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ASSESSMENT OF KITCHEN BIOWASTE AND SEWAGE SLUDGE SUSCEPTIBILITY TO METHANOGENIC CO-DIGESTION IN BATCH TESTS

OCENA PODATNOŚCI BIOODPADÓW KUCHENNYCH I OSADÓW ŚCIEKOWYCH DO KOFERMENTACJI PROWADZONEJ W WARUNKACH STATYCZNYCH

Abstract: The article presents the results of a study meant to establish the most favourable proportion of source-sorted kitchen biowaste undergoing mesophilic methane fermentation along with waste activated sludge (WAS). The optimum combination of substrates was supposed to ensure the stability of the process in a batch mode. An attempt was made to replace a part of sludge with waste foam floating periodically on the surface of the aeration tank. The assessment of the various combinations of substrates was based on the following criteria: total biogas production and biogas yield, degree of organic matter decomposition and indices of process stability (VFA, VFA/TA). It was established that the co-digestion of kitchen biowaste with sewage sludge influenced the quantity and quality of the biogas produced as well as organic matter biodegradation in a positive way. The optimum kitchen biowaste proportion in digestion mixtures amounted to 60 % TS, which is tantamount to about 25 % if expressed as wet weight proportion. Under those conditions, the total biogas production increased more than three times and the process exhibited the greatest biogas yields. Moreover, the addition of kitchen biowaste did not deteriorate the stability of the process. In case of optimum kitchen biowaste and sewage sludge co-digestion run, the replacement of a part of sewage sludge by waste foam did not impact the effectiveness as well as the stability of the process. However, the addition of waste foam had a positive impact on the biogas production rate

Keywords: methane fermentation, co-digestion, biogas, sewage sludge, sewage sludge foaming, kitchen biowaste

The main by-product of municipal and industrial wastewater treatment is sewage sludge, which amount is steadily increasing. It is estimated that the amount of sewage sludge generated in municipal wastewater treatment plants will amount to 700 000 Mg

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in 2015, which is 23 % more than the equivalent amount in 2008 [1]. One of the most popular methods used for wastewater treatment is activated sludge method, which allows to remove both organic and biogenic substances. Excess biomass, ie *waste activated sludge* (WAS), generated as a by-product of wastewaters treatment, is periodically removed from bioreactor's chamber. The method was proved to generate foam layer on the surface of the bioreactors. It hinders wastewaters aeration and has a negative impact on the effectiveness of their treatment [2–3]. The main factors behind the negative process of sewage sludge foaming are: excessive growth of zoogloea bacteria, activated sludge swelling caused by excessive amounts of polysaccharides as well as disturbances of the treatment process. Most methods meant to counteract sewage sludge foaming consist in a permanent monitoring of activated sludge conditions as well as adding chemical substances which suppress foaming. The chemicals, however, very often work only for a limited period of time. In practice, the foam is frequently removed mechanically from the bioreactor's chambers and requires to be utilized [2–4].

Similarly, excessive sewage sludge, needs to be treated. It is usually stabilized in anaerobic conditions in the process of methane fermentation. Despite high investments costs and seasonally occurring technological problems, the anaerobic digestion for biogas production is considered to be an attractive method of wastes utilization. The main advantage of the process is the possibility to generate renewable energy in the form of biogas, which in turn allows to meet energy demands of the wastewater treatment plants, especially in winter. Co-digestion of wastewaters treatment by-products with substrates containing a higher easily-biodegradable organic matter seems to an interesting alternative allowing their utilization as well as enhancement of the biogas production.

The literature contains multiple accounts of successful treatment of a primary or/and surplus activated sludge combined with: source-sorted or mechanically separated *organic fraction of municipal solid waste* (OFMSW) [5–10], livestock wastes [11–12] as well as industrial organic wastes, predominantly from food industry [13–14]. However, cases concerning integrated co-digestion of wastewater treatment by-products in the form of waste activated sludge (WAS) and waste foam together with source-sorted kitchen biowaste are very scarce. Besides, increasing popularity of the municipal solid waste collection at the place of origin as well as growing environmental awareness of the society are important factors behind the fact that source-sorted kitchen biowaste – exhibiting a high content of easily-biodegradable organic matter – is considered as a valuable substrate in biogas plants. Poland generates about 10 mln Mg of solid municipal wastes, whose one of the main fraction is just kitchen biowaste [1].

The article presents the results of a study meant to establish the most favourable proportion of kitchen biowaste undergoing anaerobic digestion for biogas production along with excess activated waste (WAS). In case of the optimum combination of kitchen biowaste and sewage sludge, an attempt was made to replace a part of the activated sewage sludge with foam floating seasonally on the surface of the wastewater treatment chambers. The assessment of various combinations of substrates was based on the following criteria: total biogas production and biogas yield, degrees of organic matter decomposition and indices of process stability.

Materials and methods

Kitchen biowaste referred to as *kitchen biowaste* (KB) below, thickened waste activated sludge (WAS) referred to as sewage sludge below and foam floating on the surface of the nitrification chamber of the bioreactor treating municipal wastewater referred to as *waste foam* (WF) below were used as a digestion feedstock. The kitchen biowaste was collected selectively from households as well as institutions (restaurants, school canteens etc) located in the vicinity of the wastewater treatment plant which provided the sewage sludge. A domestic food blender was used to homogenize the various components of biowaste into granules smaller than 2 mm in diameter. Then, it was stored in a refrigerator at 5 ^{o}C. The sewage sludge was taken after thickening from a full-scale municipal treatment plant based on *Enhanced Biological Nutrients Removal* (EBNR), operated on the activated sludge method. The digested sludge taken from the same wastewater treatment plant which provided the thickened sludge was used as an inoculum. It was a full-scale continuous process operated in mesophilic conditions. Characteristics of the substrates used is presented in Table 1.

Table 1

Characteristics of the digestion feedstock

Indicator	Kitchen biowaste (KB)	Waste activated sludge (WAS)	Waste foam (WF)	Inoculum
pH [-]	4.65 (0.15)	6.44 (0.11)	6.19 (0.10)	7.76 (0.09)
TS [%]	23.44 (0.98)	5.20 (0.21)	5.82 (0.15)	3.09 (0.17)
VS [%]	21.64 (0.82)	3.57 (0.16)	4.05 (0.12)	1.73 (0.11)
$C_{org.}$ [% d.m.]	55.18 (0.32)	38.44 (0.47)	33.22 (0.99)	31.02 (0.89)
$N_{tot.}$ [% d.m.]	2.94 (0.02)	4.98 (0.06)	4.23 (0.04)	3.28 (0.04)
NH_4^+ [mg/dm^3]	—	18.3 (1.5)	20.5 (2.5)	1 850 (124)
COD [mgO$_2$/dm^3]	—	292 (70)	158 (62)	1 620 (212)

In the bracket standard deviation values.

The process was carried out in a set of digesters with a working volume of 3 dm^3. Digesters were maintained at a constant temperature of 36^{o}C (±0.5) for 35 days. Their contents were mixed periodically – 5 minutes in every 3 hours. The experiment was divided into two parts. In the first one, digestion process was carried out for a sewage sludge as well as mixtures of kitchen biowaste and sewage sludge – based on the *following total solids* (TS) ratio: 20:80; 40:60; 50:50; 60:40 and 70:30. During the second part of the experiment, for the most favourable co-digestion mixture of substrates (kitchen biowaste + sewage sludge), 10 % TS and 20 % TS of the sludge undergoing digestion was replaced by waste foam. The digestion feedstock was mixed with the inoculum at the weight ratio of 1:2, which was established as an optimum, based on preliminary tests. The criterion for assessing the optimum substrates-to-inoculum ratio was total biogas production. The biogas production from the inoculum itself was subtracted from biogas production of all digested samples. All samples were prepared in duplicates. The characteristics of the digestion input is presented in Table 2.

Table 2

Characteristics of the digestion input

Indicator	Digestion mixtures composition [% TS]							
	KB:WAS						KB:WAS(WF)	
	0:100	20:80	40:60	50:50	60:40	70:30	60:40(10)	60:40(20)
pH [-]	7.25	7.21	7.19	7.16	7.01	6.81	7.08	7.12
TS [%]	3.77	4.22	4.67	4.88	5.33	5.83	5.54	5,56
VS [%]	2.36	2.77	3.23	3.48	3.93	4.43	3.94	3.96
C:N [-]	7.7	8.9	10.3	10.9	11.7	12.6	11.8	11.9

The scope of the analyses conducted encompassed: pH value measurement as well as determinations of total solids (TS), volatile solids (VS), chemical oxygen demand (COD), total volatile fatty acids (VFA), total alkalinity (TA), ammonia-nitrogen (NH_4^+) as well as total organic carbon (C) and total Kjeldahl nitrogen (TKN). The biogas produced was stored in a plexus tube containing 5 % NaOH solution. The recorded amounts of biogas were adjusted to the volume at standard temperature (0°C) and pressure (1 atm). The biogas was periodically analysed for CH_4 content (% vol.) [15].

Results and discussion

As the assays were undergoing digestion, the daily biogas production was recorded – Fig. 1. As expected, co-digestion mixtures produced more biogas than sewage sludge itself. The highest biogas production, ie 13.19 dm^3 was recorded for the digestion mixture containing 60 % TS from kitchen biowaste, which is almost three times more than in case of sample containing exclusively sewage sludge (3.58 dm^3). It was established that further increase in kitchen biowaste proportion in digestion trials led to the significant decrease of biogas production which might have been caused by VFAs accumulation. In the most favourable combination of digested substrates, ie 60 % TS of kitchen biowaste and 40 % TS of sewage sludge, a part of sewage sludge treated was replaced with periodic foam floating on the surface of the wastewater treatment chambers. Similar amounts of biogas were generated irrespective of the amount of waste foam added. Adding 10 % TS and 20 % TS of waste foam led to the biogas production of 13.30 m^3/m^3 d and 13.16 m^3/m^3 d, respectively. Both above – mentioned amounts of biogas were comparable with the amount of biogas generated by trial without waste foam addition, ie 13.19 m^3/m^3 d. However, foam addition had a positive impact on the biogas production rate. Digestion mixtures containing waste foam reached biogas production peak already in the fourth day of the experiment, ie 1.63 $m^3/m^3 \cdot d$ (10 % of foam) and 1.53 $m^3/m^3 \cdot d$ (20 % of foam). Whilst the biogas production peak for digestion trials without foam was reached on the 12th day of the process. Dependency of the composition of digestion mixtures on the biogas production was illustrated in Fig. 1 and 2.

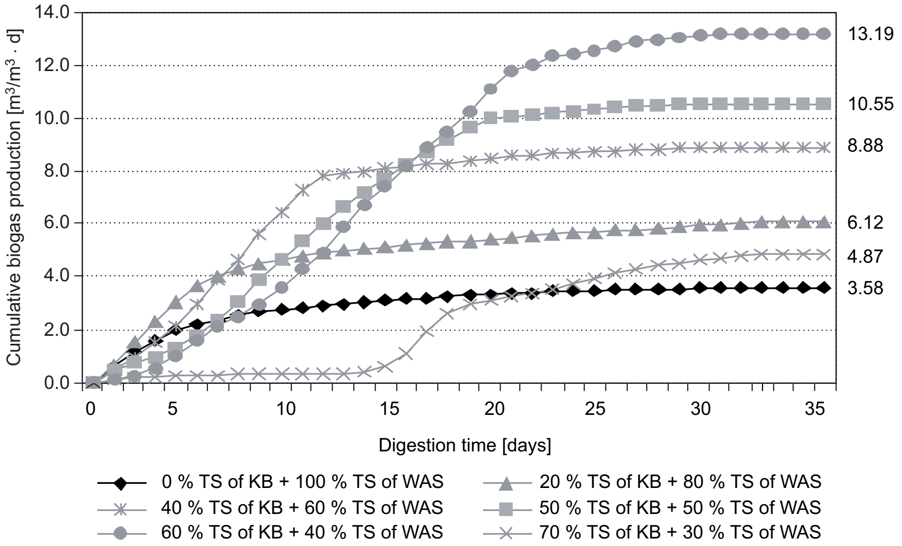

Fig. 1. Influence of kitchen biowaste addition on the amount of biogas produced

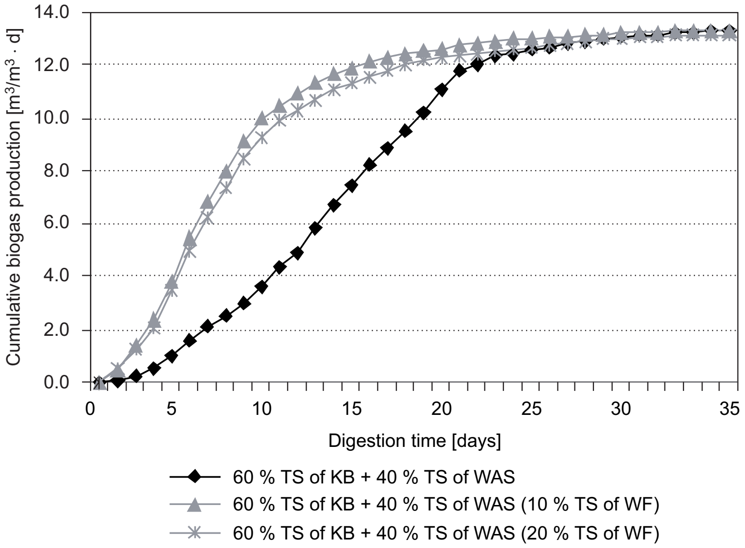

Fig. 2. Influence of waste foam addition on the amount of biogas produced.

On the one hand, the amount of biogas generated depends primarily on the amount of biodegraded organic matter. On the other hand, the composition of the biogas produced is conditioned by the feedstock chemical structure, ie the content of proteins, fats and carbohydrates and their derivatives. Accordingly, the study was not focused exclusively on the amount of biogas generated but also on its methane content. The average methane content measured in a stable state of the process for the run containing sewage sludge without kitchen biowaste amounted to 56 %. By contrast, the amount of methane in the co-digested runs fluctuated between 67 and 72 %. The addition of waste foam to the digestion feedstock did not have any influence on the CH_4 content. A relative increase of CH_4 concentration in kitchen biowaste-loaded trials may be caused by the introduction of a substrate rich in proteins and fats [16–17].

During multi-step process of anaerobic digestion macromolecular substances are converted into simpler compounds. One of the most common parameters to measure the bioconversion is the degree of volatile matter (VS) reduction. Compared with the run containing sewage sludge exclusively (42.8 %), all co-digested samples exhibited a higher degree of VS reduction (45.8–63.6 %) – Table 3. Accordingly, it allows to conclude that more varied composition of the digested mixtures positively impacts the efficiency of bioconversion, mainly by improving the C/N ratio. In our case, the C/N ratio of the analysed sludge amounted to 7.7 (Table 1). The optimal value of the ratio reported in the literature varies widely. It is frequently mentioned to fluctuate between 10:1 and 25:1 [18]. The addition of biowaste as a co-substrate allowed to increase the C/N ratio to the level of 8.9–12.6. Whilst introducing the waste foam in mixtures undergoing anaerobic digestion did not impact both C/N of the digestion feedstock and degrees VS reduction (Tables 2 and 3).

Table 3

Organic matter reduction

Indicator	Digested mixtures [% TS]							
	KB:WAS						KB:WAS(WF)	
	0:100	20:80	40:60	50:50	60:40	70:30	60:40(10)	60:40(20)
TS [%]	2.59	2.80	3.02	3.04	2.82	3.27	3.23	3.22
VS [%]	1.35	1.50	1.67	1.63	1.43	1.69	1.51	1.55
TS reduction [%]	31.3	33.6	35.3	37.7	47.1	43.9	41.7	42.1
VS reduction [%]	42.8	45.8	48.3	53.2	63.6	61.9	61.7	60.9

In order to assess the influence of co-substrates addition, biomethanization results were recalculated and expressed in terms of biogas yield – Fig. 3.

The highest value of the parameter in terms of VS added (0.336 m^3/kg VS) as well as degraded (0.527 m^3/kg VS) was achieved for sample containing 60 % of TS from kitchen biowaste. The above values are about 121 % and 49 % higher than those recorded for sewage sludge without kitchen biowaste addition respectively. Similarly to the biogas production and degrees of organic matter reduction, the adition of waste foam did not change significantly values of biogas yields.

Finally, the influence of the kitchen biowaste and foam addition on the stability of the methane fermentation was taken into consideration. Due to excessive production of VFAs, uncontrolled introducing of substrates rich in easily-biodegradable organic matter in anaerobic condition may cause a significant decrease in pH value beyond the range ensuring an appropriate growth and development of methane generating bacteria [18–19]. Optimum concentration of VFA in a bioreactor amounts to about 500 mg CH_3COOH/dm^3, while, the critical value, which indicates some instability in the

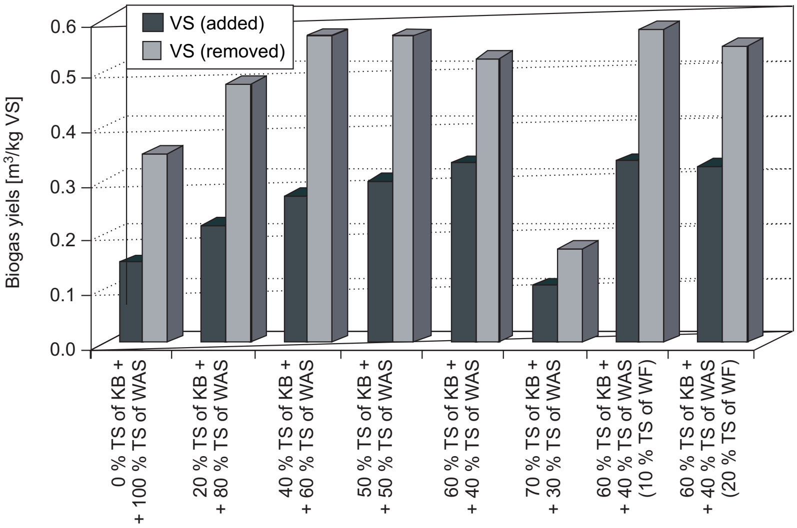

Fig. 3. Efficiency of the methane fermentation, expressed as biogas yields

process oscillates at the level of 2000 mg CH_3COOH/dm^3 [19]. The latter value was only exceeded (2600 mg CH_3COOH/dm^3) in case of a digestion run including the highest content of kitchen biowaste, ie 70 % TS. However, the accumulation, which occurred was not related to a significant decrease in pH value (7.6) – Table 4. The fact is not very unexpected, mainly because of high content of proteins in kitchen biowaste. Due to mineralization of proteins in anaerobic conditions, the ammonia concentration increases, which in turn counteracts to a some extend the decrease of pH value in spite of significant VFAs accumulation.

Table 4

Factors affecting the stability of the methane fermentation

Indicator	Digested mixtures [% TS]							
	KB:WAS						KB:WAS(WF)	
	0:100	20:80	40:60	50:50	60:40	70:30	60:40(10)	60:40(20)
pH [-]	7.8	7.9	7.8	7.9	7.9	7.6	7.9	7.8
NH_4^+ [mg/dm^3]	1370	1390	1410	1490	1870	2160	1765	1864
VFA [mg CH_3COOH/dm^3]	690	890	1030	1060	890	2600	790	815
Total alkalinity [mg $CaCO_3/dm^3$]	6182	6846	6059	6438	9865	4333	9655	9456
VFA/TA [-]	0.11	0.13	0.17	0.16	0.09	0.60	0.08	0.09

Taking into account the fact that significant changes in pH value caused by VFAs accumulation usually occurs after the collapse of the process and when the acid phase dominates in the bioreactor; a more reliable stability indicator seems to be a volatile fatty acids to total alkalinity, ie VFA/TA ratio. If the latter exceeds the threshold of 0.3–0.4, it is believed to have an inhibitive effect on the process stability and may even lead to the collapse of the biogas production [19–20].

On the basis of the – above mentioned ratio, we can figure out that the process exhibited stable conditions for digestion mixtures containing the kitchen biowaste in the range of 20–60 % TS. In case of run containing the largest kitchen biowaste proportion (70 % TS), the value of the parameter (VFA/TA = 0.60) exceeded significantly the critical value. The addition of waste foam to the optimum co-digestion mixture comprising of sewage sludge and kitchen biowaste did not deteriorate stability of the process (Table 4).

Conclusions

1. The addition of kitchen biowaste to the mesophilic digestion of sewage sludge had a positive effect on the quantity and quality of the biogas produced as well as organic matter biodegradation. The optimum kitchen biowaste proportion in digested mixtures ensuring stable conditions of the process amounted to 60 % TS, which is tantamount to 25 % if expressed as wet weight proportion. Under those conditions, the total biogas production increased more than three times and the process exhibited the greatest biogas yields.
2. The addition of a co-substrate in the form of waste foam to the optimum co-digestion mixture comprising of 60 % TS from kitchen biowaste and 40 % TS from sewage sludge did not impact the effectiveness as well as the stability of the process. Whilst the waste foam addition had a positive impact on the biogas production rate.
3. Biogas plants allows both to produce energy and utilize wastes impacting the natural environment in a negative way. Taking into account the fact that the capacity of biogas facilities at wastewater treatment plants are frequently exceeding the amount of sewage sludge treated, the introduction of additional co-substrates, eg in the form of kitchen biowaste would increase the energy balance of the facility.
4. The co-digestion of kitchen biowaste and sewage sludge may be a promising solution of their utilization. According to the European Council Directive on the landfill of waste (1999/31/EC), the member states are obliged to reduce gradually the amount of biodegradable waste deposited at municipal dump sites [21].

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OCENA PODATNOŚCI BIOODPADÓW KUCHENNYCH I OSADÓW ŚCIEKOWYCH DO KOFERMENTACJI PROWADZONEJ W WARUNKACH STATYCZNYCH

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Abstrakt: Przedstawiono wyniki badań dotyczące ustalenia najkorzystniejszego udziału selektywnie zbieranych bioodpadów kuchennych poddawanych procesowi mezofilowej fermentacji z nadmiernym osadem czynnym. Wyznaczony optymalny skład mieszaniny kofermentacyjnej miał zapewnić stabilność prowadzonego procesu w warunkach statycznych. Podjęto również próbę zastąpienia części osadu czynnego poddawanego fermentacji metanowej pianą występującą okresowo na powierzchni komory napowietrzania. Jako kryterium oceny prawidłowości doboru składu poszczególnych mieszanin substratów, zapewniającego optymalny przebieg beztlenowego procesu rozkładu substancji organicznych przyjęto: sumaryczną oraz jednostkową produkcję biogazu; stopień usunięcia suchej masy organicznej oraz stabilność procesu (LKT; LKT/Zasadowości). Wykazano, że kofermentacja bioodpadów kuchennych i osadów ściekowych wpłynęła pozytywnie na ilość i skład produkowanego biogazu oraz stopień usunięcia materii organicznej. Najkorzystniejszy udział bioodpadów kuchennych wyniósł 60 % s.m., co w przeliczeniu na udział mas odpowiadało około 25 % mas. Wykazano, że dla najkorzystniejszego składu mieszaniny kofermentacyjnej (60 % s.m. bioodpady kuchenne + 40 % s.m. osad ściekowy) uzyskano ponad trzykrotny wzrost sumarycznej produkcji biogazu, w porównaniu z ilością biogazu generowanego w procesie fermentacji metanowej osadu nadmiernego. Nie zaobserwowano również znaczącego pogorszenia stabilności procesu (LKT/Zasadowości). Zastąpienie części osadu ściekowego pianą osadu czynnego nie wpłynęło negatywnie na efektywność oraz stabilność kofermentacji bioodpadów kuchennych i osadów ściekowych. Natomiast dodatek piany wpłynął pozytywnie na dynamikę produkcji biogazu.

Słowa kluczowe: fermentacja metanowa, kofermentacja, biogaz, nadmierny osad czynny, pienienie osadu czynnego, bioodpady kuchenne