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Influence of Ultrasonic Pretreatment on Anaerobic Digestion of Excess Sludge from the Food Industry

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1. Introduction

Sewage sludge is a natural product obtained after sewage treatment. The amount of sludge generated is about 1 to 3% of the volume of the supplied wastewater, but the outlays on processing the sludge amount to ca. 50% of the costs incurred on sewage and sludge treatment in the plant.

Sewage sludge treatment consists in subjecting it to a variety of processing methods based on the processes of biological, physical and chemical nature which help obtain a product which is safe for environment and human health [12, 13, 18, 19].

Current facilities in treatment plants, with high-performance biological methods of sewage sludge treatment and removal of biogenic compounds supported with chemical methods, generate huge amounts of sewage sludge. Sewage sludge is a product that causes substantial environmental nuisance due to unpleasant odour as a result of putrification and it represent a serious sanitary threat. The sludge which is generated should be processed and treated or be used in industry or agriculture. Due to sludge harmfulness to the environment, all the safety recommendations for sludge management should be respected. The main aim of anaerobic process of sludge stabilization is to reduce the sludge mass. Reduction of the amount of sludge minimizes its harmful effect on the environment. Methane fermentation is very popular since it transforms strongly hydrated and hydrophilic sewage sludge with unpleasant odour and high viscosity which is dangerous in bacteriological terms. The generated low-viscosity sludge is easily dewatered and it resembles soil [11]. Sewage sludge treatment using methane fermentation is advantageous in energetic terms since it does not necessitate the supply of high energy while a product of reactions that occur in the process is high-energy biogas. One drawback of this process is low rate of degradation of organic compounds contained in the sludge [3, 23].

In the aspect of improving the effectiveness of anaerobic stabilization, ultrasonic field disintegration represents a very good method. However, it necessitates choosing optimum value of wave frequency. Using ultrasound energy to decompose biomass involves application of low ranges of field frequencies. The choice of frequency depends on the medium exposed to the effect of ultrasound [5, 6, 8, 20].

Depending on the frequency and physical conditions of the medium, high-intensity ultrasound might cause coagulation i.e. connecting small particles into bigger aggregates or dispersion, that is, fragmentation of bigger particles into smaller ones. Ultrasonic coagulation processes occur usually in suspensions of solid particles, liquid drops, gas bubbles in gaseous or liquid medium and they consist in creation of forces in the acoustic field that take them closer to each other and connect into bigger particles that fall down due to gravity forces [17].

It is generally accepted that the disintegrating effect is mainly caused by ultrasonic cavitation. Resonance vibrations of gas bubbles that represent cavitation nuclei and rapid formation and collapsing of vacuum bubbles is observed in the area of cavitation, accompanied by local increases of temperature and pressure. The latter phenomenon is a source of impact waves that cause e.g. dispersion and homogenization of solids in the liquid [17]. Vibrations of media and particles accelerate deformation of a double diffusion layer of colloidal particles, which is manifested with changes in the potential of sonicated sludge particles and offers opportunities for improving the effect of coagulation/flocculation of the sludge [10].

Ultrasound wave is produced as a result of rhythmic vibrations of the particles in the medium it travels through. The wave is characterized by acoustic wave intensity. Intensity is given by the following formula [9]:

$$I = \frac{P}{A}, W \cdot cm^{-2} \tag{1}$$

where:
P – power transferred through ultrasonic waves, W;
A – surface of wave propagation, cm^2.

Basic parameters used in description of ultrasonic waves that are formed is wavelength and frequency. Wavelength depends on a medium the ultrasounds propagate in. The basic relationship that occurs between frequency and wavelength is [21]:

$$\lambda = \frac{v}{f}, m \tag{2}$$

where:
v – velocity of wave propagation in a particular medium, m/s;
f – ultrasonic wave vibration frequency, Hz.

There are five options of using ultrasonic disintegration in a technological line of a wastewater treatment plant [20].

- disintegration of activated sludge in order to improve sedimentation properties during de-clearing in order to remove a fermentation scum,
- disintegration of a partial stream of the thickened excess sludge in order to intensify methane fermentation,
- disintegration of partial stream of the suspension in order to improve thickening of excess sludge,
- disintegration of the recirculated sludge in order to utilize the potential of residue gas,
- disintegration of partial stream after initial mechanical dewatering of the sludge in order to improve dehydration.

Using ultrasonic field is a fast and convenient technology that does not generate contamination of the solid phase [4]. Ultrasonic disintegration is based on the use of ultrasonic field with the frequency of 10–50 kHz and ultrasonic field intensity of over 1 W/cm^2 [2, 7, 24].

After propagation through liquid and gaseous media, ultrasonic field creates both primary and secondary phenomena. The primary phenomena include cavitation and radiation pressure while secondary phenomena are those with physicochemical nature, such as ultrasonic coagulation, dispersion, electrokinetic phenomena, oxidation or reduction [1, 24].

The aim of this study was to evaluate the effect of excess sludge disintegration with ultrasonic field on hydrolysis that occurs during methane fermentation of the sludge from the food industry. The rate of generation and value of volatile fatty acids, as well as the degree of sludge fermentation was determinate.

2. Experimental Part

2.1. Substrate

The substrate for the experiments was excess sludge from the mechanical-chemical-biological wastewater treatment plant. This wastewater treatment plant purify wastewater from carbonated drinks factory "Jurajska" in Myszków, Poland, as well as from the mentioned city. The test excess sludge is produced by purification ca. 90% of technological wastewater and ca. 10% of domestic wastewater. Excess sludge was inoculated with fermented sludge with 10:1 ratio. The excess sludge was characterized by the following contents: dry mass 13.31–18.08 g/dm^3, dry organic matter 9.86–13.3 g/dm^3 and dry mineral mass 3.45–4.78 g/dm^3.

2.2. Methodology

During the first stage of the research, in order to determine the best conditions of disintegration possible, the authors used ultrasonic disintegrator VCX-750. The disintegrator's operation consists in active effect of ultrasonic field on the sludge. The energy is produced by power converter which converts the electrical energy supplied into mechanical vibration energy. The mechanical vibration of the converter is transferred as a longitudinal wave to a working tip. The working tip was immersed into a vessel with the excess sludge studied at the depth of 3 cm from the vessel's bottom. The volume of the conditioned sample was 0.5 dm^3 and the ultrasonic conditioning occurred in a no-flow system, with a single filling of the vessel.

During sonication by means of disintegrator VC-750, the authors used vibration amplitudes of ultrasonic field of 15, 21, 31, 37 and 46 μm and sonication time of t_s = 30–360 s.

In the case of second stage of research the aim was to analyze the influence of ultrasonic disintegration of excess sludge on the anaerobic stabilization efficiency. The tests were carried out under mesophilic laboratory conditions in ten glass flasks that represented the models of fermentation chambers. Methane fermentation processes were carried out 10 days. Every day of the process the sludge was collected for analysis from one of the flasks. The flasks were secured from air access with a rubber plug with liquid-column gauge. The plug prevented from the outflow of the biogas generated inside the flasks. The flasks with active volume of 0.5 dm^3 were incubated in a laboratory thermostat at the temperature of 37°C. In order to mix the whole volume of the sludge and prevent from formation of the areas overloaded with contaminants and to prevent from formation of the scum, the content of the flasks was mixed manually several times a day. The mixture procedure ensured mixing of the whole bacterial population in the fermented sludge used as an inoculum with the excess sludge.

Anaerobic stabilization was carried out for the following mixtures:

- Mixture 1 – excess sludge, non-conditioned + fermented sludge;
- Mixture 2 – excess sludge conditioned with ultrasonic field amplitude (A= 21 μm and sonication time of 360 s, acoustic wave intensity 1.02 W/cm^2) + fermented sludge;
- Mixture 3 – excess sludge conditioned with ultrasonic field (A= 46 μm and sonication time of 360 s, acoustic wave intensity 2.09 W/cm^2) + fermented sludge.

The following physicochemical parameters were evaluated:

- volatile fatty acids (VFAs) according to the standard PN-75/C-04616/04 [14],
- dry matter, dry organic matter, dry mineral matter by means of a direct weighing method according to the standard PN-EN-12879 [15],
- chemical oxygen demand by means of a dichromate method based on HACH 2100N IS tests according to (ISO 7027) [16].

3. Results and discussion

An increase in concentration of organic substances contained in supernatant liquor conditioned with ultrasonic field (expressed in COD) was found after exposure of excess sludge to ultrasonic field disintegration. Based on changes in the content of COD and VFAs vs. time, the authors chose the most beneficial parameters of conditioning, pointing to the amplitude of ultrasonic field vibration of A= 46μm and sonication time of 360 s (acoustic wave intensity 2.09 W/cm^2). Furthermore, the effect of disintegration with vibration amplitude of UD A=21 μm (acoustic wave intensity 1.02 W/cm^2) on methane fermentation was also measured for the most favourable sonication time of 360 s. A 3-time and 5-time increases in COD and 2-time and 3-time increases in VFAs were observed respectively for the above indices compared to the initial values.

Fig. 1–5 present changes in COD and VFAs, the indices determined in supernatant liquor depending on sonication time for individual amplitudes of ultrasonic field vibration.

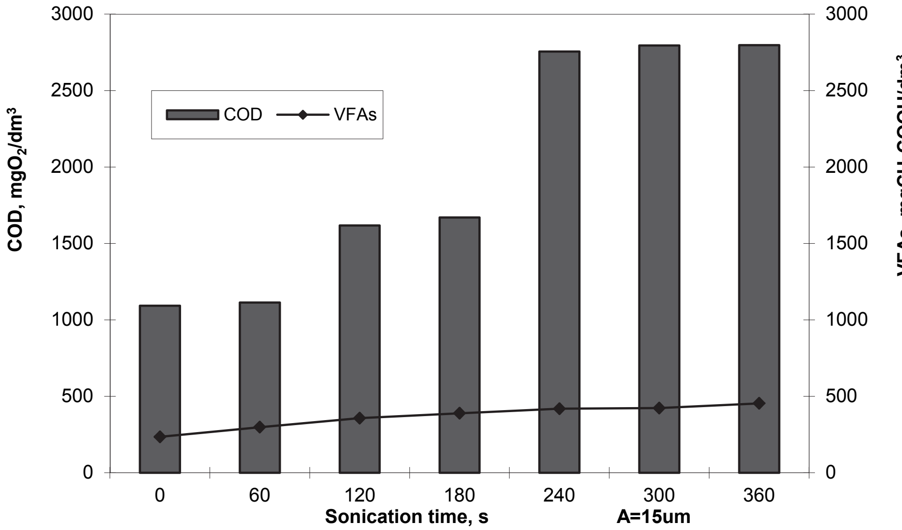

Fig. 1. Changes in COD and VFAs in supernatant liquor vs. sonication time for ultrasonic field vibration amplitude of A=15μm
Rys. 1. Zmiany wartości ChZT oraz LKT w cieczy nadosadowej, w zależności od czasu sonifikacji dla amplitudy drgań pola UD A=15μm

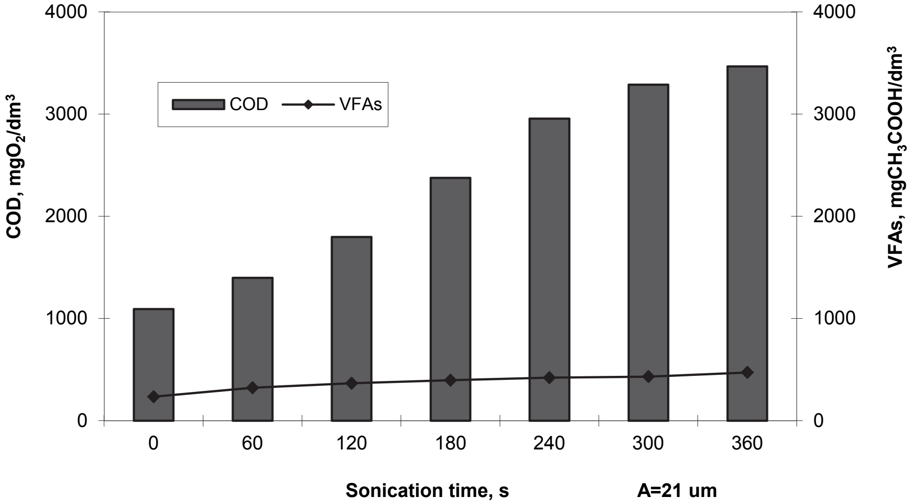

Fig. 2. Changes in COD and VFAs in supernatant liquor vs. sonication time for ultrasonic field vibration amplitude of A=21μm
Rys. 2. Zmiany wartości ChZT oraz LKT w cieczy nadosadowej, w zależności od czasu sonifikacji dla amplitudy drgań pola UD A=21μm

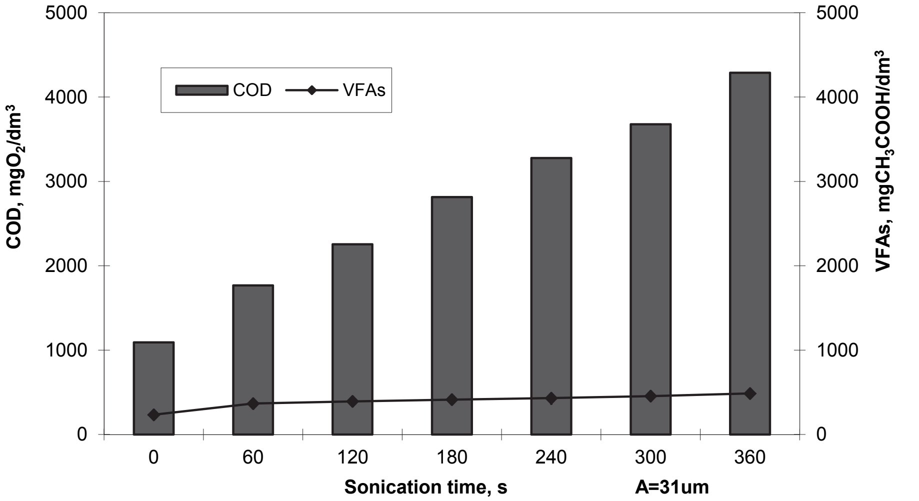

Fig. 3. Changes in COD and VFAs in supernatant liquor vs. sonication time for ultrasonic field vibration amplitude of A=31μm
Rys. 3. Zmiany wartości ChZT oraz LKT w cieczy nadosadowej, w zależności od czasu sonifikacji dla amplitudy drgań pola UD A=31μm

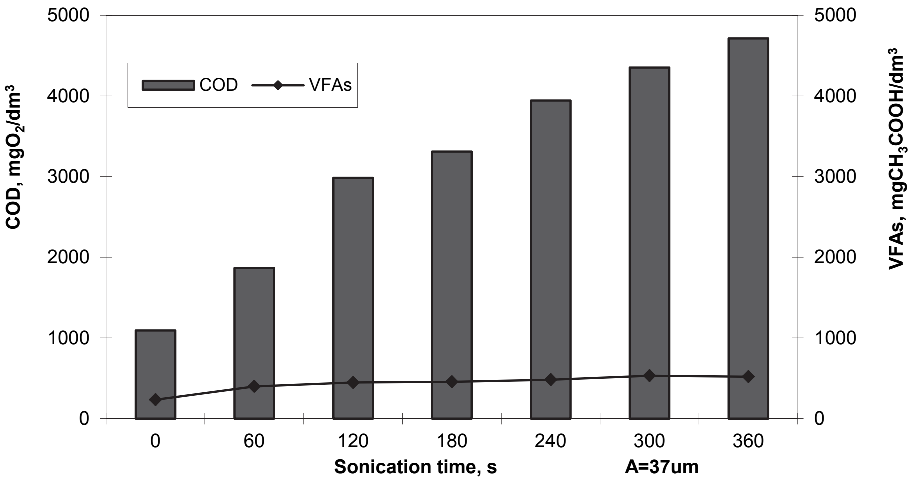

Fig. 4. Changes in COD and VFAs in supernatant liquor vs. sonication time for ultrasonic field vibration amplitude of A=37μm
Rys. 4. Zmiany wartości ChZT oraz LKT w cieczy nadosadowej, w zależności od czasu sonifikacji dla amplitudy drgań pola UD A=37μm

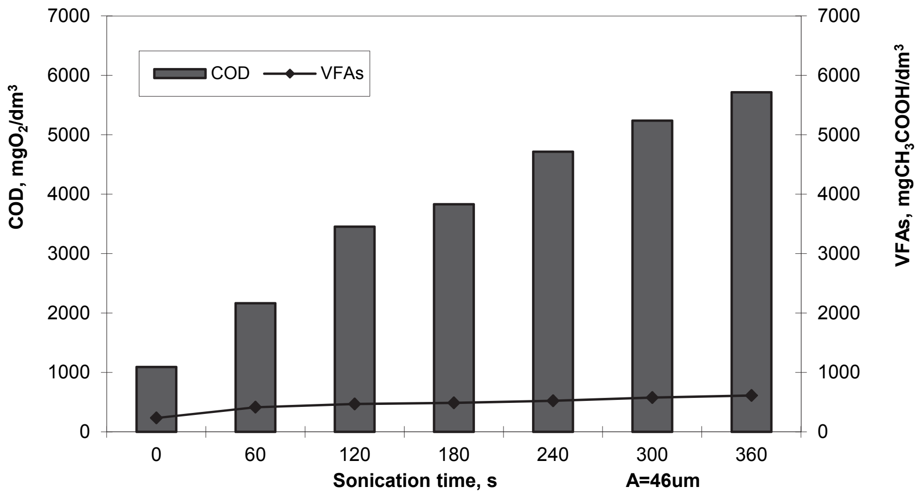

Fig. 5. Changes in COD and VFAs in supernatant liquor vs. sonication time for ultrasonic field vibration amplitude of A=46μm
Rys. 5. Zmiany wartości ChZT oraz LKT w cieczy nadosadowej, w zależności od czasu sonifikacji dla amplitudy drgań pola UD A=46μm

At the next stage of the experiments, the anaerobic stabilization was carried out for a mixture of non-conditioned sewage sludge and fermented sludge used as an inoculum. At this stage of the study, the anaerobic stabilization was carried out for Mixture 1.

Excess sewage sludge is difficult to be biochemically decomposed under anaerobic conditions. This is supported by the degree of sludge fermentation obtained on the tenth day of the stabilization process. Therefore, the results obtained in the study suggested that the effectiveness of the process might be improved through subjecting the process of initial conditioning to the exposure to ultrasonic field.

The degree of sludge fermentation during the process of methane fermentation of Mixture 1 carried out in fermentation flasks was ca. 17%. The initial value of VFA content in Mixture 1 (non-conditioned sludge) was 360 mg CH_3COOH/dm^3. The highest VFA content (805 mg CH_3COOH/dm^3) was found during anaerobic stabilization of Mixture 1, was found on the sixth day of the process. After this day, VFA was constantly decreasing until the 10th day of the process. VFAs content recorded on the last day was 102 mg CH_3COOH/dm^3.

Changes in VFAs content on individual days of methane fermentation of the non-conditioned sewage sludge is presented in Fig. 6.

The process of methane fermentation was also carried out for the excess sludge disintegrated initially with ultrasonic field (Mixtures 2 and 3) with amplitude of ultrasonic field vibration of 21 μm and 46 μm, respectively, for sonication time of 360 s.

The initial value of VFAs content for Mixture 2 was 411 mg CH_3COOH/dm^3. The highest VFAs content (737 mg CH_3COOH/dm^3) was found on the second day of the process. After this day, the value of VFAs generated showed a downward tendency until it reached the value of 257 mgCH_3COOH/dm^3 on the 10th day of the process. Changes in VFAs recorded during methane fermentation for Mixture 2 are presented in Fig. 7.

With regard to Mixture 3, VFAs content on the day of initiation of of anaerobic stabilization was 943 mg CH_3COOH/dm^3. The highest VFAs content (1714 mg CH_3COOH/dm^3) was found on the second day of the process. Final VFAs content on the 10th day of the process was 658 mg CH_3COOH/dm^3. Changes in VFAs observed during methane fermentation of the sludge disintegrated with ultrasonic field are presented in Fig. 8.

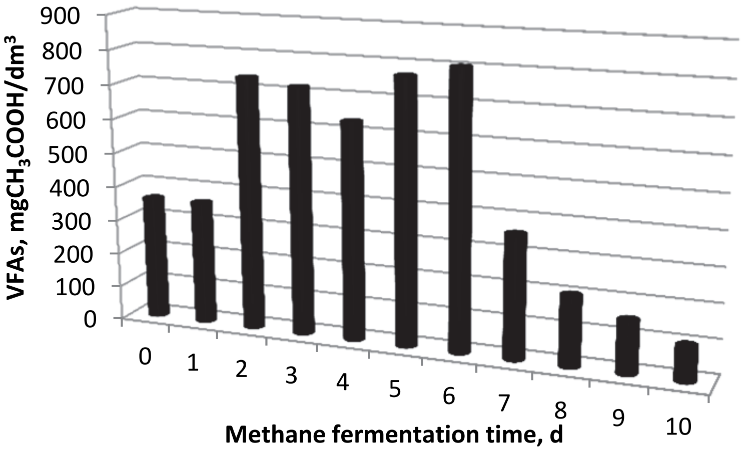

Fig. 6. Changes in VFAs recorded during methane fermentation of unconditioned excess sludge (Mixture 1)
Rys. 6. Zmiany wartości lotnych kwasów tłuszczowych odnotowane podczas procesu fermentacji metanowej niekondycjonowanych osadów nadmiernych (Mieszanina 1)

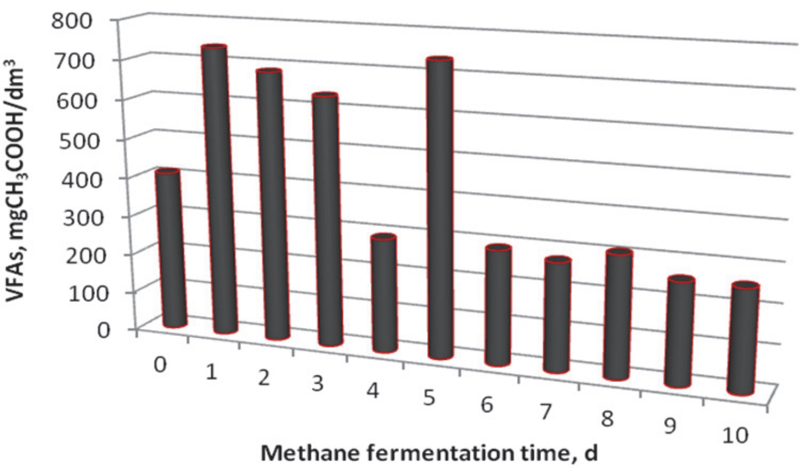

Fig. 7. Changes in VFAs observed during methane fermentation for excess sludge conditioned with ultrasonic field (Mixture 2)
Rys. 7. Zmiany wartości lotnych kwasów tłuszczowych zaobserwowane podczas procesu fermentacji metanowej osadów nadmiernych kondycjonowanych polem ultradźwiękowym (Mieszanina 2)

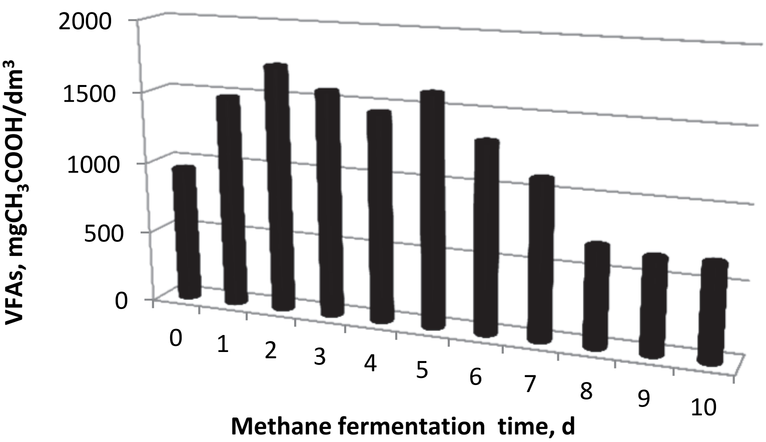

Fig. 8. Changes in VFAs observed during methane fermentation of the excess sludge conditioned with ultrasonic field (Mixture 3)
Rys. 8. Zmiany wartości lotnych kwasów tłuszczowych zaobserwowane podczas procesu fermentacji metanowej osadów nadmiernych kondycjonowanych polem ultradźwiękowym (Mieszanina 3)

It was found based on the present study that disintegration of excess sludge with ultrasonic field before anaerobic stabilization improves the degree of sludge particles disintegration, thus causing an increase in VFAs content recorded on the following days of fermentation. Maximum generation of VFAs during anaerobic stabilization of unconditioned sludge (Mixture 1) was obtained on the 6th day of the process. The use of ultrasonic field conditioning of sludge caused that the highest intensity of VFAs generation in Mixtures 2 and 3 was found on the second day of methane fermentation.

Evaluation of the effect of excess sludge disintegration with ultrasound on anaerobic stabilization included analysis of changes in the content of dry organic matter that occurred during the process. In Mixture 1, the degree of sludge fermentation after 10 days was ca. 17%. Furthermore, initial modification of sludge with ultrasonic field caused an increase in the degree of sludge fermentation during acid fermentation. In Mixture 2, the degree of fermentation was ca. 23% whereas this value for the Mixture 3 was 29%.

Fig. 9 presents changes in the content of dry organic matter of non-disintegrated sludge and the sludge disintegrated with ultrasound.

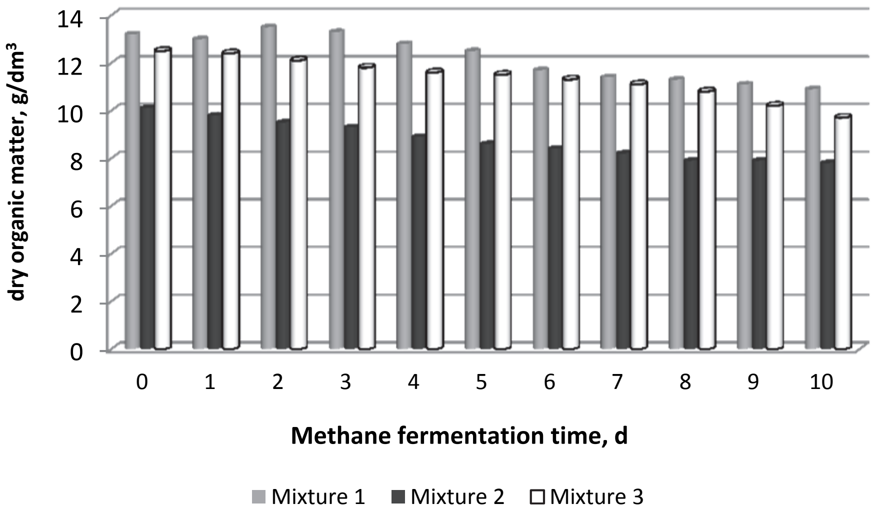

Fig. 9. Changes in the content of dry organic matter recorded during 10-day anaerobic stabilization of non-disintegrated excess sludge (Mixture 1) and the sludge disintegrated with ultrasonic field (Mixtures 2 and 3)
Rys. 9. Zmiany zawartości suchej masy organicznej odnotowane w czasie 10-dobowej stabilizacji beztlenowej osadów nadmiernych niedezintegrowanych (Mieszanina 1) oraz dezintegrowanych polem ultradźwiękowym (Mieszanina 2, 3)

4. Summary and conclusions

Excess sludge treatment using popular methods based on selected processes supported with additional disintegrating effect represents promising (in terms of the obtained degree of mineralization and economics of the process) practical solution. However, it should be stressed that the use of a disintegration method and the choice of the most favourable parameters depends on the character of the sludge that reaches treatment plant, sludge load and technical and economic aspects that condition modernization of the technological line. Obtaining the most effective solution possible in terms of optimum anaerobic stabilization necessitates compilation of current disintegration methods in consideration of the sludge modification using physical, chemical and biological processes. The analysis of the results of the present study leads to the following conclusions:

1. Sonication improved fragmentation of organic substances solved in the sludge liquor, which translated into an increase in COD and VFAs values. The greatest effectiveness of sludge disintegration with ultrasonic field was found for exposure time of 360 s and field vibration amplitude of 46 μm (acoustic wave intensity 2.09 W/cm^2). 5-time and 3-time increases in COD and VFAs with respect to initial value of the indices were observed for the above conditions of disintegration.
2. Increased susceptibility to biodegradation of the conditioned sewage sludge caused a faster increase in VFAs content recorded on the following days of the process. With regard to anaerobic stabilization of the non-conditioned sludge (Mixture 1), the highest value of VFAs was observed on the sixth day of the process. The highest content in Mixture 2 (ultrasonic field vibration amplitude: 21μm, sonication time: 360 s) and Mixture 3 (ultrasonic field vibration amplitude: 46 μm, sonication time: 360 s) was found on the second day of the process.
3. Submission of sludge ultrasonic disintegration contributed to the intensification of hydrolysis phase and the increase of efficiency of the next steps in the process of anaerobic digestion, especially methanogenic phase. This creates a 12% increase in the degree of fermentation was observed in the Mixture 3 (sludge disintegrated with ultrasonic field) compared to the value obtained for anaerobic stabilization of Mixture 1 (unconditioned sludge) after exposure of the sludge to ultrasonic field.

Acknowledgements

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Wpływ dezintegracji ultradźwiękowej na proces stabilizacji beztlenowej osadów nadmiernych pochodzących z przemysłu spożywczego

Abstract

Przeróbka i unieszkodliwianie osadów ściekowych stanowi niezwykle aktualny problem technologiczny, co wiąże się z powstawaniem w ostatnich latach nowych obiektów oczyszczalni, modernizacją już istniejących, jak również z rozwojem wysokoefektywnych metod oczyszczania ścieków. Przez lata wiodącym trendem w zagospodarowaniu osadów ściekowych w Polsce było ich składowanie, jednak obowiązujące w Unii Europejskiej uwarunkowania prawne uniemożliwiają zastosowanie takiego rozwiązania w przyszłości. Modernizacja ciągu technologicznego oczyszczalni ścieków poprzez poprzedzenie wybranych procesów oczyszczania ścieków oraz utylizacji osadów procesem dezintegracji o odpowiednio dobranych parametrach wiąże się ze wzrostem efektywności działania obiektu, nie tylko pod względem technologicznym ale również ekonomicznym.

Dezintegracja osadów nadmiernych przed procesem stabilizacji beztlenowej wpływa na zwiększenie podatności osadów na biochemiczny rozkład w warunkach beztlenowych, czego efektem jest przyspieszenie fazy hydrolitycznej procesu, warunkującej powstawanie w kolejnych etapach procesu lotnych kwasów tłuszczowych. Wartość oraz tempo generowania LKT znajduje bezpośrednie odbicie w efektywności produkcji biogazu oraz uzyskanym stopniu mineralizacji osadów. Celem prowadzonych badań była ocena wpływu dezintegracji ultradźwiękowej osadów nadmiernych pochodzących z przemysłu spożywczego na proces hydrolizy będący pierwszym etapem fermentacji metanowej. W badaniach użyto dezintegrator ultradźwiękowy typu VC-750. Osady poddano modyfikacji polem ultradźwiękowym (UD) o amplitudzie drgań pola UD 15, 21, 31, 37, 46μm i czasie sonifikacji t_s = 60–360 s. Następnie przeprowadzono procesy 10-dobowej fermentacji metanowej osadów, poprzedzone modyfikacją osadów nadmiernych polem UD o wybranych, najkorzystniejszych parametrach dezintegracji. Największą skuteczność nadźwiękawiania osadów odnotowano dla czasu ekspozycji równego 360 s oraz amplitudy drgań pola UD 46μm, uzyskując ok. 5-kotny wzrost wartości ChZT oraz ok. 3-krotny LKT w odniesieniu do wartości początkowych wskaźników.

Słowa kluczowe:
dezintegracja, pole ultradźwiękowe (UD), lotne kwasy tłuszczowe (LKT), chemiczne zapotrzebowanie na tlen (ChZT), fermentacja metanowa, stopień przefermentowania osadów

Keywords:
disintegration, ultrasonic field, volatile fatty acids (VFAs), chemical oxygen demand (COD), methane fermentation, degree of sludge fermentation