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Microwave disintegration of sludge as a method of accelerating the aerobic stabilization process

Maciej Malarski*, Justyna Czajkowska, Piotr Nowak

Warsaw University of Life Sciences, Faculty of Civil and Environmental Engineering, Institute of Environmental Engineering, Department of Hydraulics and Sanitary Engineering, Warsaw, Poland, Tel. +48 22 59 351 50; email: maciej_malarski@sggw.edu.pl (M. Malarski), Tel. +48 22 59 351 07; email: justyna_czajkowska@sggw.edu.pl (J. Czajkowska), Tel. +48 22 59 351 59; email: piotr_nowak@sggw.edu.pl (P. Nowak)

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ABSTRACT

This paper presents the results of aerobic stabilization tests, controlled by total dissolved solids and total organic solids (TOS), for three process temperatures (12°C ± 1°C, 15°C ± 1°C and 22°C ± 1°C) and five ratios of the share of sludge subjected to initial microwave disintegration (1:0, 3:1, 1:1, 1:3, 0:1). As expected, the disintegration process preceding the sludge stabilization process increases COD and BOD_5 in the supernatant liquid. As the proportion of disintegrated sludge in the stabilized liquid increases, these values are higher. The process of aerobic sludge stabilization was carried out for 35 d. Constant aeration of the sludge resulted in a decreasing mass of TOS in the following days of stabilization. At the same time, faster sludge stabilization at higher process temperatures was confirmed. Research has shown the acceleration of the sludge stabilization process with an increase in the share of disintegrated sludge (from 0% to 50%). This effect is more pronounced at a lower temperature (12°C, 15°C) than at a higher temperature (22°C). Regardless of the temperature of aerobic stabilization, a decrease in process efficiency and extension of stabilization time was observed when the disintegrated sludge content was above 50%. Research has shown a beneficial effect of the share of disintegrated sludge in the proportion of 1:1 (50%) on the reduction of TOS in the process of aerobic stabilization. For this proportion, a potential energy gain of up to 18% was obtained, and the stabilization time was shortened by about 3 d when conducting the process at 22°C and by about 10 d at 12°C. This should be taken into account in the economic assessment of the treatment of sewage sludge at wastewater treatment plants.

Keywords: Microwave disintegration; Aerobic stabilization; Dry organic matter

1. Introduction

As urbanization progresses, more and more municipal sewage treatment plants are being built, which at the same time contributes to the production of larger amounts of sewage sludge. As a by-product, sewage sludge is a complex and heterogeneous material consisting of microorganisms, heavy metals, inorganic minerals and organic toxic substances that are harmful to humans and the surrounding environment [1–3].

Because of environmental reasons, sewage sludge generated during biological treatment of wastewater in WWTPs must be treated. Sludge should be stabilized so that it does not biodegrade and emit unpleasant odors.

Sludge stabilization is energy-consuming and time-consuming, therefore, an expensive process. Although the sludge represents only 1%–2% of the treated wastewater volume, the cost of stabilization and depollution processes is high and can reach the level of 60% of all operating costs generated in wastewater treatment plants [4–8].

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* Corresponding author.

Conventional methods for stabilizing sludge can be divided into three processes: physical, chemical and biological. The main biological processes are aerobic digestion, anaerobic digestion and composting [9].

The efficiency of the process is limited by hydrolysis, which slows down the stabilization. The phase determining the rate of sludge stabilization is the hydrolytic phase. In this phase, water-insoluble organic compounds of sludge (e.g., proteins, cellulose, fats) are broken down into their mono- or dimers by bacteria [10–12]. Hydrolysis can last from several hours (e.g., carbohydrates) to several days (e.g., proteins, fats). In order to accelerate the hydrolysis, while improving the efficiency of stabilizing processes, methods known as disintegration processes are used [4]. These can be divided into mechanical (homogenization, ultrasounds, microwaves), chemical (ozonation, acid and alkaline hydrolysis), biological (enzymes, autolysis, fungi, bacteria) and thermal methods (low temperature, high temperature). They aim to disperse and reduce the particle size of organic compounds so that they are more susceptible to biological degradation [13].

Short disintegration time resulted in sludge floc deagglomeration without the destruction of bacterial cells. Longer disintegration brought about the break-up of cell walls; the sludge solids were disintegrated and dissolved organic compounds were released [14]. During the process, the cytoplasmic membranes of the cells are destroyed and dispersed [15]. Lysis of microbial cells and the release of biologically bound water occur [16]. The sludge becomes liquefied, with a finely divided solid phase and an increased value of the dissolved COD and concentration of volatile fatty acids [17]. The organic constituents included in the cell become readily available as a substrate for living heterotrophic biomass [18]. The homogenised and liquefied substrates are easier to pump and are characterized by a larger active surface. This makes later methane fermentation faster and more stable.

Disintegration as a method of pre-treatment of the sludge, although it increases the rate of its stabilization, often generates high costs of operation and maintenance of equipment. Corrosion problems appear. Frequently, the long reaction time limits the practical application of disintegration techniques in the treatment of sewage sludge.

Some studies described in the literature have focused on the application of microwaves in environmental engineering. By using microwave heating, the desired temperature can be reached faster along with lower energy consumption. In addition, there is less potential for the emission of hazardous substances [19].

The microwaves affect the deposit thermally and non-thermally. The variable electric field interacts with dipolar molecules such as water, proteins, fats and other organic particles, causing them to rotate. Ultimately it leads to the heating of the sludge. The non-thermal effect is attributed to dipoles that rapidly change orientation in polarized side chains of macromolecules, which gives the opportunity to break hydrogen bonds. As a result of this process, the flocs disintegrate and changes in the secondary and tertiary structures of proteins in the cell membrane of microorganisms occur forming the activated sludge, which in turn leads to their death [20–22].

Most of the research attached to the disintegration of sewage sludge described in the literature concerns larger wastewater treatment plants (above 15,000 PE), in which the anaerobic sludge stabilization process is carried out [23,24]. In small and medium wastewater treatment plants (up to 15,000 PE), however, the aerobic sludge stabilization process is used. The process of traditional aerobic stabilization of sewage sludge for small and medium wastewater treatment plants is a very energy-consuming and long-term process, requiring large amounts of oxygen (up to 1.6 kg O_2/m^3 d [25]) for at least 15 d at 20°C. The use of sludge microwave disintegration can accelerate this process by breaking up sludge flocs into fine particles along with the breakdown of cell membranes. Disintegrated sludge is more susceptible to biological decomposition in the process of aerobic stabilization. The acceleration of the process by up to several days can bring significant benefits.

The share of disintegrated sludge in the process of aerobic stabilization of sewage sludge can contribute to increasing its efficiency, reduction of the aerobic stabilization time of the sludge and at the same time reduce the operating costs of the wastewater treatment plant. The sludge aerobic stabilization process can be completed when the sludge's oxygen demand is below 0.1 kg O_2/kg dry organic matter per day [25].

The aim of the present work is to determine the most economically advantageous parameters for conducting aerobic sludge stabilization process in cooperation with the sludge disintegration. Moreover, the paper aims to demonstrate a novel approach to both, the stabilization of sludge and the reduction in sludge biomass using microwaves.

2. Materials and methods

2.1. Source of sludge

The sewage sludge from the "Mokre Łąki" WWTP in the Izabelin commune, near Warsaw in Poland was used for research. The WWTP was designed for an average daily volume of wastewater of 2,200 m^3/d and operates on the basis of the activated sludge method. The technological system of the mechanical and biological part consists of: a first stage pumping station, a sewage catchment station, a sewage retention tank, a gate chamber, a screen chamber, a grit chamber, a biological block, a secondary settling tank, and an excessive and recirculated sludge pumping station. The sludge part of the WWTP consists of an aerobic stabilization tank and belt press with the possibility of adding calcium.

Due to the need to ensure low phosphorus concentration in treated wastewater, the support of the biological process with chemical phosphorus precipitation using the PIX 113 ($Fe_2(SO_4)_3$)/PAX ($Al(OH)_xCl_y + H_2O$; $x + y = 3$, where $1.05 < x < 2$) coagulant was used. The material was taken from the pumping station located after the secondary settling tank, and then transported to the Laboratory of Chemistry and Technology of Water and Wastewater at Warsaw University of Life Sciences WULS.

2.2. Experimental procedure and chemical analysis

This paper presents the results of aerobic stabilization tests of 40 measurement series carried out in 2016–2018 in autumn (12), summer (14) and winter (12). Each of the measurement series included five proportions of the share of sludge subjected to initial microwave disintegration. In each of these periods, the aerobic stabilization process was carried out at the sludge temperature most often recorded at the wastewater treatment plant "Mokre Łąki" during the period of testing. In the autumn, it was 15°C ± 1°C, in the summer 22°C ± 1°C and in the winter 12°C ± 1°C. For each of these temperatures, aeration of the sludge (air flowrate 100 L/h) was carried out in bench reactor in the following proportions of non-disintegrated sludge to disintegrated sludge (N:D): 1:0 (15 L non-disintegrated sludge, 0 L disintegrated sludge), 3:1 (11.25 L non-disintegrated sludge, 3.75 L disintegrated sludge, 1:1 (7.5 L non-disintegrated sludge, 7.5 L disintegrated sludge), 1:3 (3.75 L non-disintegrated sludge, 11.25 L disintegrated sludge), 0:1 (0 L non-disintegrated sludge, 15 L disintegrated sludge). The 1:0 ratio was the starting material taken from the "Mokre Łąki" wastewater treatment plant, stabilized in the traditional method of aerobic sludge stabilization without the participation of disintegrated sludge. The stabilization process was carried out each time for 35 d.

The methodology of preparing the samples for stabilization is presented in the paper [4]. To disintegrate the sludge, a commercial microwave oven (power of microwave was 700 W) was used. A single portion of the sludge, with a volume of 2 L, was disintegrated microwave cooking for 16 min. The temperature of sludge reaches levels of approximately 75°C. Oxidation of the sludge was carried out in volumes of 15 L for each series in glass tanks. After preparing the samples for aerobic stabilization, the following parameters were determined in the supernatant liquid:

- turbidity – nephelometric method [26] using a 2100N IS turbidimeter,
- pH – electrometric method [27] using a pH 510 pH-meter (produced by Eutech Instruments) and IJ44C electrodes (produced by Elmetron),
- COD – titration method [28] with potassium dichromate,
- BOD_5 – the WTW bottle method using an OXI-TOP set, in accordance with the standard [29].

The same parameters were also determined after the completion of the test cycle, that is, on the 35th day of stabilization.

The progress of the stabilization of the sludge was controlled by total dissolved solids [30] and total volatile solids [31], reflecting the loss of organic solids (TOS) in the process under investigation. In addition, the oxygen concentration of the Elmetron CO-505 oxygen meter was tested in a stabilized sludge in accordance with PN-EN 25813: 1997P [32].

2.3. Statistic and economic viability analysis

On the basis of the test results, where the concentration of TOS in the individual test days was determined, the function of the dependence of the stabilization time on TOS concentration values was determined for each measurement series. To minimize analytical error, a linear hyperbolic function was used in the analysis, using the R^2 determination coefficient as a fit indicator. The analysis was carried out analogously to the methodology presented by Czajkowska et al. [5]. To determine the effectiveness of sludge stabilization from the function of stabilization time and TOS concentration, Eq. (1) was used:

$$\eta = \frac{S_p - S_i}{S_p} \tag{1}$$

where η – the efficiency of reducing the organic dry matter concentration, S_p – the initial dry organic matter concentration, S_i – the organic dry matter concentration in the analyzed test time.

For specific stabilization times of individual measurement series, a statistical analysis was carried out in relation to the constant temperature of the process and the proportion of the sludge subjected to initial microwave disintegration. On the basis of the obtained results, the energy consumption per m^3 of sludge, which was necessary to perform sludge stabilization in individual measurement series, was calculated. On this basis, the potential energy gain possible to obtain with sludge stabilization using disintegrated sludge in relation to sludge stabilization without its disintegration at various process temperatures was determined. Eqs. (2) and (3) were used:

$$E = E_A + E_M = \frac{t_A \cdot P_A + t_{D1} \cdot P_M \cdot V_D / V_1}{V_C} \left[\text{kWh/m}^3\right] \tag{2}$$

where E – energy used for stabilizing m^3 of sludge in kWh/m^3, E_A – energy used for sludge aeration in kWh/m^3, E_M – energy used for microwave disintegration of sludge in kWh/m^3, t_A – time of sludge stabilization (aeration time) in h, P_A – power of the aeration device in W, t_{D1} – time needed for disintegration of a single portion of sludge (16 min) in h, P_M – the power of the microwave oven in W, V_D – the volume of the disintegrated sludge (0, 3.75, 7.5 or 11.25 L), V_1 – the volume of a single portion of disintegrated sludge (2 L), V_C – the total volume of the stabilized sludge (15 L).

$$Z_X = \frac{E_{1+0} - E_X}{E_{1+0}} \left[\%\right] \tag{3}$$

where Z_X – energy gain of sludge stabilization with the use of sludge disintegrated in relation to sludge stabilization without initial disintegration, E_{1+0} – energy used for sludge stabilization without initial disintegration, E_X – energy used for sludge stabilization with the use of disintegrated sludge.

3. Results and discussion

3.1. Supernatant liquid

Table 1 presents the results of testing the preliminary supernatant liquid in the sample prepared for the aerobic stabilization process (first day of the process – beginning) and at the end of the process (the 35th day of the process), distinguishing between the temperatures at which the stabilization process is carried out. An increase in the value of particular indicators (COD, BOD_5) is noticeable

Table 1
Values of quality indicators of supernatant liquid in samples with different mixing proportions of non-disintegrated (*N*) and disintegrated (*D*) sludge for different process temperatures

Temperature of the sludge stabilization process	Mixing proportions *N*:*D*		1:0	3:1	1:1	1:3	0:1
	Indicator		Range of values/(average)				
12°C	COD (mgO$_2$/L)	Beginning	70.0–113.4 (92.7)	165.6–354.5 (206.2)	605.8–880.2 (762.8)	1,585.6–1,931.0 (1,731.7)	2,034.5–2,397.0 (2,247.1)
		End	112.0–506.0 (362.2)	103.5–324.6 (290.8)	174.3–415.8 (301.0)	345.2–702.3 (510.2)	287.0–512.3 (350.0)
	BOD$_5$ (mgO$_2$/L)	Beginning	2.1–17.9 (13.9)	51.1–103.4 (79.2)	221.3–385.2 (306.0)	501.1–635.2 (591.0)	665.3–785.5 (716.0)
		End	1.0–5.3 (3.0)	1.6–6.9 (5.3)	2.5–16.9 (12.4)	10.4–45.9 (33.7)	0.2–1.6 (0.6)
	Turbidity (NTU)	Beginning	2.0–10.2 (6.02)	15.6–24.3 (20.6)	55.0–80.0 (73.7)	172.1–207.3 (194.0)	215.9–275.0 (243.0)
		End	121.0–161.9 (141.0)	98.6–132.8 (115.0)	131.1–174.5 (152.0)	254.8–299.9 (285.0)	101.7–148.6 (128.0)
	pH (–)	Beginning	6.90–7.78 (7.37)	7.45–7.84 (7.69)	7.45–7.89 (7.70)	7.15–7.69 (7.57)	6.95–7.41 (7.26)
		End	5.02–6.98 (5.54)	5.41–5.87 (5.56)	5.25–6.00 (5.66)	5.21 -5.97 (5.62)	6.18–7.19 (6.82)
	Time of expected stabilization (d)		36.5	36.5	35.2	26.4	38.5
15°C	COD (mgO$_2$/L)	Beginning	60.6–103.5 (88.7)	84.6–145.5 (111.0)	625.0–765.3 (718.3)	1,002.6–1,084.2 (1,047.6)	1,850.3–1,901.0 (1,882.4)
		End	98.8–640.0 (341.3)	695.3–995.3 (850.9)	101.6–165.7 (136.4)	355.6–624.8 (491.0)	674.9–962.3 (750.1)
	BOD$_5$ (mgO$_2$/L)	Beginning	1.9–15.8 (10.7)	10.2–48.2 (35.6)	298.4–368.2 (327.0)	324.3–398.6 (371.5)	732.2–802.6 (779.0)
		End	2.6–48.1 (23.9)	36.2–67.6 (52.6)	0.6–7.1 (4.7)	24.3–41.2 (37.1)	3.6–25.2 (17.5)
	Turbidity (NTU)	Beginning	4.54–14.7 (9.9)	9.1–25.3 (17.9)	101.6–128.7 (115.0)	101.0–135.9 (120.0)	120.8–179.8 (155.0)
		End	8.58–303.0 (120.6)	254.6–784.3 (416.0)	10.4–21.6 (17.6)	141.8–197.4 (176.0)	298.7–385.0 (339.0)
	pH (–)	Beginning	6.75–7.20 (7.00)	7.01–7.98 (7.63)	7.12–7.66 (7.43)	7.01–7.45 (7.36)	7.18–7.45 (7.32)
		End	4.24–7.10 (5.60)	5.05–5.98 (5.63)	6.30–6.84 (6.60)	5.84–6.26 (6.06)	5.97–6.32 (6.19)
	Time of expected stabilization (d)		30.4	30.4	33.6	24.6	34.3
22°C	COD (mgO$_2$/L)	Beginning	30.6–440.0 (282.1)	237.6–408.1 (316.4)	795.4–2,080.0 (1,229.1)	1,795.0–3,680.0 (2,663.8)	1,959.2–4,560.0 (3,312.5)
		End	272.3–730.8 (508.1)	277.2–730.8 (488.5)	168.3–576.9 (392.8)	267.3–500.0 (387.7)	384.6–1,021.0 (669.8)
	BOD$_5$ (mgO$_2$/L)	Beginning	6.5–103.0 (42.1)	52.0–791.0 (402.3)	82.7–574.0 (317.4)	386.0–667.0 (511.2)	221.0–1,005.0 (567.0)
		End	2.9–24.0 (12.7)	6.4–18.0 (13.0)	2.9–15.0 (8.0)	2.4–21.0 (11.5)	21.0–39.8 (28.9)
	Turbidity (NTU)	Beginning	8.4–26.5 (15.8)	21.9–80.1 (50.8)	40.0–242.0 (136.0)	32.3–447.0 (238.7)	250.0–575.0 (422.0)
		End	97.6–254.0 (173.2)	81.5–205.0 (144.2)	38.2–181.0 (105.4)	88.1–212.0 (156.0)	122.0–436.0 (271.3)
	pH (–)	Beginning	7.02–7.31 (7.21)	7.41–7.68 (7.50)	7.01–7.53 (7.34)	7.09–7.49 (7.36)	7.10–7.88 (7.44)
		End	3.95–5.67 (5.09)	4.03–5.84 (4.66)	5.27–6.41 (5.66)	4.2–5.6 (4.82)	5.59–6.91 (6.27)
	Time of expected stabilization (d)		20.0	20.9	17.6	25.0	20.4

in the first (initial) day of the experiment together with an increasing share of sludge disintegrated in the stabilization process. This is the result of the passing of some of the impurities to the supernatant from the decomposition of the sludge during its disintegration. At the same time, this confirms the observations presented in the article by Czajkowska et al. [5].

The tested stabilization process carried out in the experiments led to a reduction of the BOD_5 value in the supernatant liquid. The organic matter is decomposed during the process. Exceptions to this are experiments carried out at a temperature of 15°C with the participation of a sludge disintegrated in the proportions of 1:0 and 3:1, where a slight increase in value was noted. On average, BOD_5 values of samples without the disintegration sludge increase from 10.7 mg O_2/L on the first day to 23.9 mg O_2/L on the last day. With a 25% share of disintegrated sludge, the average value of the indicator changed from 35.6 to 52.6 mg O_2/L.

It is obvious that the stabilization of the sludge affects the COD concentration of the supernatant. It can be assumed that as the BOD_5 value decreases as a result of the decomposition of organic constituents in the aerobic stabilization process, the COD value will also decrease. On the 35th day of experiments (end of experiments), the value of COD increase in two proportions of non-disintegrated to disintegrated sludge (1:0 and 3:1 ratio). At bigger share of sludge disintegrated in the trials (≥50%), the COD value decreases at all stabilization process temperatures.

Along with the increasing share of disintegrated sludge in the research series, an increase of turbidity is noticeable on the first day of the experiments. Solid disintegration parameters were used in the research, which causes the breakdown of sludge flocks, and the destruction of cell walls as well as cytoplasmic membranes of microorganisms, with the effect being an increase in turbidity [33]. Therefore, the increase in turbidity in the series with the increasing share of the disintegrated sludge is justified.

3.2. *Total organic solids in the aerobic stabilization process*

Aerobic stabilization of sludge was carried out for 35 d. At that time, a level of oxygen of 7–9 mg O_2/dm^3 was maintained in the chambers. Permanent aeration of the sludge causes the decomposition of organic solids of the sludge. In the individual research series, a decreasing concentration of TOS was observed in the subsequent days of stabilization (Table 2). This is in line with the characteristics of the stabilization process described in the literature [34,35]. Differences in the initial values of the total organic solids concentration in individual research series are caused by the variability of the analyzed sewage sludge. This is due to the different collection times of sludge from the sewage treatment plant. Efforts were made to carry out five parallel series of sludge stabilization with different disintegration shares and at a constant process temperature on a single sludge collection from the sewage treatment plant.

According to Bartkowska [36], and Podedworna and Umiejewska [37], sewage sludge can be considered stabilized when there is a 38% reduction in TOS concentration. The analysis of the effectiveness of organic solids distribution (TOS) for individual measurement series was based on the analysis of the values presented in Table 2. The analysis was carried out in accordance to the methodology described in Section 2.3. The obtained equations of the inverse TOS concentration function and aerobic stabilization of the sludge time are presented in Table 2 together with determined R^2 determination coefficient, and the predicted sludge stabilization time. As can be seen in Table 2, all R^2 determination coefficients have values of over 0.9, which, according to Bobrowski and Maćkowiak-Łybacka [38], corresponds to a strict dependence and very good function matching. On the basis of Eq. (1) and the function of the relationship of inverse TOS concentration and stabilization time, the effectiveness of the decomposition of organic solids was determined. After averaging the results for the series of measurements performed under the same temperature conditions and the mixing ratio of the non-disintegrated to disintegrated sludge, the average values of organic solid degradation are shown in Fig. 1 for different mixing ratios and different process temperatures.

As can be seen in Fig. 1, the line determining the effectiveness of the process with the participation of the 1:1 disintegrated sludge is higher than the results for the remaining samples. This is particularly evident for a temperature of 12°C. It is noticeable that the process conducted at such parameters is more effective than in the case of a larger share of disintegrated sludge. The sludge disintegration process causes an increase in sludge temperature and the emission of volatile substances into the atmosphere. There may be a measurement error of the TOS concentration as a result of the artificial underestimation of the sample weight at larger shares of the disintegrated sludge. The sludge for analytical tests was taken after determining the temperature at the level assumed for the tests.

For easier comparison of the stabilization processes carried out at different temperatures and a different share of the disintegrated sludge, a bar graph of the sludge stabilization time depending on the proportion of sludge mixing at different temperatures of the process was made and shown in Fig. 2.

The presented results confirm the tendency of faster sludge stabilization at higher process temperature as has been reported in literature [8,39,40]. They also illustrate the acceleration of the sludge stabilization process accompanying an increase in the share of sludge disintegrated from 0% to 50% of the share in the research. This effect is more evident at the lower process temperature (12°C, 15°C) than at a higher temperature (22°C). At the same time, the effect of the rapid extension of the sludge stabilization time and coinciding decreased effectiveness of the process is observed with the use of sludge disintegrated above 1:1. This happens regardless of the temperature at which the stabilization process is carried out.

Kennedy et al. [41] conducted research on the effectiveness of biogas production from sewage sludge subjected to microwave radiation in 100% and 60% of the sample volume. They noticed greater efficiency of biogas production for completely disintegrated sludge. There is relationship between faster biogas production and the time of sludge biodegradation (in this case anaerobic). At own research (aerobic stabilization) described in the article, the stabilization time was shorter for the ratio of 1:1 and 0:1 (Fig. 3).

Table 2
Concentration of total organic solids in successive days of stabilization for three temperatures of the process and for different mixing ratios of the non-disintegrated (*N*) and disintegrated (*D*) sludge

Temperature of the sludge stabilization process	Mixing proportions *N*:*D*	1:0	3:1	1:1	1:3	0:1
	Stabilization day *x* (d)			Total organic solids (g/L)		
12°C	1	9.4500	9.7920	9.2930	9.0240	9.5900
	2	7.4520	10.1980	9.3000	8.0380	8.3580
	4	8.1820	9.2560	8.4280	8.6920	8.2110
	7	7.3530	8.5340	7.4830	8.3330	7.9060
	9	7.4060	8.3170	7.1380	8.1450	7.3660
	11	6.8830	7.9090	6.7580	7.8520	7.3200
	16	6.5180	7.4450	6.4800	7.3050	6.5840
	18	6.3160	7.3050	5.8470	7.2220	6.3950
	23	5.7430	6.3860	5.6460	6.3550	5.7250
	25	5.5330	6.2800	5.3520	6.0770	5.5560
	28	5.5820	6.3940	6.1030	6.2040	5.6480
	30	5.5200	6.3340	5.3150	5.9880	5.6420
	32	5.6130	6.4550	5.3140	5.9790	5.5400
	35	5.4840	6.3860	4.6360	5.9240	5.4860
	Stabilization time (d)	36.5	35.1	26.4	38.5	31.7
	Inverse TOS function	$y = 0.002069x + 0.119088$	$y = 0.001858x + 0.102659$	$y = 0.002700x + 0.110711$	$y = 0.001814x + 0.110340$	$y = 0.002268x + 0.112712$
	R^2	0.92	0.92	0.92	0.95	0.95
	Stabilization day *x* (d)			Total organic solids (g/L)		
15°C	1	5.4090–11.3300	5.3840	10.7000	10.8000	9.5910
	4	4.7860–10.1100	4.8470	9.8150	10.5490	7.2440
	6	4.2140–9.6300	4.3230	9.4590	10.4000	
	8	4.3770–8.9640	4.6560	8.9800	10.2030	6.9350
	11	4.0350–8.5380	4.1530	8.3990	9.6710	6.7870
	13	3.8010–8.4270	3.9650	8.0280	9.2350	6.7360
	15	3.6790–8.3270	3.6940	7.7550	9.1410	6.0530
	18	3.4980–8.3440	3.7270	7.3610	8.6030	
	19	3.7400–7.8680	3.8460	6.8460	8.2600	6.0260
	22	3.4410–7.7940	3.5540	6.6940	7.6540	5.5330
	25	3.3760–7.3880	3.6130	6.3180	7.7350	6.0360
	27	3.3000–6.9760	3.4270	5.6930	7.6910	5.2160
	29	3.4060–7.0610	3.3720	5.8640	8.1240	5.1430
	32	3.2880–6.8950	3.2850	6.1510	7.4490	5.0120
	35	3.0620–6.5650	2.9910	6.1040	6.4560	4.9670
	Stabilization time (d)	22.9–49.5	33.6	24.6	34.3	29.9
	Inverse TOS function	$y = 0.002640x + 0.126136$	$y = 0.003665x + 0.194076$	$y = 0.002438x + 0.093236$	$y = 0.001623x + 0.087367$	$y = 0.002499x + 0.117277$
	R^2	0.93	0.94	0.93	0.92	0.92

	Stabilization day x (d)	Total organic solids (g/L)				
22°C	1	8.2210–12.9560	8.1820–12.4260	9.1660–11.6230	9.0060–12.4780	8.1620–12.7060
	5	7.6870–9.6740	6.7110–11.0990	7.0100–10.3840	7.4900–10.4170	6.5990–9.5180
	7	8.6440–8.6670	6.2700–10.6300	7.8680–9.3950	7.9960–9.8210	6.4880–9.1250
	9	7.0330–8.4170	5.9650–10.2290	6.5570–8.7390	7.0330–9.4040	5.6850–8.2720
	12	6.3370–8.1450	5.6830–9.3200	5.6780–8.3890	6.6750–9.0460	4.8550–7.4530
	14	6.3180–7.3120	5.2560–8.6150	5.6170–7.0770	6.5110–8.2200	4.7350–6.6590
	16	6.4790–7.6770	5.4920–8.7950	5.3970–7.3260	6.4360–8.0740	4.8310–6.8740
	19	5.5120–7.0450	5.2420–7.7840	5.3290–6.8210	6.1900–7.9320	4.7670–6.3120
	21	5.2070–6.7100	4.7090–7.9030	4.8700–6.6370	5.7890–7.4290	4.4800–5.9950
	23	5.1600–6.6880	4.6000–7.1890	4.5550–6.2830	5.7230–7.1030	4.3080–5.4730
	26	5.0220–6.4270	4.4980–7.0240	4.4070–5.8750	5.2530–6.8130	4.1830–5.4860
	28	5.2800–6.4040	4.3290–6.9760	4.5770–6.0710	5.5200–6.7760	4.3580–5.4200
	30	4.5090–6.2810	3.9000–6.6920	4.2650–5.8960	5.0530	4.1680–5.5130
	33	3.8060–5.1000	4.2360–4.4250	4.0450–4.6820	4.8680–5.7600	3.7060–4.5200
	35	4.0500–5.6660	4.2400–6.5600	3.7760–5.2760	4.5530–6.2500	3.5060–5.3780
	Stabilization time (d)	18.1–24.0	22.5–24.7	15.8–20.9	28.0	18.3–26.5
	Inverse TOS function	$y = 0.003147x + 0.098010$	$y = 0.003172x + 0.101934$	$y = 0.003661x + 0.098067$	$y = 0.002584x + 0.100166$	$y = 0.003613x + 0.113065$
	R^2	0.94	0.93	0.95	0.96	0.93

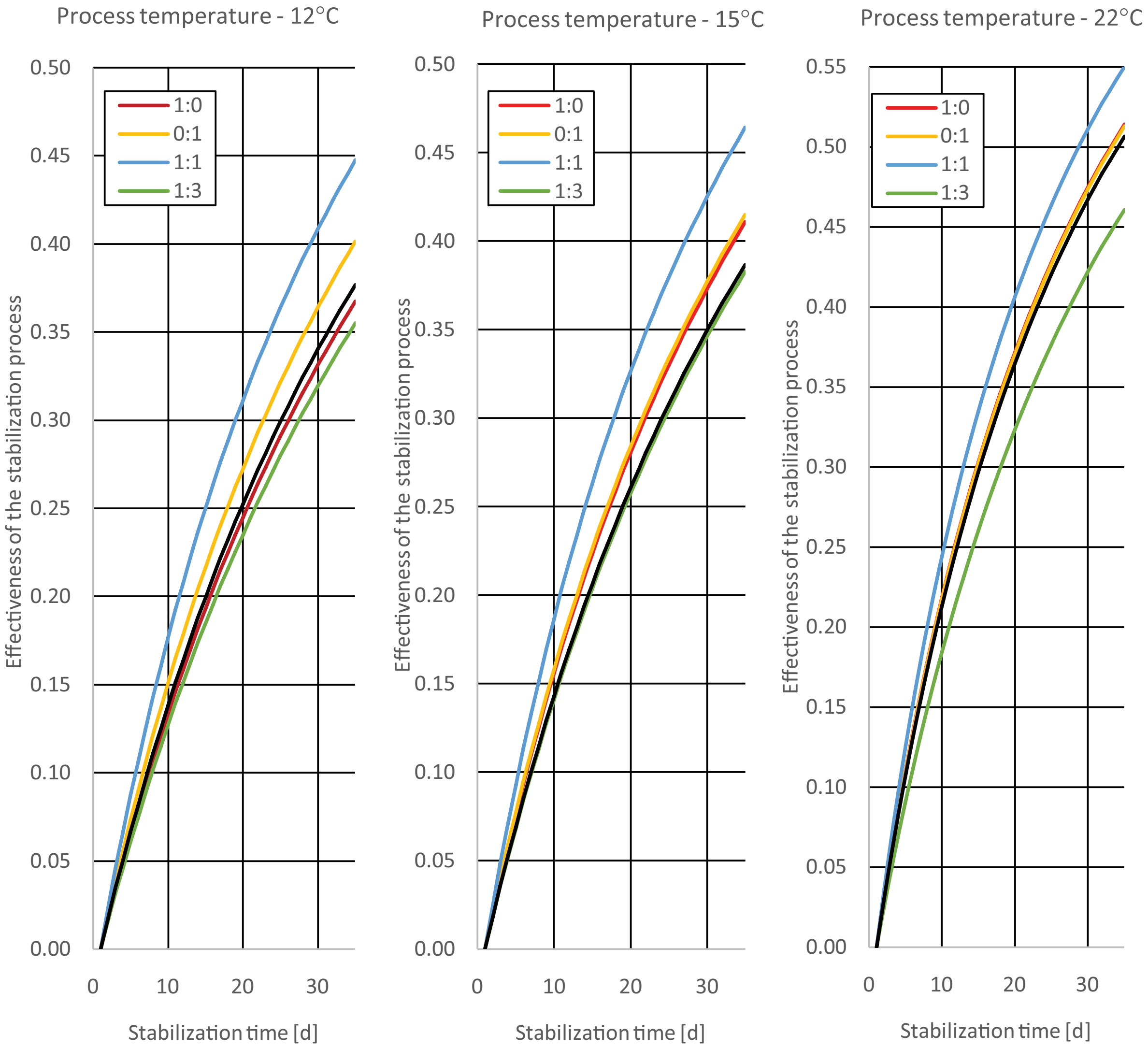

Fig. 1. Sludge stabilization process expressed in the effectiveness of the sludge stabilization process over 35 d TOS reduction for various proportions of non-disintegrated and disintegrated sludge for various process temperatures (12°C, 15°C, 22°C).

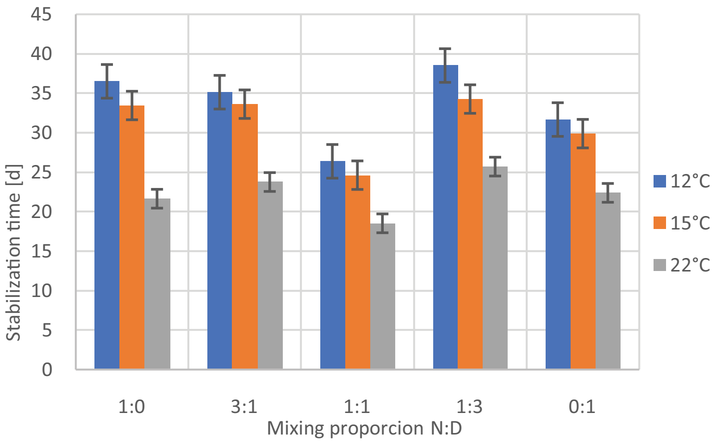

Fig. 2. Time of sludge stabilization depending on the proportion of mixing non-disintegrated and disintegrated sludge and the temperature of the stabilization process.

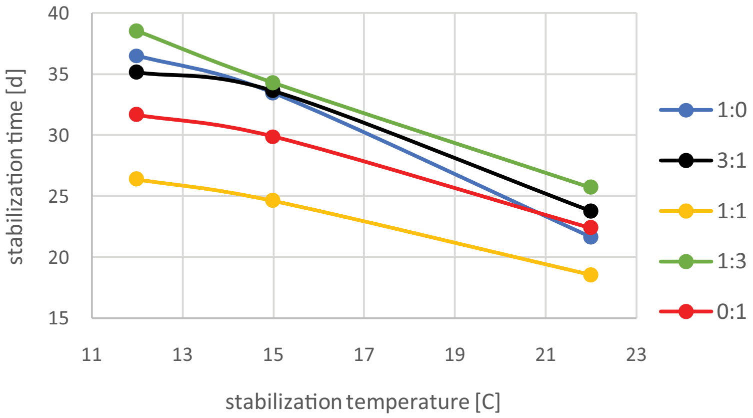

Fig. 3. Dependence of the sludge stabilization time on the sludge temperature for different mixing ratios of the non-disintegrated sludge to the disintegrated sludge.

Each time that the samples were prepared for research on sludge stabilization, an attempt was made to cool the disintegrated sludge (microwave disintegration increased the temperature of the sludge batch subjected to the process) to an ambient temperature (about 20°C) before mixing the disintegrated sludge with the non-disintegrated sludge in specified proportions. However, the decrease in the effectiveness of the process, with the participation of disintegrated sludge at a level of over 50%, may be related to the release of volatile substances in the process of sludge disintegration and, because of it, incorrect determination of the starting point of TOS measurements. At the same time, this may be the result of the excessive addition of disintegrated sludge (dead sludge constituting a large load of pollutants) to the live sludge. The live sludge (non-disintegrated sludge) in the aerobic conditions initiates the process of sludge stabilization. This may have resulted in the living organisms to receive an increased dose of disintegrated sludge, which resulted in a longer time needed for the adaptation of living organisms and stabilization of the sludge (high load of disintegrated sludge – dead organic solids).

The confirmation of the dependence of the decreasing stabilization time of the sludge on the temperature is also Fig. 3. Higher temperature accelerates the stabilization of the sludge. At the same time, a significant improvement in the stabilization time for a 1:1 sludge ratio relative to other proportions is noticeable.

Fig. 3 also shows the intersection of the curve showing the non-disintegrated sludge (1:0) with the lines showing sludge disintegrated in the proportions of 3:1 and 0:1. It should be remembered that oxygen stabilization of the sludge is a biological process. At the same time, the process of microwave sludge disintegration affects the sludge thermally, killing microorganisms contained within it. Mixing the non-disintegrated sludge with the disintegrated sludge in the assumed proportions changes the ratio of live sludge to dead, during aerobic stabilization, which consequently changes the characteristics of the sludge stabilization process relative to the process temperature. Thus, the curves of the time dependence of the aerobic stabilization of the sludge on the process temperature for different mixing proportions of the non-disintegrated and disintegrated sludge have different, not always parallel, characteristics.

3.3. Energetics of the stabilization process

Table 3 presents the results of the descriptive statistics of the aerobic stabilization time of the sludge. On this basis, using Eqs. (2) and (3) presented in the methodology (Section 2.3), the approximate energy consumption per m^3 of stabilized sludge and the potential energy gain in relation to the traditional method of sludge stabilization without the participation of disintegrated sludge (1:0) were determined. Energy gain is presented in the form of a bar graph in Fig. 4. The values shown in the chart with a positive sign represent a potential profit, whereas negative ones signify a loss. Czajkowska and Kazimierczak [4], on the basis of preliminary research, determined energy profit at the level of 50% share of the disintegrated sludge in the tests. However, according to the analysis carried out in the work, a smaller potential energy profit was determined, found to be at the level of 18% at the same share of disintegrated sludge in the experiments (1:1 ratio), but at a lower temperature of stabilization (12°C). At this process temperature, a potential energy gain was obtained only for the 1:1 ratio of disintegrated sludge, with a loss recorded in the case of other ratios of disintegrated sludge in the process.

Analyzing the obtained results, it is noticeable that there is no energy gain that goes along with higher temperatures of the stabilization process, that is, about 22°C. However, considering the statistical error indicated in Fig. 4 for samples made at 22°C, it is possible to obtain an energy profit also in this case for the share of disintegrated sludge in the ratio of 1:1.

Iskra and Miodoński [19], in their article, presented the potential energy gain using ultrasonic disintegration of sewage sludge before the methane fermentation process. They showed that, to carry out the ultrasonic disintegration process itself, it is necessary to use energy at the level of approximately 5 kWh/m^3 of sludge subjected to the process (for example, the energy consumption was 250 kWh/d, the daily volume of processed sludge was 50 m^3/d). For comparison, in our own research presented in Table 3, energy consumption for the microwave disintegration process is shown to be at the level of 93 Wh/m^3 of sewage sludge in the case of the share of disintegrated sludge in the ratio of 0:1 (sample with 100% share of disintegrated sludge).

Table 3
Energy consumption for the disintegration and aeration of samples in the process of aerobic sludge stabilization

Temperature (°C)	Mixing proportions *N*:*D*	Stabilization time (d)			Energy of disintegration	Stabilization process energy (kWh)			Stabilization process energy (Wh/m^3)
		Max.	Min.	Average	(Wh/m^3)	Max.	Min.	Average	
12	1:0	36.52	36.52	36.52	0	7.01	7.01	7.01	467.51
	3:1	35.15	35.15	35.15	23.3	7.10	7.10	7.10	473.22
	1:1	26.39	26.39	26.39	46.7	5.77	5.77	5.77	384.43
	1:3	38.53	38.53	38.53	70.0	8.45	8.45	8.45	563.16
	0:1	31.68	31.68	31.68	93.3	7.48	7.48	7.48	498.89
15	1:0	49.48	22.85	33.46	0	9.50	4.39	6.42	428.31
	3:1	33.63	33.63	33.63	23.3	6.81	6.81	6.81	453.81
	1:1	24.64	24.64	24.64	46.7	5.43	5.43	5.43	362.00
	1:3	34.28	34.28	34.28	70.0	7.63	7.63	7.63	508.78
	0:1	29.90	29.90	29.90	93.3	7.14	7.14	7.14	476.01
22	1:0	24.00	18.10	21.65	0	4.61	3.47	4.16	277.12
	3:1	24.72	22.48	23.77	23.3	5.10	4.67	4.91	327.56
	1:1	20.87	15.76	18.53	46.7	4.71	3.73	4.26	283.85
	1:3	27.97	23.54	25.72	70.0	6.42	5.57	5.99	399.20
	0:1	26.53	18.29	22.39	93.3	6.49	4.91	5.70	379.94

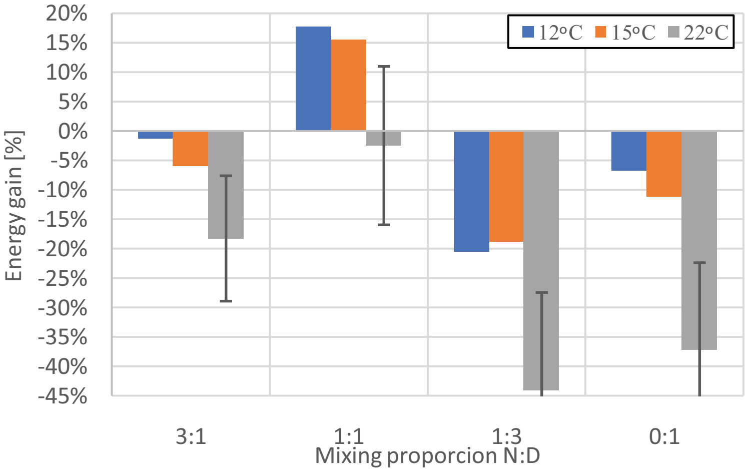

Fig. 4. Stabilization effect determined by the energetic gain of the sludge stabilization process in relation to standard sludge stabilization in different mixing ratios of non-disintegrated and disintegrated sludge and various process temperatures.

This is about 50 times less energy demand for carrying out the sludge disintegration process.

4. Conclusions

This study has shown a reduction in the time of sewage sludge aerobic stabilization from a typical small municipal WWTP by using microwave disintegration. The conclusions were drawn as follows:

- With the increase of the proportion of the microwave disintegrated sludge to the ratio of 1:1, the stabilization of the sludge is accelerated.
- Above 50% share of the disintegrated sludge, a rapid increase in the sludge stabilization time occurs regardless of the process temperature.
- At the first day of experiment, an increase in COD and BOD_5 values in the supernatant liquid was demonstrated along with the increasing share of disintegrated sludge. At the end of experiment (the 35th day), there is no dependencies for these indicators. This may be the result of the different times needed to stabilize individual measurement series.
- Disadvantage of the aerobic stabilization of sewage sludge is an increase in turbidity of the supernatant liquid. The supernatant liquid in the sewage sludge

treatment processes is returned to the biological part of the wastewater treatment plant. Decreased pH index of the supernatant liquid after the stabilization process may disrupt the nitrification and denitrification process at the sewage treatment plant.

- The beneficial effect of the proportion of sludge disintegrated in a 1:1 ratio on the reduction of organic dry solids in the aerobic stabilization process was determined. The stabilization time has been reduced by about 3 d for the stabilization process at 22°C, and about 10 d at 12°C. This parameter obviously gets converted into a reduction in the unit (tank) volume necessary to carry out the proces, due to the shorter time of sludge retention required. This information, combined with a specified potential energy gain of 18% for the process temperature of 12°C, can be considered in the economic assessment of sewage sludge treatment at a wastewater treatment plant.

The tests were carried out in stable laboratory conditions. In real conditions, the sewage sludge inflow to the stabilization chamber is continuous. Therefore, the tests should be extended to semi-technical tests at a sewage treatment plant. This would make it possible to determine the most favorable ratio of the non-integrated to disintegrated sludge mixture. At the same time, tests should be carried out on sewage sludge from other wastewater treatment plants.

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