (40% amplitude); 23.65 μm (60% amplitude); 31.54 μm (80% amplitude), and 39.42 μm (100% amplitude). The adopted vibration amplitudes corresponded to the intensity of the ultrasonic wave and were 1.6, 2.2, 2.7, 3.2, and 3.8 W/cm^2, respectively. The sonication time ranged from 0 to 600 s. It was adopted on the basis of preliminary research.

Capillary suction time (CST) was measured using the Baskerville and Galle methodology, which is based on the measurement of time of transition of a frontal boundary layer of filtrate as a result of the effect of suction forces in the paper used (Whatman 17). Gravitational thickening was performed to determine the sedimentation capacity of the sludge. The tested sludge samples were poured into 100 cm^3 measuring cylinders, where observation of sludge particle falling was then carried out at appropriate time intervals of 5, 10, 15, 20, 25, 30, 45, 60, 90, and 120 min. Based on the results, thickening curves were plotted and thickening rates were calculated.

Sludge dewatering was conducted in a vacuum filter. The final water content and specific resistance of the sludge were determined using a vacuum filtration process.

The process of sewage sludge sonication used ultrasound processor Sonics VCX-1500 with a maximal power output of 1,500 W. Frequency of ultrasound field vibration was 20 kHz whereas maximal wavelength for the amplitude of 100% was 39.42 µm. The device is used to transform electricity into mechanical energy supplied to the titanium tip in the form of a wave. The volume of the samples subjected to sonication for sludge digested in flasks was 500 cm^3. The sonication time used in the study ranged from 0 to 10 min. Ultrasonic wave intensity was calculated from the formula:

$$I_a = \frac{E_a}{S \cdot T_s} \tag{1}$$

where I_a – ultrasonic wave intensity, W/cm^2, E_a – the amount of energy supplied, J, S – cross-sectional area of the vessel in which the sonication was performed, cm^2, T_s – sonication time, s.

Fermentation of initially prepared sludge samples was performed to determine the effect of stabilization on thickening and dewatering efficiency. The process occurred in glass flasks that represented models of digesters. The sludge samples were placed in 10 laboratory flasks with the volume of V = 0.5 dm^3. To maintain a constant process temperature (mesophilic conditions), the flasks were placed in a laboratory thermostat at 37°C for 10 d. To prevent the entry of air, the flasks were plugged with a stopper equipped with a manometer tube to allow the biogas produced to escape. The contents of the flasks were stirred using magnetic stirrers to remove the skin that formed on the surface and to prevent overload with contaminants. On each day of the process, capillary suction time, final water content, sludge specific resistance, and thickening curves were determined after one of the flasks was removed from the thermostat.

3. Results and discussion

3.1. Capillary suction time

At the assumed wave intensities of the conditioning agent, a proportional increase in capillary suction time was found to occur with increasing ultrasound exposure. The lowest values were obtained for sewage sludge preconditioned by ultrasound exposure at wave intensity of 1.6 W/cm^2, for which the capillary suction time in the first minute of the exposure was 249 s. An increase in CST was observed in subsequent minutes, reaching a peak of 1,234 s in the 10th minute of the exposure. The application of a higher ultrasound intensity (2.2 W/cm^2) in the conditioning of sewage sludge caused an increase in the capillary suction time to 499 s already in the first minute (a twofold increase compared to the amplitude of 20%). The upward trend continued throughout the range of exposure times used. The highest value of capillary suction time of 1,461 s was obtained for sludge after 10 min of ultrasound exposure at a wave intensity of 3.8 W/cm^2.

By subjecting sewage sludge to the process of digestion, a decrease in the value of the index discussed was observed. The capillary suction time of sonicated sewage sludge showed a decreasing trend throughout the time interval studied. The greatest reductions were observed in the first five days of the stabilization process, yielding CST values of 406 s (wave intensity of 2.7 W/cm^2), 673 s (wave intensity of 3.2 W/cm^2), and 232 s (wave intensity 3.8 W/cm^2) (Fig. 1). Of the three amplitudes tested, CST were lowest for sewage sludge conditioned at wave intensity of 3.8 W/cm^2 on

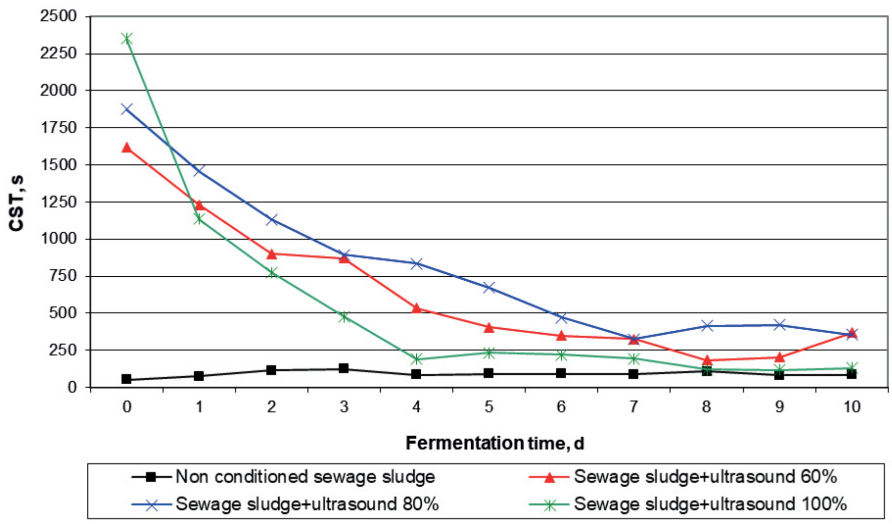

Fig. 1. Capillary suction time of sonicated sewage sludge subjected to digestion (ultrasound exposure time: 5 min).

day 10 of the stabilization process (116 s). This value was comparable to capillary suction time for the unconditioned sludge (86 s).

When the sludge was subjected to longer periods of ultrasound exposure and then stabilization, a further decrease in the value of this indicator was observed (Fig. 2).

3.2. Sewage sludge thickening

The positive effect of ultrasound on the final thickening effect was noted for each ultrasonic wave intensity used in the study (Figs. 3–7). As shown in the study, the unconditioned sewage sludge did not sediment despite being subjected to thickening for 120 min. The propagation of the ultrasonic wave accelerated the sedimentation process through the dispersion of sewage flocs, resulting in better packing and releasing free water. The use of higher amplitudes and propagation times of the ultrasonic wave allowed the sedimentation process to be accelerated. The use of longer sonication times and higher ultrasonic wave intensities improved the sedimentation characteristics of sludge flocs. The most noticeable trend in the effect of the conditioning factor on thickening efficiency for each amplitude used was observed after the fifth minute of sonication. In the following minutes of ultrasonic exposure, the decreasing trend was increasingly noticeable, with the lowest sludge volume values in the 10th minute. Using an ultrasonic wave intensity of 1.6 W/cm^2 and a propagation time of 10 min led to a significant reduction in sludge volume of 58% compared to the unconditioned sludge. The thickening rate after 30 min of sedimentation in the thickening zone was 2.9 cm/min, which, despite the high energy demand, greatly improves thickening efficiency. The separation of the two phases at the thickening stage was very evident, even more so using

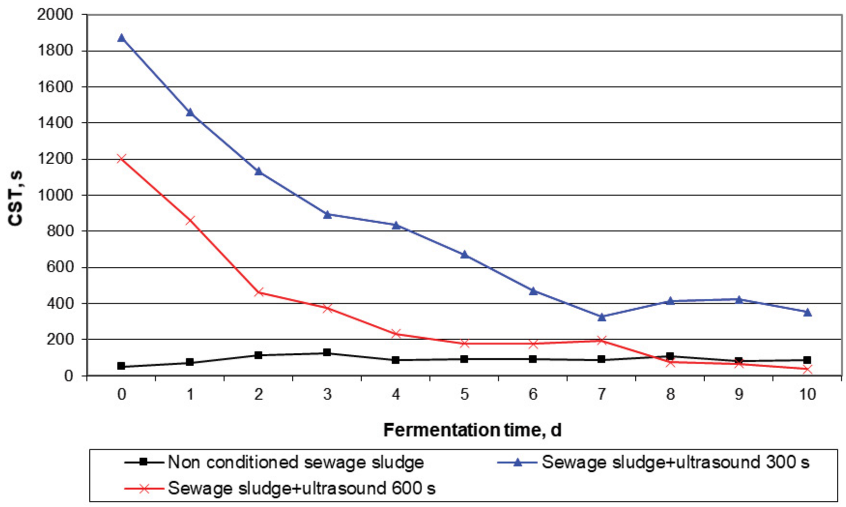

Fig. 2. Capillary suction time of sonicated sewage sludge subjected to digestion (ultrasonic wave intensity: 3.2 W/cm^2).

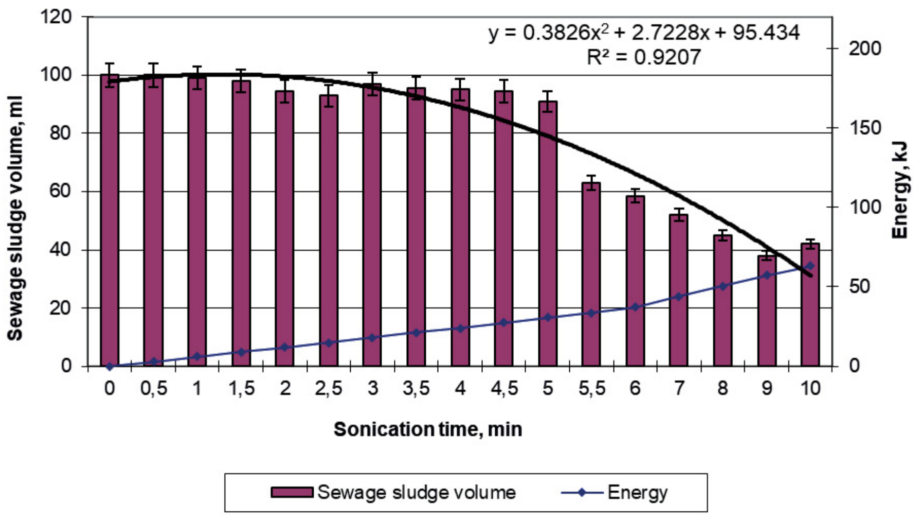

Fig. 3. Thickening of sludge treated with ultrasound (at wave intensity of 1.6 W/cm^2) after 30 min of sedimentation.

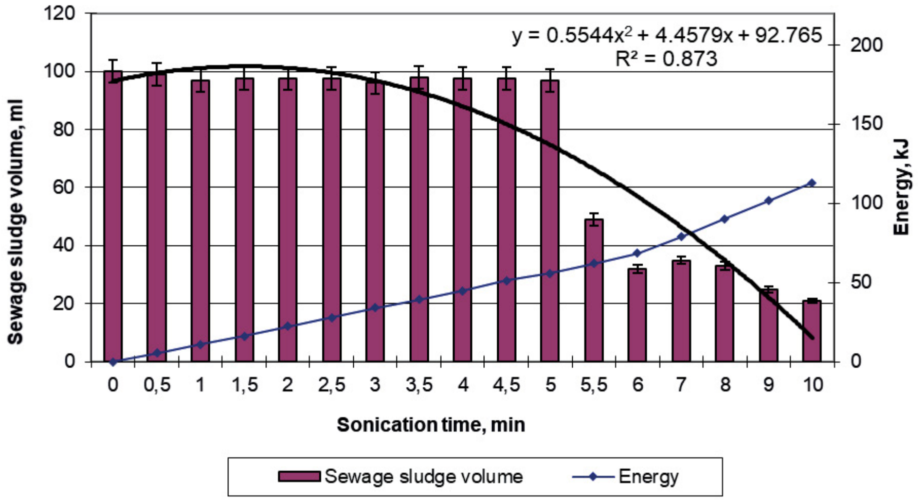

Fig. 4. Thickening of sludge treated with ultrasound (at wave intensity of 2.2 W/cm^2) after 30 min of sedimentation.

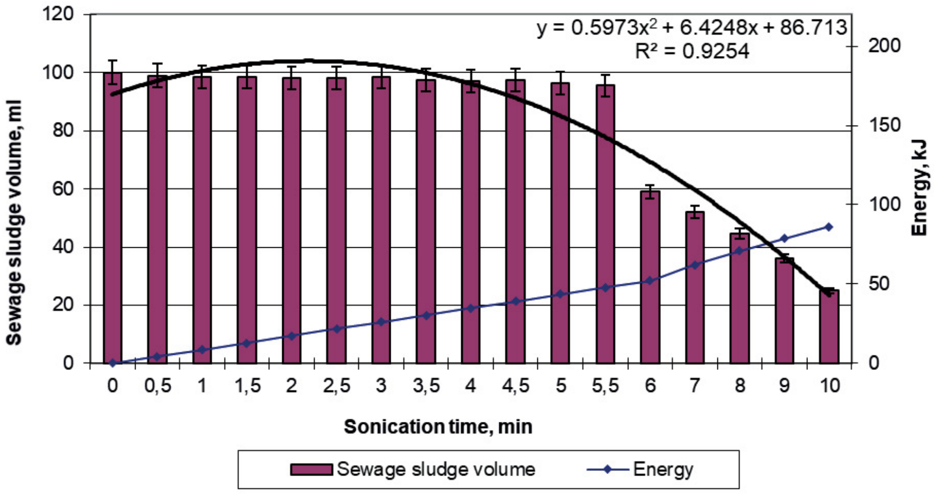

Fig. 5. Thickening of sludge treated with ultrasound (at wave intensity of 2.7 W/cm^2) after 30 min of sedimentation.

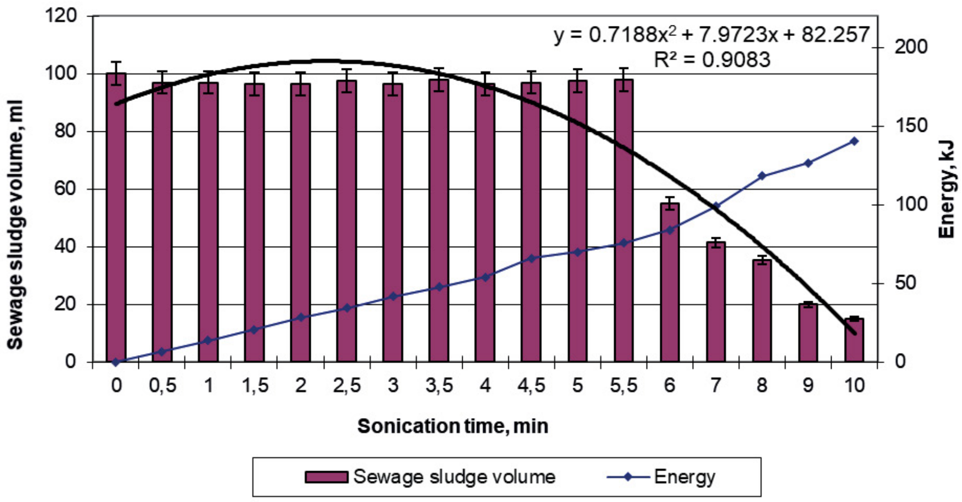

Fig. 6. Thickening of sludge treated with ultrasound (at wave intensity of 3.2 W/cm^2) after 30 min of sedimentation.

the active effect of ultrasound, where the separation of solids (sludge) and the supernatant liquid was very intense, as evidenced by the results obtained.

The presented Figs. 3–7 illustrate sedimentation of sewage sludge after 30 min of thickening. Changes in sludge volume between 30 and 120 min were negligible compared to volume changes between 0 and 30 min. Based on literature data, it is known that the sedimentation process is most intense during the first 30 min.

A further increase in sludge thickening was noted when the sludge was subjected to sonication followed by a stabilization process. Digestion itself improved sludge thickening but the volume of unconditioned sludge on each day of the process was higher compared to the sonicated sludge (Fig. 8). A marked improvement in the thickening of unconditioned sludge was observed after day 6 of stabilization. After 30 min of thickening on day 7 of the process, the sludge volume decreased to 53 mL, translating into a 50% volume reduction rate. During the following minutes of thickening, the efficiency of the process was lower, reaching a final value of 27 mL after 120 min.

An increase in thickening efficiency as early as in the first days of the digestion process was noted for sludge treated with ultrasound exposure. A rapid decrease in volume was found for the sludge prepared at each ultrasound wavelength. For example, already on day 3 of stabilization, the sludge volume was 28 mL (at wave intensity of 3.8 W/cm^2 and sedimentation time of 30 min). Sludge thickening was also at a high level for other wave intensities. On day 10 of digestion, the sludge volume was 25 mL (wave intensity: 2.7 W/cm^2, sonication time: 5 min), 40 mL (wave intensity: 3.2 W/cm^2, sonication time: 5 min), and 24 mL (wave intensity: 3.8 W/cm^2, sonication time: 5 min). Digested sludge preconditioned with ultrasound exposure at wave

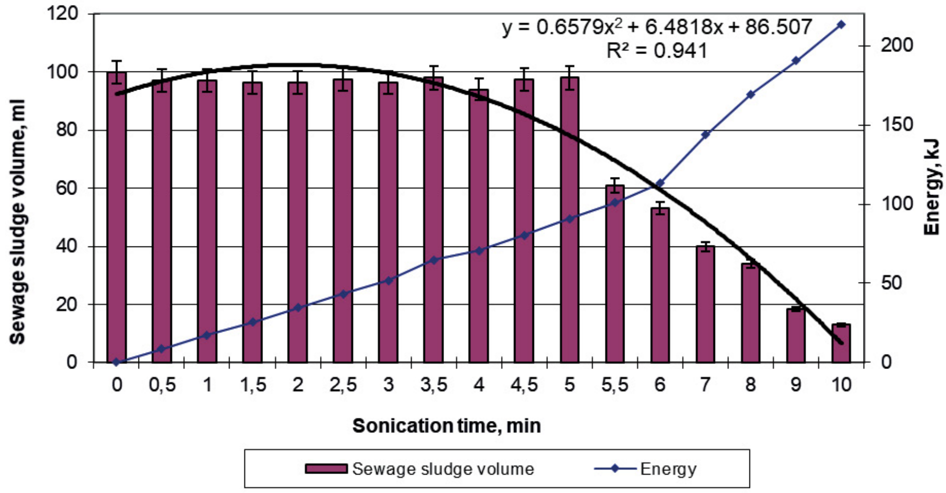

Fig. 7. Thickening of sludge treated with ultrasound (at wave intensity of 3.8 W/cm^2) after 30 min of sedimentation.

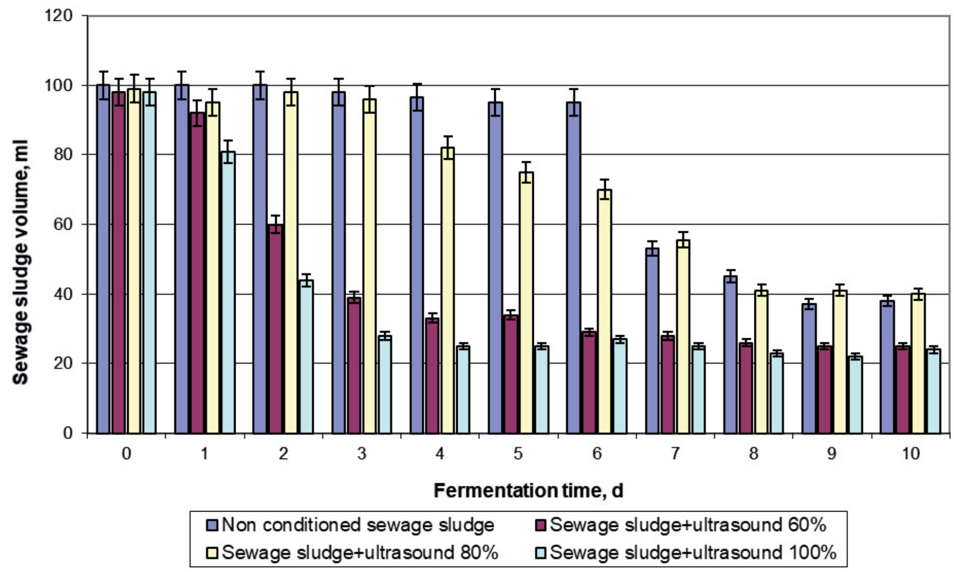

Fig. 8. Thickening of sonicated sludge subjected to digestion (ultrasound exposure: 5 min, sedimentation time: 30 min).

intensities of 2.7 and 3.8 W/cm² underwent thickening most effectively, with the smallest volume and the highest values of thickening rate. It can be stated that the tendency for sludge volume to decrease was proportional to the digestion time. Analysis of the process as a whole revealed that the reduction in the sludge volume, and thus the increase in thickening was also affected by ultrasound exposure time (Fig. 9). The study showed a nearly twofold increase in thickening for the sludge subjected to longer ultrasound exposure. On day 10 of digestion, the volume of sludge subjected to 5 min of ultrasound exposure was 40 mL, while at 10 min this value was 19 mL.

3.3. Final water content

The final water content of the sewage sludge studied after filtration was 84.8%. The 10-d stabilization carried out in flasks resulted in an increase in the value of the parameter studied. On the first day of the stabilization, water content increased to 92.2%. On the second day, there was another increase in water content (to 95.7%). On subsequent days, the final water content of the sludge remained the same until the last day of stabilization. The highest water content for the digested unconditioned sludge was recorded on days 6 and 9 of the process, yielding water content after filtration of 96.8% and 96.5%, respectively.

Pre-modification with ultrasound exposure of stabilized sewage sludge resulted in the reduction of final water content. For the lowest ultrasound intensity used in the study (2.7 W/cm²), there was a slight decrease in the value of the index studied in subsequent days of the stabilization process. When a higher ultrasound wave intensity (3.2 W/cm²) was applied, there was a marked reduction in the final water content on subsequent days of the process. For the unconditioned sludge on the 10th day of stabilization, the water content decreased by 3%. A further trend of improved dewatering efficiency was observed after conditioning of the sludge studied with the highest ultrasound wave intensity of 3.8 W/cm² used in the study. For the ultrasound amplitude, a decrease in the final water content in the sludge was observed after the 4th day of stabilization, with a further downward trend in subsequent days. The final water content in sewage sludge preconditioned with ultrasound (wave intensity: 3.8 W/cm²) subjected to stabilization was 89.3% on day 10 of the process, 9.2% lower than that for non-stabilized sludge. Preconditioning with increasing ultrasound wavelength improved the dewatering efficiency of the stabilized sludge.

3.4. Specific resistance of sewage sludge

Subjecting the sludge to digestion yielded an increase in filtration resistance, with 8.11×10^{12} m/kg on the first day of the process. On subsequent days, specific resistance decreased slightly to 6.59×10^{12} m/kg, remaining the same until the end of the process on day 10.

Sludge sonication resulted in increased resistance values. At the lowest wave intensity (2.7 W/cm²) used in the study, the resistance was 12.1×10^{12} m/kg. For other ultrasound wave intensities, the specific resistances were 10.9×10^{12} m/kg (wave intensity: 3.2 W/cm²) and 10.1×10^{12} m/kg (wave intensity: 3.8 W/cm²). Digestion of the sonicated sludge contributed to a reduction in specific resistance of the sludge. Such a relationship was observed for each intensity used in the study. At a wave intensity of 2.7 W/cm³, the specific resistance decreased from 10.69×10^{12} on the first day of stabilization, to 5.33×10^{12} m/kg on the 10th day of the process.

4. Summary and conclusions

Depending on its intensity, wavelength, and exposure time, ultrasound energy can have a dispersive or coagulating effect. The analysis of the results of the effect of the

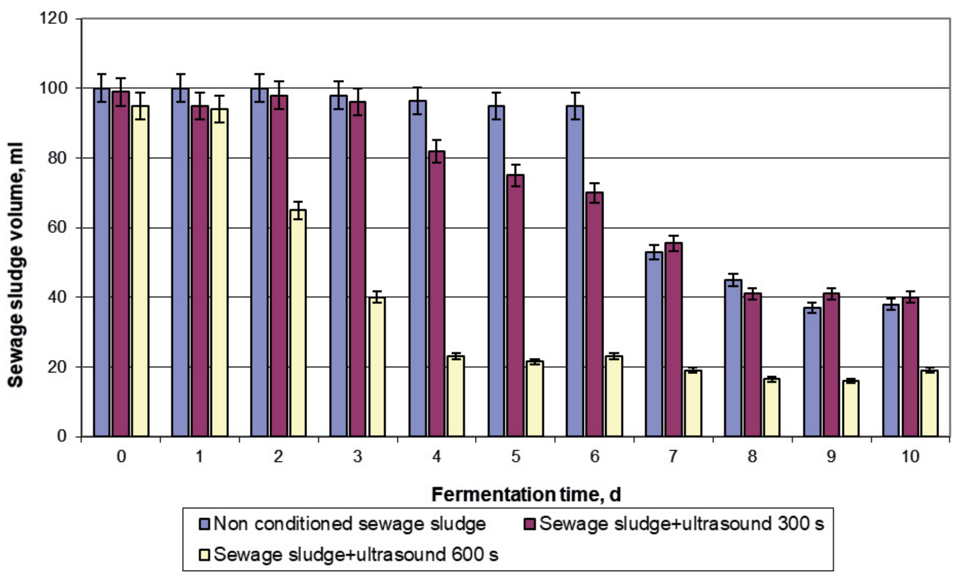

Fig. 9. Thickening of sonicated sludge subjected to digestion (wavelength: 31.54 μm, sedimentation time: 30 min).

ultrasound field wavelength and operation time on the values of the capillary suction time of the sludge reveals the dispersive effect of the medium used.

The dispersive effect of ultrasound had a very positive effect on sludge thickening. Single, fragmented flocs were better packed and released free water. By deteriorating the filtration capacity, ultrasound had a positive effect on sludge thickening efficiency. A noticeable effect for each amplitude tested was reported at the 6th minute of the ultrasound exposure. The dispersive effect of ultrasound is confirmed by the final water content of the preconditioned sludge. Regarding the final water content of unconditioned sludge, with its value of 84.8%, the modification with ultrasound exposure increased the discussed index. The final water content of sludge conditioned with ultrasound increased to 98.8% (60% amplitude), 98.7% (80% amplitude), and 98.5% (100% amplitude).

Preliminary modification with a conditioning factor increases the efficiency of the sludge stabilization process. Furthermore, the stabilization of preconditioned sludge changes the values of parameters characterizing its dewatering efficiency. Analysis of the capillary suction time of the fermented sludge showed a decrease in the value of this index with each day of the process. The decrease in CST was directly proportional to fermentation time. Stabilization thus resulted in lower CST times and improved the filtration capacity of the preconditioned sludge.

A positive effect of the initial modification of the stabilized sludge was also observed after the thickening process. Similar to the capillary suction time, also the process of sludge thickening was more intensive during the initial modification with the ultrasound field. The highest increase in thickening was found for the highest wavelength (39.42 μm), with the lowest values of volume (25 mL) were recorded after 4 d of fermentation carried out in flasks and 30 min of thickening. The process stabilized in the following days. For other amplitudes, process improvements were also found for the unconditioned sludge. In addition to the wavelength of the ultrasound field, the initial sonication time also affected the increase of the thickening efficiency. The improvement and positive effect of stabilization on the thickening efficiency of preconditioned sludge is also evidenced by the thickening rate. Its values also confirm the thesis of obtaining the best thickening values at the highest wavelength and the longest exposure time. At an ultrasound exposure time of 5 min and a wavelength of 39.42 μm, the highest thickening rate on day 10 of stabilization (2.533 cm/min) was found after 30 min of thickening. For a longer sonication time, an increase in the thickening rate was observed, reaching a final value of 2.7 cm/min.

Digestion of preconditioned sludge resulted in lower final water content with each day of the process. It was observed that also in this case, water content values were lowest at the highest ultrasound wavelength. Mineralization of organic matter is more intense due to the dispersion of sludge flocs, which is reflected in the results obtained. The changes in water content correlated with the specific resistance of the sewage sludge studied. Similar to the determination of the previous indices, also in the case of specific resistance, its increase, caused by sonication of sewage sludge, was observed. Stabilization led to its reduction, with a steady decrease in resistance values on each day of the process.

The findings of the study lead to the following conclusions:

- The application of ultrasonic field in sewage sludge conditioning leads to an increase in capillary suction time in proportion to increases in wavelength and operating time. The highest value of the index studied of 1461s was recorded for the highest wavelength (39.42 μm) and exposure time of 10 s.
- Stabilization of sewage sludge preconditioned by sonication led to an increase in filtration capacity of the sludge expressed by reduced capillary suction time. The highest reduction in capillary suction time was found at the highest wavelength (39.42 μm) and ultrasound exposure time (10 min).
- The use of sludge preconditioning intensifies sludge thickening. Digestion leads to further intensification of the process, obtaining the lowest volume values and the highest thickening rates at the longest ultrasound wavelength and exposure time. The sludge volume reduction was 90%.
- Ultrasound used to condition digested sludge led to a reduction in final water content. Water content decreased on each day of stabilization, with the lowest values found for the highest ultrasound wavelength (water content was 89.4%).

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