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Filtration properties of conditioned sewage sludge

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ABSTRACT

This paper presents the results of a study on the effects of different conditioning methods on the filtration properties of sludge, that is, specific resistance, efficiency, and filtration rate. Sludge conditioning was carried out using a thermal method, sonication, and a combination of the previous methods known as hybrid conditioning. Tests were conducted for both undigested sludge and sludge digested in laboratory flasks. The conditioning methods used reduced filtration efficiency and filtration rate. The digestion process was a factor in increasing the parameters studied. The lowest filtration resistance was obtained when the sludge was conditioned using an ultrasonic field of 31.54 and 39.42 μm, resulting in values of 4.37–4.29 × 10^{12} m/kg on day 5 of the process. At these wavelengths, the sludge also showed the highest filtration rate. During thermal conditioning, resistance increased with increasing temperature. The stabilisation process did not result in major changes in filtration resistance. At a temperature of 80°C, a decrease in the discussed indicator was observed.

Keywords: Sewage sludge; Filtration; Conditioning; Stabilisation process

1. Introduction

Sewage sludge is a multiphase mixture considered as a two-phase mixture of water and dispersed solids [1]. According to Bień et al. [2], the amount of sludge depends on the wastewater treatment technology adopted and implemented, and the degree of decomposition of organic matter during the stabilisation process. The ratio between liquid and solid phases determines the water content in the sludge. Water content alone does not determine how much water can be removed from the sludge but it determines its consistency. Also, the ability to lose water classifies sludge into the categories of easy to dehydrate, difficult to dehydrate, and very difficult to dehydrate.

The primary objective of sludge treatment is the mineralisation of organic compounds, leading to the stabilisation of the sludge and reduction in its volume [3,4]. Effective treatment of sewage sludge helps reduce its weight. It is important to remember that environmental fees charged for sludge disposal are calculated based on water content and sludge mass. Therefore, sludge is usually subjected to operations such as thickening, stabilisation, and dewatering [5–7]. Any removal of water from the sludge reduces its volume. For example, dewatering the sludge by 3%–4% translates to an approximately 5-fold reduction in volume.

Depending on the method used, sludge conditioning leads to the neutralisation of the electrical charge of sludge grains and particle bonding (agglomeration), increases the shear and compression resistance, improves the R separation factor (better quality of the treatment leachate), reduces the alkalinity and viscosity of the filtrate, and increases the dry mass of the sludge cake without increasing the total mass of the sludge. Research in the field of waste management is aimed, among other things, at reducing the amount of sludge generated and thereby increasing the economic efficiency of the processes used. Popular alternative conditioning methods and approaches include mechanical disintegration, examinations using UV, magnetic, and electric

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fields, and sludge preparation using acids and bases [8,9], Fenton's reagents [10,11], studies of sludge conditioning with ultrasonic exposure [12,13], thermal conditioning [14], sludge conditioning with microwave exposure and addition of ash, coal, or diatomaceous earth as structure-building substances.

Combined methods used for sewage sludge conditioning can increase the efficiency of dewatering, depending on the methods and parameters used. The application of ultrasonic exposure, flocculation, and skeleton-forming agents leads to a significant reduction in water content and, consequently, a 73% increase in filtration rate compared to raw sludge [15]. Changes in the sludge floc structure have a significant positive impact on improving sludge dewatering efficiency. Ultrasound breaks down microbial cells thus improving organic matter stabilization, reducing sludge viscosity and increasing sludge homogeneity [16].

As found by Anderson et al. [17], thermal treatment improves sludge dewaterability. The most common treatment temperatures range from 60°C to 180°C to destroy cell walls, making proteins readily available for biological degradation. Treatment at temperatures below 100°C is considered a low-temperature thermal treatment, and, despite longer contact times compared to high-temperature methods, it is considered effective in increasing biogas production from secondary sludge. Another advantage of thermal treatment is that it reduces the viscosity of the sludge, thus improving sludge processing. The main disadvantage of this treatment, however, is its high energy requirements.

In a study by Feng et al. [18], the physical properties (particle size, bound water content, and viscosity) of municipal sludge were significantly modified after thermal hydrolysis at 170°C for 60 min. The treated sludge exhibited characteristics more similar to inorganic particles and could be accurately described using a Newtonian model. The reduced softness and increased stiffness of the treated sludge particles contributed to the formation of the sludge cake with higher permeability and a lower compression ratio during the filtration. Thermal conditioning improves the dewatering properties of sludge by simultaneously applying heat and pressure to break down the structure, reducing the sludge's water affinity [19].

Sludge stabilisation reduces the volume of the sludge, thereby increasing biogas production [20]. Many articles and publications can be found in the related literature on various methods used to facilitate the digestion processes [21–23].

The aim of the present research was to evaluate the effect of different conditioning and digestion methods on the efficiency of water release by determining the filtration properties of the sludge, for example, specific resistance, filtration efficiency, and filtration rate.

2. Material and methodology

The research material was the excess sludge from a mechanical–biological wastewater treatment plant (P.E. of 314835). The sludge used in the study was characterised by a dry matter content of 11.0 ± 2.9 g/dm^3, organic dry matter content of 7.3 ± 2.8 g/dm^3, capillary suction time of 24 ± 2 s, initial water content of 98.6%, final water content of 84.8%, and sludge specific resistance of 2.96 × 10^{12} m/kg.

Sludge conditioning was carried out using thermal methods, an ultrasonic field and a combination of the previous methods known as combined (hybrid) conditioning. Sludge stabilisation was carried out in laboratory flasks over a period of 10 d.

Sonication of sewage sludge was carried out under static conditions in three test cycles for selected values of vibration amplitude (wave intensity): 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). The sonication time ranged from 0 to 600 s. A Sonics VCX-1500 ultrasonic processor with a maximum output power of 1,500 W was used for sludge sonication. The frequency of the ultrasonic vibrations of the generator was 20 kHz and the maximum wavelength, with an amplitude of 100%, was 39.42 μm. The device converted electrical energy into mechanical energy, transferred in the form of a wave to the titanium tip.

Thermal conditioning of the excess sludge was carried out using a water bath with an ELPIN+ laboratory shaker. Sludge samples of 0.5 dm^3 placed in laboratory flasks were tested and heated at 50°C, 60°C, 70°C, 80°C, and 90°C, according to the test schedule. Thermal conditioning times for the sludge were 90 min above.

The results obtained for the disintegration of the sludge using exposure to the ultrasonic field and thermal conditioning were used to combine the aforementioned methods to carry out the disintegration process with a hybrid method in a suitable configuration, for example, sonication + thermal method. Ultrasonic field conditioning was conducted at a wavelength of 3.2 W/cm^2 and a sonication time of 300 s. Thermal conditioning was carried out in a water bath for 90 min at temperatures of 60°C and 80°C.

Sludge dewatering was carried out on a vacuum filter. The filtration setup consisted of a glass flask, a measuring cylinder, a vacuometer, a vacuum pump, and a Buchner funnel (9.4 cm in diameter). After placing the filter paper inside the funnel, a 100 cm^3 sludge sample was poured in. The pump generated a vacuum pressure of 0.06 MPa. The volume of filtrate that flowed into the cylinder was measured during filtration. The vacuum filtration process allowed for the determination of the final water content, the specific resistance of the sludge, and the rate and efficiency of the filtration. The specific resistance of the sludge, which is a quantitative measure of its dewatering capacity, was calculated using the formula:

$$r = \frac{2 \cdot b \cdot \Delta p \cdot F^2}{\eta \cdot c}$$

where b – sludge filtration constant; Δp – pressure difference; F – filtration surface; η – filtrate viscosity; c – mass of solid particles.

3. Results and discussion

3.1. Effect of the ultrasonic field on the filtration properties of sludge

One of the most important parameters of the filtration capacity of sewage sludge is specific resistance. Based on the resistance values of the unconditioned sludge, the tested sludge was classified as difficult to dehydrate (2.96 × 10^{12} m/kg) (Fig. 1). Sludge digestion yielded an

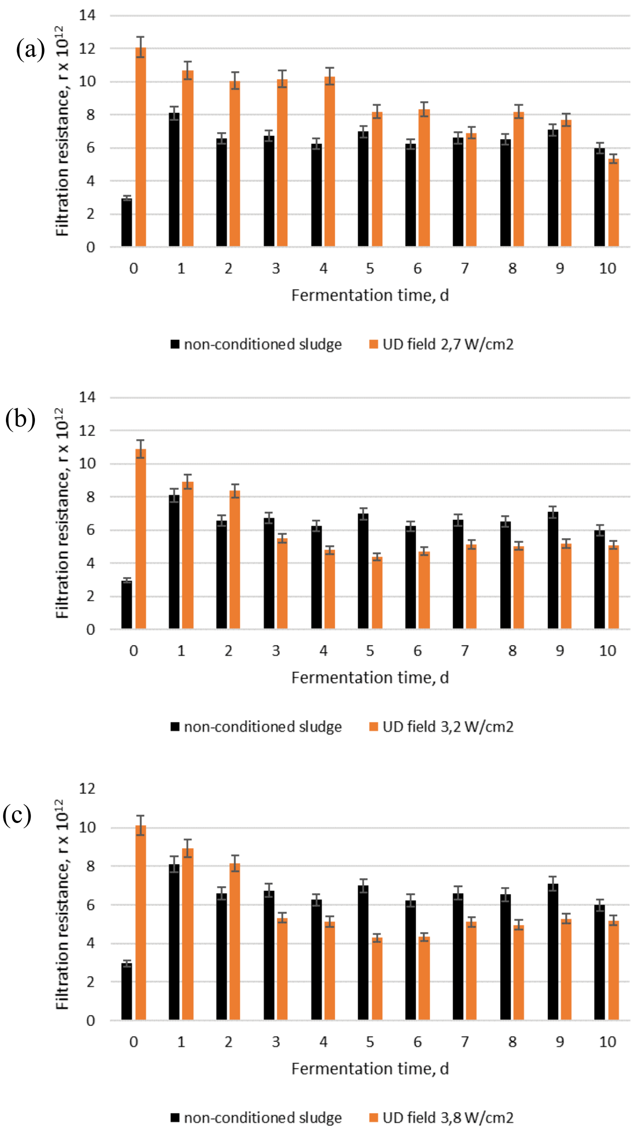

Fig. 1. Specific resistance of sonicated digested sludge: (a) ultrasonic wave intensity of 2.7 W/cm^2, (b) ultrasonic wave intensity of 3.2 W/cm^2, and (c) ultrasonic wave intensity of 3.8 W/cm^2.

increase in filtration resistance of 8.11 × 10^{12} m/kg on the first day of the process. In the following days, the resistance decreased slightly to 6.59 × 10^{12} m/kg and remained constant until the end of the process, for example, day 10.

Sludge sonication resulted in an increase in resistance. At the lowest sonication wave intensity used (2.7 W/cm^2), the resistance was 12.1 × 10^{12} m/kg (Fig. 1a). For the other applied ultrasonic field wave intensities, the specific resistance of the sludge was 10.9 × 10^{12} m/kg (ultrasonic wave intensity of 3.2 W/cm^2) and 10.1 × 10^{12} m/kg (ultrasonic wave intensity of 3.8 W/cm^2), as shown in Fig. 1b and c, respectively.

Digestion of pre-sonicated sludge contributed to a reduction in the specific resistance of the sludge. Such a relationship was observed for each ultrasonic field intensity used in the study. For an intensity of 2.7 W/cm^3, the specific resistance decreased from 10.69 × 10^{12} m/kg on the first day of stabilisation to 5.33 × 10^{12} m/kg on day 10. Similar relationships were found for the two amplitudes studied. The strength of the stabilisation effect on the specific resistance of the sludge is confirmed by the values of filtration rate and efficiency presented in Tables 1 and 2. The analysis of these results confirmed the research hypotheses. The highest efficiency and rate in the process were observed in the case of the sludge pre-sonicated with an ultrasonic field at the highest amplitude, for example, 100%. The filtration rate on day 10 of digestion compared to the non-conditioned sludge increased by 1.143 kg/m^2·h, while the filtration rate was 0.033 cm^3/s higher.

3.2. Effect of thermal conditioning on filtration properties of the sludge

Thermal conditioning of sewage sludge, used as the second conditioning method, changed the specific resistance of non-conditioned sludge. Its value for non-conditioned and non-stabilised sludge was 2.96 × 10^{12} m/kg. On the first day of digestion, this parameter significantly increased to reach 8.11 × 10^{12} m/kg. In the subsequent days of the stabilisation, the specific resistance of the unconditioned sludge remained constant at 6–7 × 10^{12} m/kg.

Thermal conditioning of sludge at 50°C and 70°C resulted in a reduction of specific resistance compared to the values observed for non-conditioned sludge (Fig. 2a and c). For a temperature of 60°C, the resistance increased by 4 × 10^{12} m/kg compared to the lower temperature tested, for example, 50°C. For the subsequent temperatures used in sludge conditioning, the resistance decreased to 1.11 × 10^{12} m/kg (70°C), followed by an increasing trend reaching values of 9.45 × 10^{12} m/kg (80°C) and 5.57 × 10^{12} m/kg (90°C), respectively.

The stabilisation process of the thermally pre-conditioned sludge resulted in successive changes in the specific resistance values of the tested sewage sludge. For a temperature of 50°C, its value was 1.33 × 10^{12} m/kg and remained constant on subsequent days of stabilisation (Fig. 2a). Also, for the other temperature values, constant values of specific resistance of the sludge were observed on successive days of digestion. The exception was the sludge conditioned at 80°C, for which the value of the specific resistance was 8.96 × 10^{12} m/kg during the 1st days, which decreased to reach 3.92 × 10^{12} m/kg on the 10th day (Fig. 2d). When a temperature of 90°C was applied, the resistance values of the thermally conditioned sludge coincided with those of the thermally unmodified sludge (Fig. 2e).

The pattern of changes in the specific resistance of the sludge is also evidenced by the filtration capacity and filtration rate (Tables 3 and 4). The calculated results correlated with the resistance values for each temperature tested. The highest filtration efficiency was obtained for the lowest resistance at temperatures of 50°C and 70°C. For the thermally-conditioned sludge at these temperatures and unstabilised sludge, this value was 3.146 kg/m^2·h. Sludge stabilisation yielded an increase in the parameter studied, with its values reaching 4.07 kg/m^2·h (50°C) and 4.25 kg/m^2·h (70°C) on day 10, respectively. For the other temperatures tested, the values of filtration efficiency were twice as low.

Table 1
Filtration capacity of pre-sonicated digested sewage sludge

Digestion time, d	Filtration capacity, $kg/m^2 \cdot h$			
	Non-conditioned sludge	Sludge + ultrasonic field 2.7 W/cm^2	Sludge + ultrasonic field 3.2 W/cm^2	Sludge + ultrasonic field 3.8 W/cm^2
0	3.050	3.840	4.363	4.534
1	3.022	3.400	3.743	3.978
2	2.667	3.571	3.696	3.723
3	2.581	3.361	3.517	3.795
4	2.347	3.462	3.653	3.821
5	2.452	3.103	3.275	3.398
6	2.207	3.139	3.259	3.389
7	2.187	3.057	3.388	3.865
8	2.347	3.255	3.177	3.543
9	2.300	2.994	3.216	3.397
10	2.335	2.476	3.591	3.478

Table 2
Filtration rate of pre-sonicated digested sewage sludge

Digestion time, d	Filtration rate, cm^3/s			
	Non-conditioned sludge	Sludge + ultrasonic field 2.7 W/cm^2	Sludge + ultrasonic field 3.2 W/cm^2	Sludge + ultrasonic field 3.8 W/cm^2
0	0.305	0.077	0.077	0.077
1	0.178	0.083	0.083	0.082
2	0.167	0.103	0.107	0.108
3	0.177	0.100	0.123	0.126
4	0.183	0.100	0.13	0.136
5	0.178	0.130	0.19	0.210
6	0.190	0.130	0.197	0.215
7	0.200	0.140	0.197	0.223
8	0.200	0.123	0.2	0.249
9	0.217	0.150	0.203	0.252
10	0.220	0.143	0.203	0.253

The digestion also increased the filtration rate of the thermally conditioned sludge (Table 4). For each temperature tested, an increase in this parameter was recorded, reaching values of 0.19–0.24 cm^3/s on day 10 of the process.

3.3. Effect of hybrid conditioning on sludge filtration properties

Modification of the sludge conditioning methods also affected the specific resistance of the sludge. With the application of the ultrasonic field and a temperature of 60°C, the resistance value of the unconditioned sludge increased to 9.96×10^{12} m/kg (Fig. 3a). An increase in resistance of 11.1×10^{12} m/kg was also recorded using the ultrasonic field and a temperature of 80°C (Fig. 3b). Subjecting pre-conditioned sludge to digestion led to a decrease in this parameter. For both sonication and a temperature of 60°C and sonication and a temperature of 80°C, the sludge resistance was decreasing on each day of digestion. For the temperature of 60°C using the combined method, sludge resistance on the 3rd day of stabilisation was lower than that of unconditioned sludge. On day 10, it was 5.99×10^{12} m/kg for non-conditioned sludge and 2.9×10^{12} m/kg for sludge pre-conditioned with an ultrasonic field and a temperature of 60°C. In the case of higher temperatures, the resistance values of unconditioned and hybrid-conditioned sludge in the final days of digestion were comparable.

The use of hybrid methods increased the efficiency of filtration of the sewage sludge. Stabilisation of both non-conditioned sludge and sludge subjected to hybrid modification led to the reduction of this indicator with each day of the process. Filtration efficiency values reached a low point on days 7–8 of stabilisation for the non-conditioned sludge and sludge pre-modified with an ultrasonic field and temperature of 60°C (Table 5). In the case of pre-conditioning the sludge treated with an ultrasonic field and a temperature of 80°C, the lowest efficiency values were recorded on day

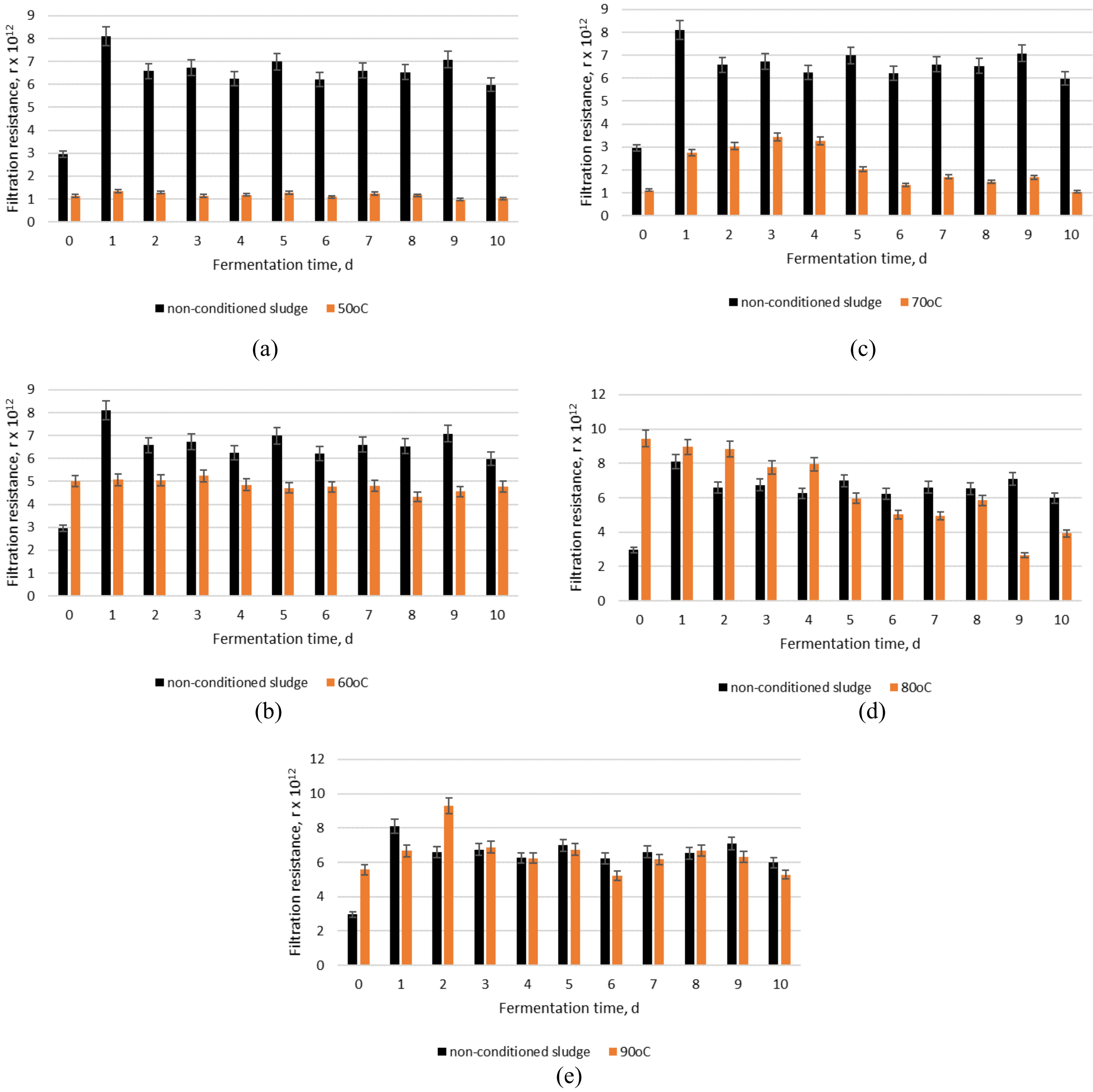

Fig. 2. Specific resistance of thermally conditioned digested sludge for different temperatures: (a) 50°C, (b) 60°C, (c) 70°C, (d) 80°C, and (e) 90°C.

10 of the process (3.11 kg/m^2·h). Also, the effect of sludge pre-conditioning was found in the analysis of the filtration rate (Table 6). Lower values were recorded for hybrid pre-conditioning. In the case of non-conditioned sludge, the digestion process resulted in a decrease and then an increase in this parameter. A similar relationship was shown for the pre-modified sludge. The highest filtration rate (0.237 cm^3/s) was found on day 10 of stabilisation for the sludge conditioned with an ultrasonic field and a temperature of 60°C.

4. Summary and conclusions

The deterioration of filtration capacity as a result of exposure to the ultrasonic field led to an increase in the specific resistance of the sludge. With regard to the non-conditioned sludge, where the resistance was 2.96 × 10^{12} m/kg, this factor increased as a result of exposure to the ultrasonic field, reaching values of 12.1 × 10^{12} m/kg (60% amplitude), 10.9 × 10^{12} m/kg (80% amplitude) and 10.1 × 10^{12} m/kg (100% amplitude). A similar relationship was shown by Kamizela and Kowalczyk [24] in their study, where sludge sonication resulted in an increase in the specific resistance of filtration, regardless of the amplitude and sonication time used. Exposure to the ultrasound field reduced the filtration rate and increased the filtration efficiency compared to the non-conditioned sludge. On day 10 of the test, these values were 0.203 cm^3/s (80% amplitude) and 0.253 cm^3/s (100% amplitude).

Table 3
Filtration efficiency of the thermally pre-conditioned digested sludge

Digestion time, d	Filtration capacity, kg/m²·h					
	Non-conditioned sludge	Sludge + 50°C	Sludge + 60°C	Sludge + 70°C	Sludge + 80°C	Sludge + 90°C
0	3.050	3.146	2.901	3.146	3.509	3.279
1	3.022	3.220	3.345	3.210	3.100	3.232
2	2.667	4.987	3.244	5.084	3.236	3.255
3	2.581	4.780	3.115	5.306	3.232	3.154
4	2.347	4.335	3.267	4.651	2.936	2.951
5	2.452	4.530	3.135	6.445	2.507	2.597
6	2.207	4.254	2.981	4.733	2.421	2.351
7	2.187	4.530	2.827	4.386	2.589	2.659
8	2.347	4.265	2.651	4.332	2.437	2.495
9	2.300	4.367	2.608	6.772	2.448	2.456
10	2.335	4.070	2.565	4.250	2.593	2.495

Table 4
Filtration rate of the thermally pre-conditioned digested sludge

Digestion time, d	Filtration rate, cm³/s					
	Non-conditioned sludge	Sludge + 50°C	Sludge + 60°C	Sludge + 70°C	Sludge + 80°C	Sludge + 90°C
0	0.305	0.317	0.163	0.317	0.107	0.145
1	0.178	0.179	0.177	0.176	0.120	0.153
2	0.167	0.150	0.187	0.070	0.117	0.113
3	0.177	0.170	0.200	0.083	0.130	0.150
4	0.183	0.177	0.213	0.100	0.153	0.167
5	0.178	0.177	0.220	0.143	0.167	0.177
6	0.190	0.217	0.220	0.047	0.200	0.203
7	0.200	0.190	0.223	0.150	0.177	0.190
8	0.200	0.200	0.227	0.147	0.193	0.200
9	0.217	0.210	0.233	0.157	0.197	0.190
10	0.220	0.215	0.240	0.186	0.213	0.233

Ultrasonic energy is useful for dewatering suspensions [25]. Ultrasonic stresses produce a sponge effect and facilitate the migration of moisture through natural channels or other channels formed by wave propagation. Sarabia et al. [26] demonstrated that the effect of high-power acoustic processing at 10 and 20 kHz can improve solid/liquid separation during cake filtration. A combination of using exposure to the ultrasonic field and other methods can improve sludge agglomeration, biomass activity, and anaerobic processes, and reduce the final water content in sludge by more than 10% [27].].

Noteworthy is the specific resistance of the sludge, with its values depending on the conditioning temperature and the digestion time. It was observed, that at lower temperatures the sludge resistance was lower compared to the specific resistance of non-conditioned sludge. Analysis of the results demonstrated that as the temperature increased, the resistance of the sludge tested also increased. In the case of stabilisation conducted in flasks, a decrease in specific resistance was found after digestion compared to the sludge before the process. Such a relationship was observed for sludge conditioned at all temperatures used.

Lin and Shien [28] found that the dewatering capacity can be greatly enhanced by thermal treatment combined with the use of polymers. In their study, these researchers showed a good correlation between capillary suction time and specific filtration resistance for the sludge obtained from water treatment. Feng et al. [29] also observed that as the hydrolysis temperature increased, there was a decrease in bound water content, and the flocs became more compact following thermal hydrolysis.

For the combined method (sonication + temperature field), there was a reduction in filtration capacity due to an increase in the specific resistance of the sludge. In each case, the indicators studied were higher than the respective values of sludge conditioned by standalone methods. It is noteworthy that, similarly to the effect of digestion on the values recorded in the sludge pre-treated with exposure to the ultrasonic field or thermally, a positive effect of stabilisation on the values of the indicators studied was also noted

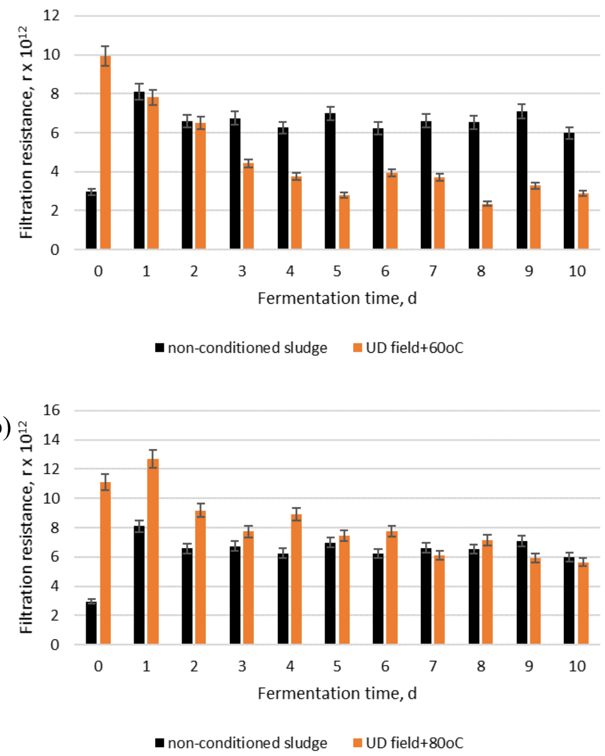

Fig. 3. Specific resistance of sewage sludge pre-conditioned with the hybrid method and subjected to digestion: (a) ultrasonic field, 3.2 W/cm² + 60°C and (b) ultrasonic field, 3.2 W/cm² + 80°C.

Table 5
Filtration efficiency of hybrid pre-conditioned sludge subjected to digestion

Digestion time, d	Filtration capacity, kg/m²·h		
	Non-conditioned sludge	Ultrasonic field, 3.2 W/cm² + 60°C	Ultrasonic field, 3.2 W/cm² + 80°C
0	3.050	5.014	4.682
1	3.022	4.632	4.316
2	2.667	4.503	4.004
3	2.581	3.805	3.801
4	2.347	3.797	3.466
5	2.452	3.279	3.79
6	2.207	3.829	3.692
7	2.187	3.166	3.485
8	2.347	3.096	3.489
9	2.300	3.54	3.363
10	2.335	3.595	3.111

in the case of combined methods. It was observed that the resistance was decreasing on each day of digestion, improving the filtration capacity of the sludge. In the last days of stabilisation, the values of the sludge modified with combined methods were similar to those of the non-conditioned sludge.

Table 6
Filtration rate of hybrid pre-conditioned sludge subjected to digestion

Digestion time, d	Filtration rate, cm³/s		
	Non-conditioned sludge	Ultrasonic field, 3.2 W/cm² + 60°C	Ultrasonic field, 3.2 W/cm² + 80°C
0	0.305	0.067	0.06
1	0.178	0.07	0.07
2	0.167	0.083	0.081
3	0.177	0.137	0.087
4	0.183	0.143	0.123
5	0.178	0.147	0.137
6	0.190	0.2	0.147
7	0.200	0.2	0.167
8	0.200	0.233	0.163
9	0.217	0.233	0.19
10	0.220	0.237	0.193

The use of ultrasonic energy and temperature for the conditioning of sewage sludge requires a large energy input. For several years now, there have been installations in the world for the sonication of sludge generated at wastewater treatment plants. Despite the significant energy requirements (15–20 PLN/m³ of sludge), the ultrasonic method offers an alternative to other methods (especially chemical) as it allows for the generation of cheap renewable energy. The ultrasonic exposure can be a clean method of sludge treatment.

The findings of the study lead to the following conclusions:

- Sludge sonication resulted in an increase in the resistance values. The digestion of the sonicated sludge resulted in a decrease in the value of this parameter, with the lowest value (4.29–10^{12} m/kg) reached on the 5th day of digestion (ultrasonic wave intensity of 3.8 W/cm²);
- Thermal modification of the sludge at 50°C and 70°C lowered the specific resistance compared to the filtration resistance of non-conditioned sludge. The lowest resistance was recorded at50°C, where its value was 0.97 × 10^{12} m/kg (day 9 of digestion) and remained constant on subsequent days of stabilization;
- The use of combined methods in sludge conditioning also increased specific resistance. When subjecting the pre-conditioned sludge to the digestion process, whether using ultrasound exposure and a temperature of 60°C, or ultrasound exposure and a temperature of 80°C, the sludge resistance values were decreasing on each day of digestion. For a temperature of 60°C and exposure to the ultrasonic field, the lowest resistance (2.35 × 10^{12} m/kg) was recorded on day 8 of digestion.

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