

Potential of the Co-Digestion of the Sewage Sludge and Plant Biomass on the Example of Lviv WWTP

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ABSTRACT

Energy strategies of most developed countries include the sustainable development of all types of renewable energy, including energy generation from biomass. Co-digestion of sewage sludge and plant biomass has a number of synergetic effects, leading to increased digestion rate and output of biogas. The range of potentially effective co-digestion of sewage sludge with plant raw materials was considered on the example of the full-scale estimation study for Lviv WWTP, Ukraine. Substitution of the 25% of dry organic matter of sewage sludge by the same amount of plant raw matter can increase the total output of the methane at the biogas station by about 5.8%.

Keywords: biogas, biomass, co-digestion, methane output, plant raw material, sewage sludge.

INTRODUCTION

The problems of ecological and energy security as well as their interconnection are particularly relevant in the light of sustainable development strategies for all countries of the world. Solving the problems of carbon-containing waste utilization with obtaining renewable energy makes it possible to tackle both environmental and energy security problems.

A promising way to utilize solid wastes is pre-selecting the organic carbon-containing component from them and subsequently using it to produce energy. The most commonly employed methods of energy production are the combustion or production of biogas. In order to achieve the optimum conditions for biogas production and maximize its output, a prerequisite is to supply biogas plants with a balanced raw material composition. This can only be achieved by balancing

this composition with different types of raw material constituents and organizing the co-digestion of the raw material mixture.

The most promising to use in the composition of the raw material mixture for biogas plants are: agricultural waste, food waste, organic municipal waste, livestock waste, activated sludge, microalgae, hydrobionts, etc. Due to the large amount of plant raw materials in Ukraine, using it as a component of a raw material mixture for biogas plants is of specific importance from the point of view of ensuring both environmental and energy security.

The prospects for intensive development of biogas production in Ukraine using plant organic raw materials are conditioned by two factors:

- 1) need to provide environmentally friendly methods of disposal of plant raw material;
- 2) urgent need to strengthen Ukraine's energy base through the development of renewable energy sources, including bioenergy.

Regarding the first factor, it should be noted that the underdevelopment of environmentally safe ways of utilizing raw plant materials has created one of the serious sources of environmental danger in Ukraine.

The National Waste Management Strategy in Ukraine by 2030 and the National Waste Management Plan in Ukraine by 2030 are aimed at addressing this danger. These documents, in turn, serve as guidelines for the development of regional waste management plans and strategies for all regions of Ukraine.

According to the National Waste Management Strategy in Ukraine, significant amounts of wastes accumulated in Ukraine and the absence of effective measures aimed at preventing their generation, utilization, neutralization and removal, exacerbate the environmental crisis and become a brake factor on the development of the national economy. The only possible way to resolve the situation is to create a comprehensive waste management system. Solving the problem is key in addressing the issues of energy and resource dependency of the state, saving natural material and energy resources, and an urgent strategic task (priority) of national policy.

Organic wastes from livestock farms are used widely to produce biogas. At the same time, it has been proven that plant organic raw materials, food wastes, organic municipal wastes and municipal sewage sludge are also effective for biogas production. The co-digestion of organic raw materials is the subject of a detailed scientific study over the past few decades. The analysis of research papers shows that in order to increase the digestion rate and output of biogas, it is expedient to use the co-digestion process of the above mentioned types of raw materials.

MATERIALS AND METHODS

The purpose of the paper was to analyze the potential efficiency of the co-digestion of sewage sludge and different types of plant matter at the example of Lviv wastewater treatment plant (WWTP), Ukraine. A number of experimental results on co-digestion of sewage sludge with different types of organic matter were analysed. The numerical method of modelling was used to find the dependency of potential increasing of methane output at biogas station of Lviv WWTP as a function of the plant biomass content.

RESULTS AND DISCUSSION

Scientific and practical aspects of biogas production from different types of raw materials and their combinations continue to be an urgent worldwide research problem, both in the field of renewable energy sources and from the ecological point of view (Szczyrba et al., 2020; Voytovych et al., 2020; Wehner et al., 2018). Concerning the issues of environmental safety, by far the most urgent for Ukraine is the solution of the problems related to utilization of household (Popovych et al., 2018) and industrial (Karabyn et al., 2018) wastes, wastewater treatment from petroleum products (Zelenko et al., 2019), heavy metals (Malovanyy et al., 2019a), highly concentrated ammonium contaminants (Malovanyy et al., 2019b). Biological (Blyashyna et al., 2018), reagent (Tulaydan et al., 2017) and adsorption methods have become most widely used for the treatment of wastewater from these contaminants.

An important factor is also the qualitative composition of biogas, which is largely dependent on the composition of the mixture (Pospelov et al., 2018). High efficiency of the co-digestion process of different types of organic raw materials was proven by Hardegen et al., 2018; Kim et al., 2013; Muenmee, 2021, etc. Generally, co-digestion increases the digestion rate and output of biogas. A certain effect of co-fermentation is observed in the cultivation of microalgae in sewage municipal waters with subsequent processing in biogas plants (Thorin et al., 2017). Such studies require further search for optimum regimes and conditions for the formation of new synergetic components of organic raw materials and methods for their biological processing.

Studies on the use of cyanobacteria for lipid extraction and biogas production by methanogenesis were presented by (Malovanyy et al., 2016). In order to intensify the biodecomposition of the biomass, the authors suggested that hydrodynamic cavitation of the biomass should be carried out beforehand. Experiments on the production of biogas from cyanobacteria have confirmed that pre-treatment with cavitation using a hydrodynamic cavitation field destroys the cell walls of cyanobacteria, since the production of biogas from such algae was much more complete. The results of the analysis of these studies showed that the intensity of biogas output is approximately the same for all samples, whereas the amount of biogas synthesized is significantly higher (40%)

when using cyanobacteria pre-treatment in the hydrodynamic cavitation field. The application of pre-concentrated cyanobacteria allows them to be used as a component of the raw material mixture of biogas plants, and the purification of waters from cyanobacteria significantly reduces the level of environmental risk from their uncontrolled development in the waters of artificial reservoirs of Ukraine (Nykyforov et al., 2016).

The results of a two-stage co-fermentation of sewage sludge (SS) and rice straw (RS) were analysed by Sawasdee & Pisutpaisa, 2015. Co-fermentation was used for the combined production of methane (CH_4) and hydrogen (H_2) in batch type digesters. The obtained results were compared with the one-stage fermentation system of these substrates for methane production. First stage of co-fermentation process of raw SS and untreated RS resulted in high enough yield of hydrogen (up to 21 dm^3 per 1 kg of VS) with considerable content of H_2 (60.9%). Second stage of co-fermentation showed both an increased biogas production ($266 \text{ dm}^3/(\text{kg VS})$) and especially high methane content of about 75–80%. Total energy production by this two-stage process reached $8.8 \text{ MJ}/(\text{kg VS})$, which is 59.6% more comparing to an analogical one-stage process. The decrease of the VS content in the mixture reached the value of 60.4% or 37.9% more, than in one-stage case. Such results are explained by synergetic effect of two processes realized in series.

Two-stage reactors for the co-digestion are recommended by (Jiang et al., 2009) to increase the biogas production and to improve the quality of the digestate as an organic fertilizer. Co-fermentation of the straw with WWTP sewage sludge was found to be useful to improve the C/N ratio in the organic mixture. The best results were obtained using the pre-treatment of the straw by sodium hydroxide and sewage sludge content of 5%. Duration of the start-up period was about 39 days. Decreasing of total solids was 54% in the first digester and 67% in the second reactor, while decreasing of volatile solids – 65% and 75%, respectively.

Other types of plants for co-fermentation of sewage sludge, which give better results in increasing the output of methane, were recommended in papers (Yang & Li, 2014; Sawasdee & Pisutpaisa, 2015). This suggests that the life of methane-forming bacteria still is not known completely and there is an actual need for further knowledge and experience accumulation in order to better use their potential.

The co-fermentation idea was deeply tested by (Sadecka et al., 2013) providing a list of types of organic raw materials, mode parameters, establishment of the corresponding particle co-substrates, a method for preparing the substrate of sewage by hydrolysis in order to disintegrate it. The authors paid special attention to the negative impact on microorganisms responsible for the process of fermentation of various inhibitors. Inhibitors are present in raw materials fermented or formed as intermediate products of transformation. Their presence may lead to reduction in biogas production, and in extreme cases to complete inhibition of the process. The toxic effects of various compounds depend on the concentration, the form of occurrence and the co-occurrence of other substances. This issue is important in the case of co-substrates which are wastes. The factors that inhibit the sewage sludge fermentation process are well-recognized, while the issues of toxicity in co-fermentation are not clearly defined. Authors dealing with the processes of anaerobic decomposition of organic substances draw attention to the toxic effect of heavy metals and some issues depending on their concentration.

Many researchers pay great attention to preparation of raw materials in order to increase the surface of mass transfer to enable biochemical processes. This ultimately increases the rate of co-fermentation and biogas output. A promising method of digestion process intensification is the pretreatment of raw biomass, in particular grinding and delignification (Barbash et al., 2010; Sklyar & Sklyar, 2014). The degradation of the lignin net, the extraction of lignin and most of hemicelluloses, as well as the break of chemical bonds between lignin and carbohydrate molecules occur in the delignification process at elevated temperatures. This leads to an increase in the mass transfer surface that becomes available for cellulolytic enzymes of microorganisms. As a result of grinding the substrate on the grinding equipment, there is also a significant increase in the mass transfer surface available for enzymes of microorganisms. This speeds up enzymatic hydrolysis and intensifies the process of biogas production (Nesterov et al., 1973). According to (Qian, 2014) lignocellulosic biomass can be considered a consistently renewable natural resource in terms of efficiency in economy. The most promising for biogas is the lignocellulosic biomass contained in agricultural and forestry wastes such as maize cobs, fallen leaves and wood chips, straw etc. Such biomass can be qualified as promising due to the fact that in aforementioned wastes

it causes no food sources and animal feed exhaustion (Ishizaki & Hasumi, 2014). It has been studied that typically, lignocellulosic biomass can include from 20% to 50% of such components as cellulose, hemicellulose and lignin and the content percentage varies based on the material chosen (Binod & Pandey, 2015). Yet it has been revealed that cellulose and hemicellulose are layered firmly within lignin what makes the enzyme digestion process more problematic for cellulose that is located in lignocellulosic biomass (Mosier et al., 2005). In order to create favourable conditions for the enzyme hydrolysis process of cellulose, it is necessary to destroy lignin layers, reveal cellulose and hemicellulose, hence improving the yield of sugars during cellulose and hemicellulose fermentation. This can be achieved with the help of the pre-treatment process (Ishizaki & Hasumi, 2014; Mosier et al., 2005; Kumar et al., 2009). It has been studied that many methods can be used for biomass pre-treatment. These methods can range from biological to mechanical and combined and this matter has recently been the subject of study among many researchers (Kumar et al., 2009). A number of approaches for the implementation of cavitation treatment of biomass, while minimizing the energy consumed and maximizing the release effect of the mass-exchange surface available for implementation of biochemical processes were considered by (Wu et al., 2019).

As a result of the review, the main quantitative parameters characterizing the composition and efficiency of anaerobic fermentation of plant biomass widespread in Ukraine are obtained (Table 1).

Modelling of the potential effectiveness of plant organic raw materials co-digestion with sewage sludge was considered on the example of the full-scale Feasibility Study for Lviv WWTP (Project of Reconstruction, 2014). The Feasibility Study was based on such assumptions for mono-digestion of sewage sludge: specific methane output is 325 Nm³ per tonne DOM, total amount of dry solids in sewage sludge – 120 t/day, total content of DOM in sewage sludge – 84 t/day, carbon-to-nitrogen ratio is equal to $(C/N)_{ss} = 10$.

Estimations of the actual capacity of Lviv WWTP as of 2021 indicate that there is a real risk of regular deficiency of sludge dry matter in the range of 20–25%, compared to the indicative value. Modelling of the partial substitution of the organic matter of wastewater sludge with plant biomass was fulfilled. Average carbon-to-nitrogen ratio for plant raw matter (PRM), containing the mixture of straw, grass, wood chips and leaves was estimated as $(C/N)_{prpm} = 50$. It was assumed that in the co-digestion process, the concept concerning the weighted average values of the specific methane output and C/N ratio can be

Table 1. C/N ratios of plant biomass and the specific yield of methane during its anaerobic fermentation

N	Type of plant biomass	C/N*	Specific methane output, m ³ /t DOM**	Source
1	Straw	71	330	(Zhong et al., 2012)
		48–150	300	(Sadecka et al., 2013)
2	Grass	12–25	440	(Sadecka et al., 2013)
3	Leaves of trees	20–60	300–350	(Sadecka et al., 2013)
4	Sugarcane leaves	67.4	360	(Luo et al., 2018)

* C/N = carbon-to-nitrogen ratio; ** DOM = dry organic mass.

Table 2. Estimation of the potential effectiveness of sewage sludge and plant organic raw materials co-digestion in the biogas station of Lviv WWTP

Plant raw matter, %	C/N	Specific methane output, Nm ³ /t DOM	Methane output, m ³ /day	Methane output, increasing, %
0	10	325.0	27300	–
2	10.8	326.5	27426	0.46
4	11.6	328.0	27552	0.92
6	12.4	329.5	27678	1.38
8	13.2	331.0	27804	1.85
10	14	332.5	27930	2.31
15	16	336.3	28245	3.46
20	18	340.0	28560	4.62
25	20	343.8	28875	5.77

used. Main results of the numerical modelling are presented in Table 2.

The estimated methane output of the biogas station at Lviv WWTP could be increased using the co-digestion of sewage sludge with plant raw materials up to almost 28,900 Nm³/day or by 5.8% comparing the baseline value 27,300 Nm³/day, declared in a Feasibility Study (Project of reconstruction, 2014). The effect of the full-scale application of such type of the co-digestion process can be even higher than predicted due to the synergetic effect of sewage sludge and plant organics, optimization of the C/N ratio, achievement of the optimum moisture content etc. Real efficiency of co-digestion process using the different types of plant raw materials should be specified on the pilot scale digester, installed at the Lviv WWTP in 2015 as part of an international Ukrainian and Poland project “Biogas production in wastewater treatment plant – support for the Lviv City program”.

CONCLUSIONS

Co-digestion of sewage sludge with different types of plant raw materials has been the subject of a detailed scientific study over the past decades. The review of up-to-date studies proves that plant raw materials are especially effective for the biogas generation when they are co-digested with municipal sewage sludge. Co-digestion has a number of synergetic effects, leading to the increase of the digestion rate and output of biogas.

The potential of co-digestion of sewage sludge with plant raw materials was considered on the example of Lviv WWTP, Ukraine. Estimation of the actual capacity of Lviv WWTP as of 2021 indicates that there is a real risk of regular deficiency of sludge dry matter in the range of 20–25% compared to the indicative value 120 t/day, stated in the feasibility study of the biogas station project.

The dependency of potential increase of methane output at biogas station of Lviv WWTP as a function of mass content of plant raw matter was obtained using the numerical modelling. Substitution of the 25% of dry organic matter of sewage sludge by the same amount of plant raw matter can increase the total output of methane at the biogas station by about 5.8%. The actual efficiency of the co-digestion process using the different types of plant raw materials will be specified using the pilot scale digester.

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