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Water and sewage sludge co-digestion: characteristic of the process and its possible applications

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Abstract: The article describes problems related to intensification of energy production at a sewage treatment plant. The authors analyze anaerobic co-digestion of sludge from a water treatment plant and sewage treatment plant. The authors proposed a methodology of the research and analyzed the preliminary results, which showed that co-digestion of sewage and water sludge enhanced biogas production. The authors hope that the results of the study will provide a basis for development of methodology for sludge control and disposal.

Introduction

Waste generation is an essential feature of human activity, but its disposal becomes a major problem for all societies and economies. Therefore, searching for technological and technical solutions providing advanced water and wastewater treatment and aimed at reduction and ultimately a no-waste technology is currently the strongest trend followed by municipal enterprises. Consequently, municipal waste management should include all activities focused on an integrated waste economy. This concept is based on the system of disposal technology (under selective collection and recycling conditions), where these technologies operate side by side, complementing each other. In this way, costs of waste management and processing can be reduced and the risk of environmental hazards minimized. Such a system should be applied mainly regionally, where all elements could be adapted to local conditions.

Furthermore, more stringent rules and guidelines regarding a surface water quality and water protection have forced many operators of water treatment plants to search for more efficient methods of water treatment sludge (WTS) utilization. According to the Polish Act of December 14, 2012 (Journal of Laws from 2013, item 21) water treatment sludge should be treated as a hazardous waste. An alternative way to dispose water treatment sludge and to reduce its volume may be sludge reuse. During such operation some valuable products may be found in both wastewater and sludge and their content is different for various water treatment methods. The processes that produce wastewater in a periodical mode include: filtration (filter backwashing), membrane processes and ion exchange (regeneration of ion exchangers). On the other hand, water treatment sludge is produced during such unit processes as: coagulation, water softening with chemicals or an iron removal (Nowacka and Włodarczyk-Makuła 2014). The amount of sludge produced during water treatment processes ranges from 2 to 5% of a treated water volume (Szerzyna 2013). Their characteristic and properties depend on a raw water quality, treatment methods as well as types of chemicals used and their doses (Leszczyńska and Sozański 2009). The predominant components of water treatment sludge include SiO_2, Al_2O_3, Fe_3O_3, CaO, MgO, and organic compounds. It is also worth to emphasize that a surface water quality changes in time, which results in the production of sludges that differ significantly in their qualitative and quantitative characteristic (Sun et al. 2015). The main compounds removed from surface water include: clay minerals, aluminum and sand particles, colloidal and dissolved organic matter as well as plant or animal residues (Verrelli et al. 2009). The amount of particulate components determines sludge dewaterability. Also organic substances participate in the water sludge dewatering process in a significant way; they amount to 50–60% of dry solids (Płonka and Barbusiński 2007). Microorganisms found in the organic suspensions come directly from the treatment processes. Their number increases during the spring blooms and varies seasonally (Falkus et al. 2000). The content of microorganisms in the sludge and its fluffy structure determines the amount of biologically and physically bound water, which subsequently affects the sludge dewaterability (Janik and Kuś 2011).

The current worldwide research investigates the possibilities of upgrading the already well recognized methods of sludge disposal and/or finding new solutions to this problem. They could protect the environment against hazardous end products, while recovering raw materials and energy, all at the lowest possible financial effort (Chu et al. 2005). Also the methods of final disposal of water treatment sludge become a very important issue since sludge storage seems to be a predominant way of its disposal. The method is considered as the least favorable solution in waste management since raw materials that otherwise could be used as energy source, utilized in industry or as fertilizers are irretrievably wasted. Therefore, the search for alternative ways to utilize water sludge is continued (Balcerzak et al. 2007, Balcarzak and Rybicki 2011, Rybicki and Cimochowicz-Rybicka 2013, Ahmad et al. 2016, Kyncl et al. 2012, Szerzyna 2013). Water sludge can be used:

- as a coagulant in wastewater treatment,
- as an adsorbent of contaminants and heavy metals in wastewater,
- as a substrate in constructed wetlands.
- in sewage sludge dewatering,
- in cement production,
- in manufacturing lightweight aggregates,
- in brick and ceramic production,
- as a raw material for concrete and mortar,
- in agricultural and other land based uses.

One of the methods is dewatering of water sludge together with sludge from a sewage treatment plant. Dewatering characteristic of aluminum sludge mixed with the digested excess sludge was studied by Lai and Liu (2004). They found that larger amounts of water sludge improved dewatering characteristic of sludge and made the mixture less compressible. On the other hand, Yang et al. (2007) demonstrated that mixed sludge not only had better dewatering properties but also showed a higher phosphorus removal from the supernatant.

This study is focused on the issue whether the sludge from water treatment plants could be used in methane co-digestion with sewage sludge and on determining a dewatering characteristic of such mixture. The products of anaerobic stabilization (digestion) are caloric biogas and wet sludge, which needs further dewatering. In addition, water sludge disintegration was investigated as an option to increase the biogas yield and dewaterability. Sludge disintegration, ahead of its stabilization, interferes with the fermentation process by loosening the bonds existing between molecules and affecting the physical and chemical sludge characteristic. This process results in a higher chemical oxygen demand (COD) content in the supernatant and more intensive dehydration (Wolski and Wolny 2011, Rybicki 2014, Kwaśny and Balcerzak 2017). The technology, which by a combined processing of sewage and water treatment sludge produces an energy carrier (biogas), establishes a closed waste management system for water and wastewater facilities. Regardless of the obvious economic benefits, this technology initiates a change in organizational structure of municipal enterprises toward an integrated economy. Such changes significantly improve the efficiency and effectiveness of local companies.

Materials and methods

Substrates

The article is focused on digestion of water treatment sludge (WTS) after its disintegration. The research involved the application of WTS during anaerobic digestion of sewage sludge. The sludge samples were collected at the water and wastewater treatment plant in Southern Poland:

1. WTS was produced during coagulation (PAX 19, XL 10, PAX 16), ozonation, dosing of powdered activated carbon and sand filters backwashing. Samples have been taken at the facility, directly from the process treatment lines. A microbial analysis of WTS was performed at the beginning of the experiment.
2. Sewage sludge was collected at a municipal wastewater treatment plant. The treatment process configuration at the plant comprised mechanical treatment and biological treatment. The biological treatment was based on a 3-stage Bardenpho system with highly effective carbon, nitrogen and phosphorus removal. The sewage sludge was a representative mixture of primary sludge and waste activated sludge.

Anaerobic batch tests

The research included respirometric tests, which had been employed for energy research; they enabled the quantitative and qualitative analysis a fermentation gas. Respirometry results and biogas production measurements were used to describe and evaluate biodegradability or activity of anaerobic processes. In the respirometers, which monitor anaerobic processes, gas production was estimated by measuring a gas volume either at a constant pressure or at a constant sample volume. Methane was selected as an indicator of the anaerobic process efficiency, not only because of its energy properties, but also its physical and chemical characteristics (Cimochowicz-Rybicka 2013).

The test stand comprised:

1. Respirometer for aerobic – anaerobic tests (AER-208, manufactured by CHALLENGE SYSTEM),
2. Water bath,
3. Heating/cooling unit,
4. Computer for on line data processing.

Measurements were carried out over 30 days at mesophilic (35°C) conditions in three separate runs. To ensure the appropriate process conditions, the pH of the samples was adjusted to pH=7.0 with NaOH. The sample was purged with technical nitrogen for three minutes before the measurements were taken. The analysis during anaerobic batch tests also included: dry solids (TVS), volatile dry solids (VSS), chemical oxygen demand (COD), alkalinity, pH, ammonia nitrogen and total phosphorus, measured according to the current EU standards.

The sludge mixture

Samples for mesophilic anaerobic digestion of sewage sludge and its combination with WTS were composed based on a dry organic solids content and included sewage sludge and WTS. Co-substrate concentrations ranged from 3.0 to 5.5 g DVS$\cdot$dm^{-3}

Methanogenic potential

The assessment of a methanogenic potential was performed using:

1. The biogas production.
2. The methanogenic activity, calculated based on the amount of methane produced from the sludge during the respirometric tests, and expressed in g COD$_{CH4}\cdot$g VSS$^{-1}\cdot$d^{-1} (Angelidaki et al. 2009, Cimochowicz-Rybicka 2013). The maximum methane production and the R factor (as ml$_{CH4}\cdot$h^{-1}) were determined from the graphs showing a methane volume produced per

a time unit. The methanogenic activity of biomass was calculated according to the equation:

$$AKT = (R \cdot 24)/(W \cdot V \cdot VSS) \qquad (1)$$

where:

AKT – methanogenic activity of sludge [g $COD_{CH4} \cdot$g $VSS^{-1} \cdot d^{-1}$],

R – parameter determined from the methane production curve [$CH_4 \cdot h^{-1}$],

W – conversion factor [ml $CH_4 \cdot COD^{-1}$] (assumed 418 ml $CH_4 \cdot COD^{-1}$ at 35°C),

V – volume of the sample [dm^3],

VSS – volatile suspended solids in the sample [g $VSS \cdot dm^{-3}$].

Disintegration

The ultrasonic disintegration process was performed using a UD11 disintegrator with a piezoelectric converter, at a resonant frequency $f = 22.5$ kHz with varying ultrasounds intensity $I = (24–64) \cdot 10^3$ $W \cdot m^{-2}$ (the sample volume 130 ml). Thermal disintegration took place in a heated water bath with a magnetic stirrer at a fixed temperature and time (the sample volume 130 ml). Also, the tests were performed to select parameters of ultrasonic and thermal disintegration using disintegration degree (DD), which was determined from the equation (ATV-Arbeitdgruppe 2000):

$$DD = (COD_d - COD_n)/(COD_a - COD_n) \cdot 100\% \qquad (2)$$

where:

DD – disintegration degree [%],

COD_d – COD in a supernatant of a disintegrated sample [$mgO_2 \cdot dm^{-3}$],

COD_n – COD in a supernatant of a sample [$mgO_2 \cdot dm^{-3}$],

COD_a – COD in a supernatant of a chemically disintegrated sample (1M NaOH after 22 hours, 20°C) [$mgO_2 \cdot dm^{-3}$].

Filtration properties

Dewaterability of sludge mixtures was assessed by:

1. The capillary suction time (CST) conducted according to the Polish standards PN-EN 14701-1:2007. This parameter evaluates how easy moisture can be removed from the sludge; when the CST is smaller, the tested sludge releases liquid easier (faster). The main advantages of the CST test are: a relatively simple device used to conduct measurements and a short test time. It should be noted that the test results depend to some extent also on sludge concentrations and the equipment used. Therefore, the CST should be performed in a standard apparatus. The CST is primarily used to determine the ability of sludge to release water. The parameter is measured as time (in seconds) required for the liquid to wet a paper filter of the defined area by a sludge sample (3 cm^3); the liquid is drawn from the sample due to a paper capillary suction.
2. Specific resistance to filtration (SRF), defined as the pressure required to make filtrate flow through the sludge cake, having a unit mass of dry solids per a unit area of filtration surface while a filtrate viscosity equals 1. The measurement of the specific resistance to filtration was carried out on the basis of the PN-EN 14701-2:2013. The specific resistance to filtration (SRF) is calculated as follows:

$$SRF = (2 \cdot \Delta p \cdot A^2 \cdot b)/(\mu \cdot m) \qquad (3)$$

where:

SRF – specific resistance to filtration [$m \cdot kg^{-1}$],

Δp – pressure drop across the filter [Pa],

A – filtration area [m^2],

b – slope of a linear part of a curve obtained by plotting t/V vs. V [$s \cdot m^{-6}$]; b factor as in Fig. 2,

μ – viscosity of filtrate at the sludge temperature [$Pa \cdot s$],

m – mass of solids deposited on the filtering medium per a unit volume of filtrate [$kg \cdot m^{-3}$].

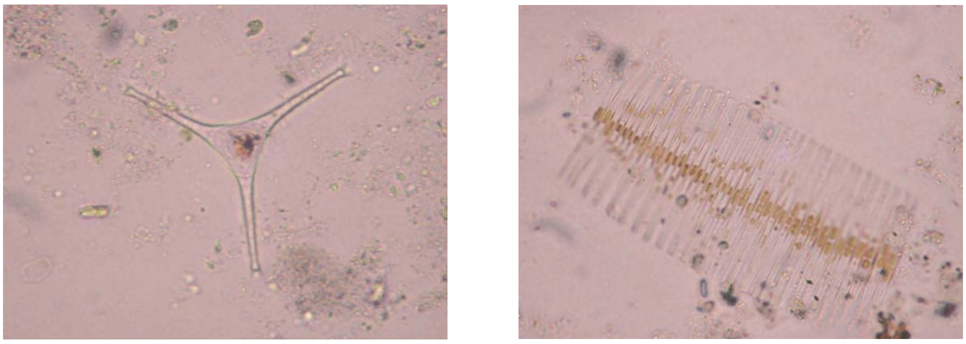
Results and discussion

The WTS structure

The study of a WTS structure revealed the presence of algae species, which might affect the co-digestion process. The two dominant species of green algae are shown in Figure 1. Algae are commonly used as a co-substrate in an anaerobic digestion of sewage sludge due to their energy potential and ability to absorb nutrients (Górka and Cimochowicz-Rybicka 2015).

Anaerobic co-digestion of sewage sludge and WTS

The cumulative biogas production data are shown in Fig. 2. During digestion of sewage sludge together with WTS a higher



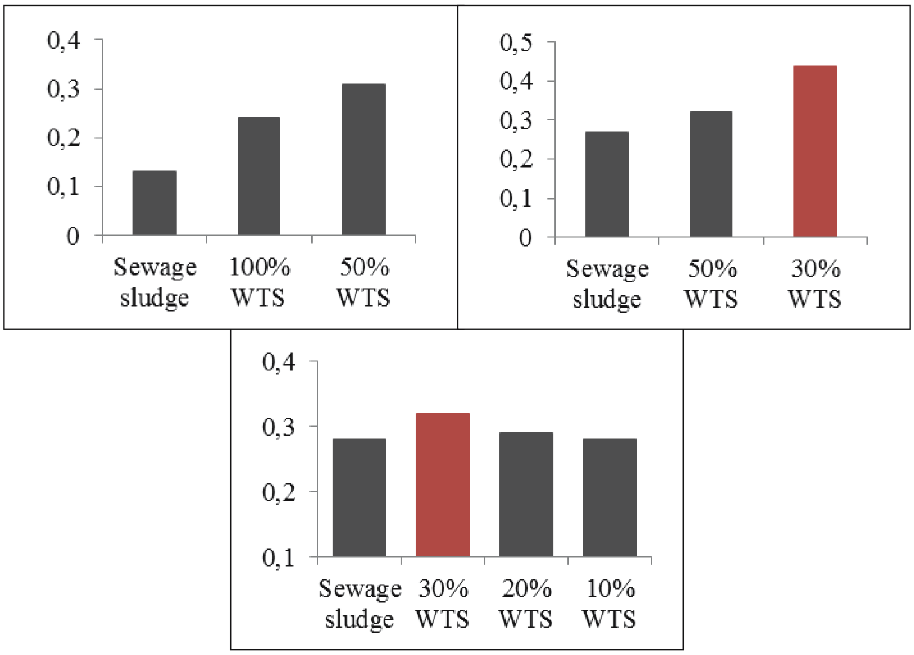
a) b)

Fig. 1. a – *Staurastum,* b – *Fragilaria*

biogas yield was observed. In fact, the biogas yield obtained during digestion of sewage sludge alone was the lowest compared to other three types of co-digestion. After 20 days of digestion, the highest cumulative biogas yield was observed for 30% WTS samples. A statistical analysis showed that differences in gas production were significant. Therefore, the 30% WTS combination of samples was selected to the disintegration tests.

The disintegration degree of WTS

The disintegration degree (DD) values (ultrasonic and thermal) for water treatment sludge are shown in Tab. 1. The DD of WTS is very low due to a low content of organic compounds (9.17 gVS·dm^{-3}) susceptible to disintegration. The DD increased with an increase of ultrasound intensity or temperature. The greatest DD value (10.71%) could be observed for WTS after thermal disintegration at 70°C and 60 min. However, in the following study, a sample at temperature 55°C and time 60 min (5.56%) was selected, because the differences in DD values were not significant. During ultrasonic disintegration, the highest values were obtained for 10 minutes of disintegration. The intensity changes did not have a strong effect on the DD (difference between 2.52 and 2.83%). Therefore, the following parameters of disintegration were selected in the next research run: thermal disintegration (55°C, time 60 min) and ultrasonic disintegration (24 kW·m^{-2}, time 10 min).



a) b) c)

Fig. 2. The biogas production in m^3·kg^{-1} DVS for three separate runs – a, b and c

Table 1. The disintegration degree (DD) of WTS after thermal and ultrasonic disintegration

DD [%]					
Thermal disintegration					
Parameters		Time [min]			
		15	30	45	60
Temperature [°C]	55	0.30	3.17	4.46	5.56
	60	0.10	5.95	6.25	7.53
	65	0.40	4.46	7.44	8.53
	70	0.50	3.17	7.83	10.71
Ultrasonic disintegration					
Parameters		Time [min]			
		3	5	7	10
Intensity [kW·m^{-2}]	24	0.17	0.47	1.05	2.75
	34	0.50	0.72	0.66	2.52
	44	0.66	1.40	1.65	2.70
	64	0.41	0.47	1.45	2.83

Anaerobic co-digestion of sewage sludge and WTS after disintegration

Next, the authors studied a mixture of sewage sludge and water treatment sludge (30% WTS by VS) with and without disintegration. The contents of carbon, nitrogen and phosphorus as well as pH are the most important parameters for anaerobic digestion. The characteristic of substrates before anaerobic digestion is shown in Tab. 2. The initial concentration of P was between 128–215 mgP·dm^{-3}. The P in sewage sludge was higher compared to its mixture with WTS. The initial pH in all samples was above 7.0 and it was the optimum pH range for anaerobic digestion. The suggested COD/N ratio for anaerobic digestion is 20–30. However, the COD/N ratio ranged from 13.4 to 15.6 for all substrates due to a high N content.

The characteristic of the mixture after co-digestion was evaluated (Tab. 3). The pH of all digesters after 20 days of digestion was 6.89–6.97. The N after anaerobic digestion was in the range of 470–560 mgN·dm^{-3}, and P was in the range of 145–232 mgP·dm^{-3}. The ammonium nitrogen (N_{NH4}) accounted for about 29–43% of N for co-digested sludge and 41% of N for sewage sludge. To determine whether disintegration of WTS had any effect on fermentation changes of COD concentrations were observed. It was found that the COD values were reduced. The highest COD reduction (11%) was found during co-digestion of 30% WTS after thermal disintegration. Also, some reduction of organic dry solids after co-digestion was noticed. The highest reduction of organic dry solids (17%) was observed for sewage sludge alone while for co-digested samples it was 11–14%.

The cumulative biogas production data are shown in Fig. 3. The co-digestion of sewage sludge and WTS exhibited a higher biogas yield while digestion of sewage sludge alone produced the lowest biogas yield, if compared to other three types of co-digestion. After 20 days of digestion, the highest cumulative biogas yield was observed for 30% WTS after thermal disintegration (about 28% higher than for sewage sludge). However, the ultrasonic disintegration did not affect the biogas production, proving a low efficiency of this disintegration method.

During the study also some measurements of methanogenic activity (AKT) were made to monitor the sludge digestion performance. The test results are shown in Tab. 4. On the basis of the results it was stated that when water sludge was used to intensify the biogas production, the methanogenic activity increased from 21 to 64%. Methanogenic activity values to

Table 2. Characteristics of different substrates before anaerobic digestion

Parameters		Sewage sludge	30% WTS	30% WTS after thermal disintegration	30% WTS after ultrasonic disintegration
pH	[–]	7.02	7.09	7.06	7.24
Alkalinity	[mgCaCO$_3$·dm^{-3}]	720	810	750	850
TS	[gTS·dm^{-3}]	7.77	10.80	10.79	10.90
DVS	[gVS·dm^{-3}]	4.66	5.04	4.91	5.04
tCOD	[mgO$_2$·dm^{-3}]	7339	6606	6514	7156
sCOD	[mgO$_2$·dm^{-3}]	112	168	171	143
TN	[mgT·dm^{-3}]	549	459	470	459
TP	[mgP·dm^{-3}]	215	157	128	196
N_{NH4}	[mgN_{NH4}·dm^{-3}]	266	224	210	196
COD/N ratio	[–]	13.4	14.4	13.9	15.6
N/P ratio	[–]	2.6	2.9	3.7	2.3

Table 3. Characteristics of different substrates after anaerobic digestion

Parameters		Sewage sludge	30% WTS	30% WTS after thermal disintegration	30% WTS after ultrasonic disintegration
pH	[–]	6.97	6.89	6.91	6.9
Alkalinity	[mgCaCO$_3$·dm^{-3}]	1120	1240	1125	1140
TS	[gTS·dm^{-3}]	7.02	10.73	9.88	10.03
DVS	[gVS·dm^{-3}]	3.87	4.39	4.39	4.35
tCOD	[mgO$_2$·dm^{-3}]	6667	6491	5789	6842
sCOD	[mgO$_2$·dm^{-3}]	103	107	107	108
TN	[mgT·dm^{-3}]	560	470	504	504
TP	[mgP·dm^{-3}]	232	184	145	216
N_{NH4}	[mgN_{NH4}·dm^{-3}]	246	224	213	224

a large extent referred to the volume of biogas generated – the AKT value remained the highest for 30% WTS and 30% WTS after thermal disintegration samples, and the lowest for the 30% WTS after ultrasonic disintegration.

Dewaterability of sewage sludge and WTS

Comparing the values of the filtration measures before and after digestion (Tab. 5) it can be concluded that neither sewage sludge nor mixed sludge improved their dewaterability after anaerobic digestion. The value of CST after digestion was higher than before the process, while SRF increased by 20–31%. Only in the samples of digested sewage sludge the SRF after digestion was higher than before the process (by about 14%). It is worth mentioning that both CST and SRF did not change with the disintegration method, so if WTS is used as a co-substrate in sewage sludge digestion the filtering characteristic of sewage sludge is not significantly affected.

The regulations regarding the surface water quality and protection, and restrictions on the storage of sludge, forced many operators of municipal companies to searching

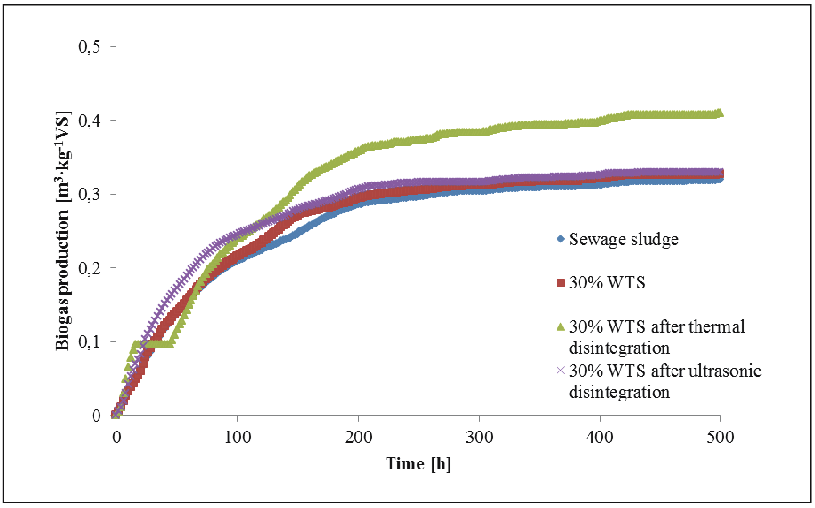


Fig. 3. The cumulative biogas production

Table 4. Parameters and results of methanogenic potential tests

Parameters		Sewage sludge	30% WTS	30% WTS after thermal disintegration	30% WTS after ultrasonic disintegration
The biogas production					
The biogas production after 500 h	[$m^3 \cdot kg^{-1}VS$]	0.32	0.33	0.41	0.33
Increase the biogas production	[%]	–	3	28	3
The methane content in biogas	[%]	70	70	70	70
The methanogenic activity test					
DVS initial	[$gVS \cdot dm^{-3}$]	7.53	8.15	8.04	8.35
DVS final	[$gVS \cdot dm^{-3}$]	4.90	5.00	5.09	4.37
R	[$mlCH_4 \cdot h^{-1}$]	6.19	12.56	11.75	11.87
AKT	[$gCOD_{CH4} \cdot g^{-1} \cdot VS^{-1} \cdot d^{-1}$]	0.14	0.23	0.23	0.17

Table 5. Dewatering characteristics of different substrates

Sample	Before anaerobic digestion		After anaerobic digestion	
	CST	SRF	CST	SRF
	[s]	[$m \cdot kg^{-1}$]	[s]	[$m \cdot kg^{-1}$]
Sewage sludge	61	$1.64 \cdot 10^{13}$	115	$1.90 \cdot 10^{13}$
30% WTS	90	$1.33 \cdot 10^{13}$	128	$1.60 \cdot 10^{13}$
30% WTS after thermal disintegration	87	$1.39 \cdot 10^{13}$	124	$1.82 \cdot 10^{13}$
30% WTS after ultrasonic disintegration	94	$1.63 \cdot 10^{13}$	107	$1.96 \cdot 10^{13}$

for effective methods for managing sludge from water and wastewater treatment plant. Reuse of WTS during anaerobic co–digestion of sewage sludge provides a sustainable end point solution to sludge disposal problem.

The application of WTS in wastewater treatment improves the efficiency of the fermentation process without affecting the dewaterability of sewage sludge. Additionally, thermal disintegration had a better effect on the biogas production and methanogenic activity during co-digestion with WTS than ultrasonic disintegration. The mixing ratio of 1:0.3 (sewage sludge to WTS) proved to be the most appropriate proportion of sludge mixing. The quantity of WTS added to sewage sludge is not without significance, because the WTS has a worse ability to decomposition in anaerobic conditions than sewage sludge.

During the implementation of integrated sludge management (e.g. co-digestion), it will be also important to analyze the composition and physicochemical properties of WTS including the seasons and the type of water source (groundwater or surface water).

Conclusions

1. The results showed that disintegration degrees (DD) of water treatment sludge (WTS) had very low values. For ultrasonic disintegration the DD varied from 0.17 to 2.83% (depending on intensity and time) and for thermal disintegration from 0.10 to 10.71% (depending on temperature and time).
2. Thermal disintegration had a better effect on the biogas production during co-fermentation with WTS than ultrasonic disintegration. During the mesophilic digestion, the biogas production for 30% WTS after thermal disintegration was 28% higher than for sewage sludge alone. However, the biogas production for 30% WTS after ultrasonic disintegration was on the same level as for 30% WTS (5% higher than for sewage sludge alone). In this case, ultrasounds were not effective way of disintegration. Also the methanogenic activity value can help to evaluate the digestion process; the measurements confirmed the above conclusions.
3. Analysis of capillary suction time (CST) and specific resistance to filtration (SRF) showed that WTS had no impact on the filtration characteristic of sewage sludge.
4. The concept assumed that using WTS at wastewater treatment plants could be the cheapest way of solving the waste disposal problem. The companies will only bear the costs of WTS transport to wastewater treatment plant. A higher biogas production could be an additional benefit. This technology can initiate a change in organizational structure of municipal enterprises toward an integrated economy.

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Współfermentacja osadów ściekowych i z uzdatniania wody: charakterystyka procesu i możliwości zastosowania

Streszczenie: Badania zaprezentowane w niniejszej publikacji, prowadziły do określenia możliwości wykorzystania osadów z uzdatniania wody jako substrat w procesie fermentacji metanowej osadów ściekowych. Autorzy zaproponowali metodologię badań i przeanalizowali wstępne wyniki, które wykazały, że dodanie osadów z uzdatniania wody do osadów ściekowych spowodowało zwiększoną produkcję biogazu. Zaproponowana technologia stanowi zintegrowany system gospodarki komunalnej, oparty na współpracy dwóch przedsiębiorstw: oczyszczalni ścieków i stacji uzdatniania, działających w systemie gospodarki cyrkulacyjnej. Rezultatem takiego rozwiązania są korzyści w zakresie odzysku biogazu, możliwego do wykorzystania w procesie kogeneracji.