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ALGAE BIOMASS AS A CO-SUBSTRATE IN METHANE DIGESTION OF SEWAGE SLUDGE

WYKORZYSTANIE BIOMASY GLONÓW JAKO KOSUBSTRATU W PROCESIE FERMENTACJI METANOWEJ OSADÓW ŚCIEKOWYCH

A b s t r a c t

The article discusses problems related to intensification of anaerobic digestion of sewage sludge. The authors have analysed the principal indicators of a methane digestion process, focusing mainly on biogas production. The most commonly used methods of sludge disintegration were reviewed. Additionally, the methods of algae biomass processing for biofuels and a methanogenic potential of the biomass were presented. The article presents the literature review to identify the possibilities of energy profit caused by using algae in anaerobic digestion of sewage sludge.

Keywords: wastewater treatment plant, anaerobic digestion, sewage sludge, algae, co-fermentation

S t r e s z c z e n i e

W artykule omówiono problemy związane z intensyfikacją procesu fermentacji beztlenowej osadów ściekowych. Autorzy przeanalizowali główne wskaźniki procesu fermentacji metanowej, skupiając się głównie na produkcji biogazu. Zostały zweryfikowane najczęściej stosowane metody dezintegracji. Dodatkowo zaprezentowano metodę przetwarzania biomasy glonów na biopaliwa, w tym potencjał metanogenny biomasy. Niniejszy artykuł stanowi przegląd literatury i na tej podstawie podjęto próbę określenia możliwości zysku energetycznego wynikającego z wykorzystania glonów w procesie fermentacji osadów ściekowych.

Słowa kluczowe: oczyszczalnia ścieków, fermentacja beztlenowa, osady ściekowe, glony, kofermentacja

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1. Introduction

A decrease of energy use and maximisation of its production through utilisation of various types of renewable energy sources has become an important aspect of the global energy management. It is worth noting that the regulations set out by the European Union imply a growing interest in energy gained from the carbon compounds stored in cells of living organisms (i.e. energy generation from biomass). For a long time, various studies on some unconventional physical, chemical and biological methods have been carried out to intensify energy production from biomass [37].

The main goal of wastewater treatment plants is to protect the water environment from excessive pollution loads. During the wastewater treatment process, an organic fraction is separated from wastewater and transferred to the sludge, which is a by-product of mechanical-biological processes. There are three types of sludge produced at a wastewater treatment plant [8]:

- primary sludge – after a mechanical treatment,
- secondary sludge (or excess sludge) – after the biological treatment,
- tertiary sludge – precipitated in chemical processes.

Table 1

Sewage sludge production (tons of dry solids (DS)/year) in different countries of the Baltic Sea region, as submitted to the European commission, and its predicted growth [27]

Country	2005/2006	2010	2020
	[tons of DS/year]	[tons of DS/year]	[tons of DS/year]
Belarus	50 000	50 000	70 000
Denmark	140 021	140 000	140 000
Estonia	n/a	33 000	33 000
Finland	147 000	155 000	155 000
Germany	2 059 351	2 000 000	2 000 000
Latvia	23 942	25 000	50 000
Lithuania	71 252	80 000	80 000
Poland	523 674	520 000	950 000
Russia	180 000	180 000	200 000
Sweden	210 000	250 000	250 000
Total	**3 405 240**	**3 433 000**	**3 928 000**

Sludge produced during treatment of municipal wastewater at new wastewater treatment plants amounts to 0.5–2% of the wastewater volume [45]. Table 1 shows the amount of sewage sludge produced by individual countries of the Baltic Sea region. It is estimated that the production of sludge would continue to grow in some countries, which translates into a global increase [27]. Therefore, a special attention should be paid to a sewage sludge digestion as a source of biogas of a high calorific value, which can satisfy the wastewater treatment plant energy needs.

2. Methane digestion of sewage sludge

Methane digestion is the most popular method of sludge stabilisation. It utilises a biochemical decomposition of organic compounds at different oxidation stages to methane and carbon dioxide using microorganisms (bacteria). A proper balance between the substrate and bacteria, mainly methanogenic ones, is the important condition for a good degradation of organic matter in sludge and wastewater. Table 2 shows the key parameters of a mesophilic anaerobic digestion. Decomposition of organic compounds can be divided into four main phases [10]:

- phase I – hydrolysis,
- phase II – acidogenesis,
- phase III – acetogenesis,
- phase IV – methanogenesis.

Table 2

Parameters of mesophilic anaerobic digestion [29]

Parameters	Optimal value	Range
Temperature [°C]	30–35	20–40
pH	6,8–7,4	6,4–7,8
Redox potential [mV]	– 520 do –530	–490 do –550
Volatile organic acids [mgCH_3COOH/dm^3]	50–500	>2000
Alkalinity [mg$CaCO_3$/dm^3]	1500–3000	1000–5000

Table 3

Sludge chemical composition (average values) [19]

Compounds	[%]		
	Raw primary sludge	**Raw activated sludge**	**Digested sludge (mixed)**
Volatile solids (VS)	60–80	60–75	45–60
Inorganic (fixed) solids	20–40	25–40	40–55
Proteins	20–30	30–40	15–20
Fats	6–35	5–12	3–20
Cellulose	5–15	5–15	5–15

Chemical composition of organic compounds, which are broken down by microorganisms under anaerobic conditions, determines the amount and the type of the end product. A caloric biogas is produced as a result of a methane fermentation of organic compounds. It is a blend of different constituents mixed in different proportions. At the optimum conditions, the biogas contains 60–70% of methane, 29–39% of carbon dioxide and 0.1–0.7% of hydrogen sulphide [22]; its content depends essentially on the nature of the substrate decomposed in the digester, i.e. sludge (Table 3). The best gas quality (the highest methane content) comes from decomposition of proteins, while a highest gas volume is obtained from fat digestion [34]. The gas yield in a digestion process is associated with a treatment process at the wastewater treatment plant [1]; from 0.75 to 1.12 m^3 of biogas can be produced from 1 kg of volatile solids [30].

Disintegration of thickened sludge before its anaerobic digestion is considered to be an interesting option that could improve the efficiency of a methane digestion. Disintegration causes a breakdown of sludge flocs (microbial cells) leading to the release of intracellular fluids to a liquid phase. This way, they become more accessible for further biological wastewater treatment and sludge processing [8]. Implementation of sludge disintegration ahead of anaerobic digesters (WKF) results in a higher biogas yield, and a higher loss of organic matter in the digested sludge are observed, in comparison with conventional systems.

Table 4

Disintegration methods

<table>
<tr><th colspan="2">Mechanical</th><th colspan="3">Others</th></tr>
<tr><td rowspan="3">Mills</td><td>Ball mills</td><td rowspan="4">Physical</td><td rowspan="2">Thermal</td><td>Drying</td></tr>
<tr><td>Pulveriser</td><td>Freezing/defrosting</td></tr>
<tr><td>Vibrating ball mill</td><td>Osmotic</td><td>Decompression</td></tr>
<tr><td rowspan="3">Homogenizer</td><td>High pressure homogenizer</td><td>Electric</td><td>Highly efficient impulse technique</td></tr>
<tr><td>Ultrasound homogenizer</td><td rowspan="3">Chemical</td><td colspan="2">Osmotic shock</td></tr>
<tr><td>Scissor homogenizer</td><td colspan="2">Disintegration with detergents</td></tr>
<tr><td rowspan="3">Press</td><td>Ball press</td><td colspan="2">Disintegration with acids</td></tr>
<tr><td>Stream press</td><td rowspan="3">Biological</td><td colspan="2">Enzymatic decomposition</td></tr>
<tr><td>Vibration press</td><td colspan="2">Hydrolysis</td></tr>
<tr><td>Centrifuge</td><td>Hydrolytic centrifuge</td><td colspan="2">Bacteriophages</td></tr>
</table>

Only excess sludge is subjected to disintegration due to a higher rate of biogas production. Primary sludge, produced during a mechanical wastewater treatment, has a different structure. It comprises mainly of easily settling solids that contain a large amount of pathogenic organisms and quickly decompose. On the other hand, excess sludge subjected to an aerobic biological decomposition with no readily available carbon source, is resistant to any kind of treatment [9, 17].

Disintegration of the sewage sludge can be carried out using different techniques. Depending on the nature of a disintegrating agent, the disintegration methods can be divided into four basic groups (Table 4) [11]:

- mechanical,
- thermal,
- chemical,
- biological.

The most promising sludge disintegration methods include mechanical methods, mostly the ultrasound method, which has recently become available and widely used [8].

Co-fermentation, which combines at least two types of organic matter in anaerobic digestion, is another method used to intensify a biogas production from sewage sludge. As a result, a higher gas yield or a higher efficiency of a digestion process is observed [5]. Recently, a wide range of plant biomass has been used as a popular co-substrate in order to intensify a fermentation process.

3. Co-digestion of sewage sludge and algae biomass

Algae are simple, autotrophic (microalgae) or multicellular (macroalgae) organisms. They are found in fresh and brackish water, both cold and warm [15]. In order to grow, they need mostly light, carbon dioxide, water and mineral salts [44]. Each species has a different morphology and properties. The size of the organisms depends on the species and ranges from microscopic microalgae to macroalgae that can have several tens of meters [20]. Algae absorb CO_2 (2 kg CO_2/kg of DS) [23] and this way reduce its emission to the atmosphere [2]. Their cells are rich in such elements as carbon nitrogen, phosphorus, iron, cobalt and tin, which have a stimulating effect on anaerobic digestion. Water, as the main component of the algal biomass, amounts to approx. 75–90% of their wet weight. Algae contain also a significant amount of mineral salts and carbohydrates (30–50%), which make up the bulk of their dry matter (approx. 60%); proteins represent approx. 7–15% of algae dry matter [18].

Table 5

Methane volumes produced during anaerobic digestion of different substrates (30 days of mesophilic digestion) [21, 25]

Substrate	Methane volume [m^3/kg DS]
Municipal waste	0,20–0,53
Sewage sludge	**0,25–0,75**
Fruits and vegetables	0,42
Jatropha oil	0,42
Pig manure	0,34
Corn and straw silage	0,31
Microalgae	**0,26**
Organic waste reach in lignin	0,20

Another important feature of these organisms is their ability to acquire nutrients. Therefore, algae can be grown on wastewater, and this way, two beneficial effects are combined: treatment of wastewater and production of biomass for energy purposes [38]. Various types of biofuels can be produced from algae (Fig. 1). A biodiesel production yield obtained from these organisms was 15–300 times higher than using oil from traditional crops [46]. In addition, algae biomass can help to solve the problem of competition between crops grown for consumption and energy production; the algal biomass can be seen as one of the most promising fuels for the future (Table 5) [42].

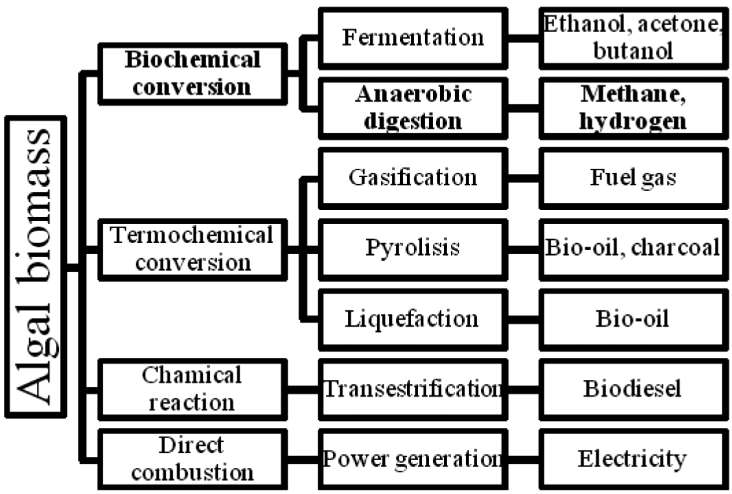

Fig. 1. Algal biomass conversion processes [26]

Table 6 shows the volumes of methane produced from the various algae species. It has been shown that the methane production from algae biomass can exceed by 2 to 20 times a production yield from conventional crops. These organisms can double their biomass during a day [3]. Additionally, small and insignificant amount of lignin present in the organisms is more easily degradable if compared to regular plants, so primary treatment of biomass before its digestion is not required. Therefore, use of algae as a co-substrate in methanogenesis may enhance the process efficiency and increase the volume of biogas produced from sewage sludge [31].

The carbon to nitrogen ratio (C N) is an important indicator of a methane digestion, which defines to what extend carbon and nitrogen are available in the feed. For example, for popular plants, the average C/N ratio is 36, while for algae 10.2 [26]. A low C/N ratio enables a nitrogen release and then its accumulation in the form of ammonium ions (NH_4^+). On the other hand, the high level of ammonium ions during the digestion process leads to a pH increase, which becomes toxic for the bacteria carrying on the digestion process [6]. Therefore, while using algae as a co-substrate supporting a sewage sludge digestion, a particular attention should be paid to the right selection of species (are relatively high C/N ratio) and a proper sludge composition (a high carbon content) [31].

Table 6

Methane production from different algae species [26]

Species	C/N	Temperature [°C]	Methane volume [m³/kgVS.]	HRT
Scenedesmus spp. *Chlorella* spp., mixed, harvested from natural lagoon	–	35	0.31	30
*Scenedesmus*spp., *Chlorella* spp., mixed, harvested from natural lagoon	–	50	0.32	30
Spirulina maxima	4.2	35	0.31	20
Nondefined mixed culture dominated by *Chlorella*	–	34	0.35	14
			0.44	25
			0.60 (biogas containing 40–65% methane)	45
Nondefined mixed culture dominated by *Chlorella*	–	41	0.28–0.35	14
			0.39–047 (biogas containing 40–65% methane	25
Scendesmus spp. and *Chlorella* spp.	6.7	35	0.10–0.14	10
Non-axenic culture of *Scendesmusobliquus*	–	33	0.21	30
Non-axenic culture of *Phaeodactylumtricomutum*	–	33	0.35	30
Non-axenic culture of *Scendesmusobliquus*	–	33	0.13	22
		54	0.17	
Non-axenic culture of *Phaeodactylumtricomutum*	–	33	0.27	22
		54	0.29	
Chlorella vulgaris	6	35	0.24	28
Chlorella vulgaris	6	35	0.147	16
Arthrospira platensis	–	38	0.293	32
Chlamydomonasreinhardtii	–	38	0.387	32
Chlorella kessleri	–	38	0.218	32
Dunaliellasalina	–	38	0.323	32
Euglena gracilis	–	38	0.325	32
Scendesmusobliquus	–	38	0.178	32
Microcystis sp. from Taihu lake	6	35	0.201	30
Microcystis sp. from Taihu lake	–	35	0.14	30
Unknown species	–	30	929–1294 ml of biogas	28
Chlorella vulgaris	–	37	0.286	49
Dunaliellatertiolecta	–	37	0.024	49

Since sewage sludge has a relatively high carbon content and includes various types of active microorganisms, it should produce, in combination with the algal biomass, biogas of a satisfactory volume and quality in anaerobic digestion. The presence of sludge improves algae digestion [43]. Several studies have been carried out on this combined biomass. Golueke and Oswald in their paper [16] showed that the biodegradation rate for algae biomass was up to 60–70% lower than for sludge. They also pointed out at some of the process constraints due to high pH, ammonia toxicity or algal cells resistance. Therefore, while estimating the fermentation process potential, one has to focus mainly on a cell composition. The change in the cell content can change the fermentation efficiency. The content of proteins, fats and carbohydrates depends on the algae species and environmental conditions. However, fats play the most important role in anaerobic digestion, so the more fat is in the biomass, the more effective the fermentation process becomes. Morandi and Briand [32] reported that fermentation of green algae resulted in methane production of 0.2 $m^3 \cdot kg^{-1}$, while fermentation of kelp by Chynoweth [7] produced 0.39–0.41 m^3 of methane per kg. Microalgae also have a high potential. Singh and Gu [36] showed that the biogas produced from microalgae contains 55–75% of methane, so it is more caloric then other plant substrates. Studies on the *Macrocystis pyrifera* and *Durvillea Antarctica* species demonstrated that biogas production from algae in a two stage anaerobic digestion system reaches 180.4 ml/g dry weight of algae and the methane concentration in the biogas is approximately 65% [24]. The test was also conducted on a mixture of these species of algae in a 1:1 by weight. Observed lower production of biogas, but the methane content was comparable [39]. In the world studied the use of such algal species as: *Macrocystis pylifera*, *Sargassum*, *Laminaria*, *Ascophyllum*, *Ulva*, *Cladphora*, *Chaetomorpha*, *Gracilaria* for compost and biogas production [13].

Samson and Leduy [35] found that the addition of primary sludge (50% of VS) increases by 2.1 times efficiency of digestion of *Spirulina maxima* blooms. In turn, Cecchi et al. [5] studied the co-digestion of sewage sludge and macroalgae in mesophilic conditions. Studies have shown that the addition of macroalgae in an amount of about 30% by dry weight resulted in methane production comparable to the one observed for sludge digestion. Dębowski [14], in his experiments, inoculated samples of algae (mixed species) from the Vistula Lagoon with 200cm^3 of digested sludge. The average biogas production yield was 420.95 ± 0.95cm^3/g VS at a methane content of 71.37 ± 0.4949%.

Mahdy et al. [28] examined the mesophilic digestion of *Chlorella vulgaris* species with sludge (after thermal disintegration). In the samples, co-substrates were mixed in algae to sludge percentage ratio of 75/25, 50/50 and 25/75.The results show (Table 7) that, after 25 days of digestion, more biogas was produced from mixed samples than from sludge samples. The highest gas volume, 225.1 ml/1g COD, was observed in samples containing 75% of algae and 25% of sludge. Also Costa et al. [12] observed an increase of methane production by 26% while studying *Ulva* and *Gracilaria* species in combination with sludge in mesophilic conditions.

Also Wang and Park [41] analysed sludge with two algae species – *Micractinium* and *Chlorella.* The samples were mixed at an algae to sludge percentage ratio of 21/79. Table 8 shows the results after 20 days of anaerobic digestion at 35°C. As it can be seen, once algae were added to sewage sludge the digestion efficiency increased and more biogas was produced.

Table 7

Biogas and methane volumes produced during methane digestion of *Chlorella* species [28]

Chlorellavulgaris	Excess sludge	Biogas volume [ml/1g COD]	CH_4 [ml/1g COD]
100%	0	266.7	180.0
75%	25%	225.1	155.3
50%	50%	208.5	135.2
25%	75%	157.8	115.0
0	100%	80	136.1

Table 8

Biogas and methane volumes produced during methane digestion of *Micractinium* and *Chlorella* species [41]

Substrate	Biogas volume [dm^3/kg VS.]	CH_4 [dm^3/kg VS.]
Chlorella	415	230
Micractinium	378	209
Chlorella + sewage sludge	431	253
Micractinium + sewage sludge	418	236
Sewage sludge	391	243

Olsson et al. [33], in their studies, also confirmed the ability of algae to improve the efficiency of a sludge methane digestion in mesophilic conditions. However, they also proved that the presence of algae in thermophilic conditions has an adverse effect on biogas production. The same conclusions were reported by Caporgno et al. [4] in the studies on *Isochrystis galbana* and *Selenastrum capricornutum* species; using these specimens as a co-substrate in thermophilic conditions the authors observed a drop of a biogas production by 40.5% and 31.7%, compared to the digested sludge samples.

The authors started respiration studies on excess sludge from a municipal wastewater treatment plant and selected fresh water algae in the laboratory of the Cracow University of Technology. During the initial stage of the research, different types of algae were identified and selected. The samples include the algae from the group of green algae (Fig. 2) – *Spirogyra*, *Oedogonium*, *Tabellaria*, *Mougeotia* and *Pleurotenium*. Then, between January and April 2015, a 3 series of runs on excess sludge were conducted. The objective of the study was to determine to what extend the sludge under goes biochemical decomposition. It was found that a biogas production ranged from 0.46 to 0.66 m^3/kg VS (60–70% CH_4) at the mesophilic conditions. These measurements will serve as an introduction to further research on co-digestion of sewage sludge and algae biomass.

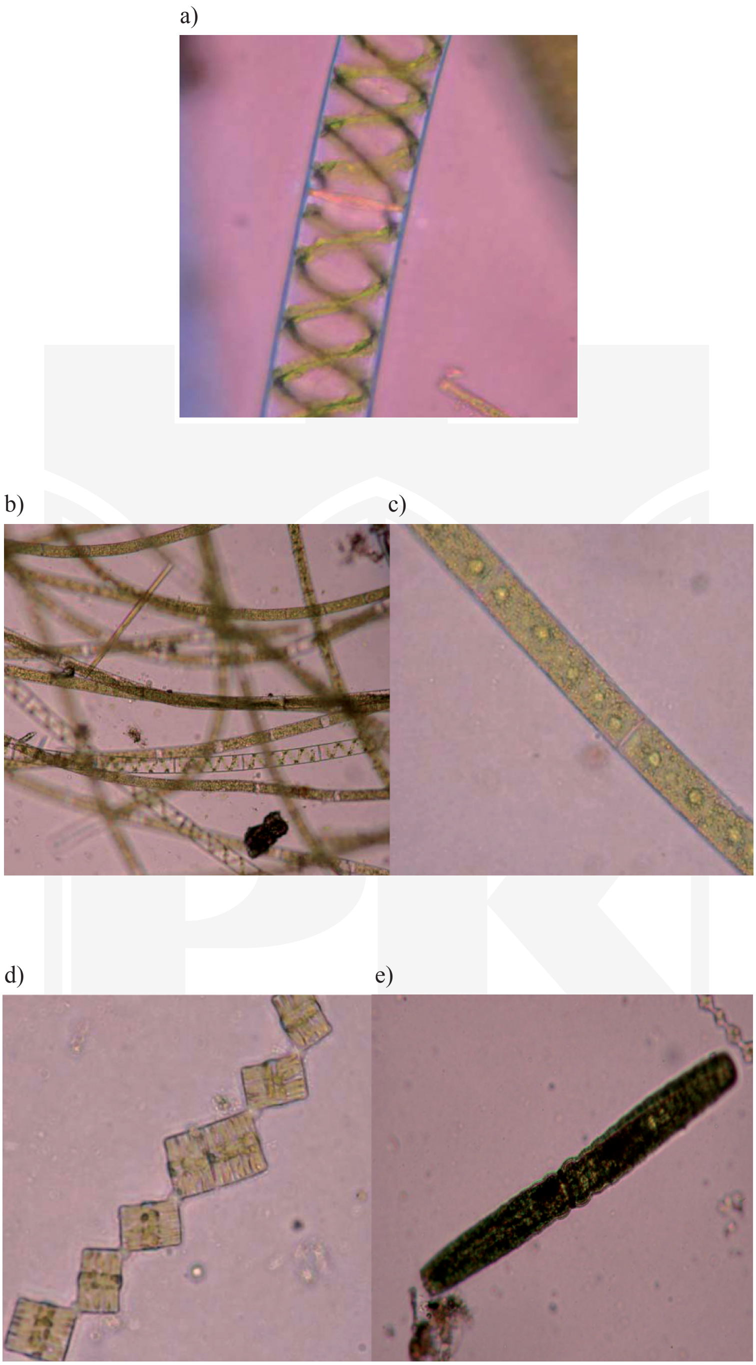

Fig. 2. Microscopic photos of algae by T. Woźniakiewicz: a) *Spirogyra*, b) *Oedogonium*, c) *Mougeotia*, d) *Tabellaria*, e) *Pleurotenium*

4. Conclusions

1. The literature review confirmed a need for new renewable sources of energy. Energy from organic biomass can be one of future carbon sources.
2. Algae and sewage sludge can serve as a convenient source for energy production. A rapid growth of algae and their ability to absorb nutrients are very advantageous features, and therefore, algae can serve for both energy production and wastewater treatment. Since the amount of sewage sludge (organic matter) produced during a wastewater treatment process will increase, in perspective, the need for sensible use of such organic matter becomes urgent.
3. Co-digestion of sludge and algae biomass is one of the methods used for intensification of an anaerobic sludge digestion, apart from sludge disintegration. The analysis of the literature data suggests that the use of algae as a co-substrate in a sewage sludge digestion increases a biogas yield and then improves the efficiency of an anaerobic digestion in mesophilic conditions.

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