BIOGAS POTENTIAL FROM CO-FERMENTATION OF FOOD LEFTOVERS AND LIGNOCELLULOSIC BIOMASS AT MESOPHILIC TEMPERATURES

Indulis Straume, Imants Plume, Vilis Dubrovskis, Viktors Dreimanis, Eriks Zukovskis
Latvia University of Life Sciences and Technologies, Latvia
indulis.straume@lbtu.lv, imants.plume@lbtu.lv, vilisd@inbox.lv,
viktorsdre@gmail.com, eriks.zuk@gmail.com

Abstract. Every year, large amounts of food leftovers are thrown away in catering establishments and households. Industry and agriculture produce lignocellulosic residues, including paper dust and willow biomass, which cause environmental problems if not properly disposed of. The aim of this study is to investigate the biogas and biomethane yields of these biomasses during anaerobic co-fermentation under mesophilic conditions. Biogas yields were determined by co-fermentation of food (hospital canteen, cafeteria, and household) residues and lignocellulosic (paper dust and shredded willow) biomass in a number of 0.72 L bioreactors. All bioreactors were divided into groups having the same content in reactors within each group to ensure the reliability of the results. Groups of bioreactors used for anaerobic fermentation were inoculums (0.5 L) only, inoculums with individual biomass, and inoculums with mixture of two or more biomass. Bioreactors were placed in three different thermostats with 16 bioreactors in each thermostat. Single fill batch anaerobic fermentation (AF) process was provided at 28, 33 and 38 ºC. Individual reactor groups were equipped with graphite electrodes connected to DC voltage of 0.7 V. The biogas released in the bioreactor was collected into a gas bag outside the reactor. AF was maintained until gas emission ceased. The highest biogas yield in the AF process was obtained from the bioreactors at a temperature of 38 ºC and the lowest at a temperature of 28 ºC. Co-fermentation of biomass increased biogas and methane yields compared to AF treatment of individual biomasses. Exposure to the electric field decreased the methane yield. The energy balance on the AF process with the application of the electric field should be calculated by considering also the energy of hydrogen released from substrates with electrodes installed.

Keywords: food leftovers, paper waste, lignocellulose, anaerobic co-fermentation, biogas.

Introduction

There are lots of food waste and leftovers in the world. It is estimated that in developed countries, such as the USA, Germany, food waste per capita per day is respectively 0.51 and 0.34 kg, and in poor countries, such as Vietnam, Nigeria – 0.06 and 0.1 kg, respectively [1].

Studies have found that adding food waste to sludge of sewage treatment plants accelerates the methane production process, increases its yield, and also increases the degree of degradation of organic solids (if it is in the range of 38-57% for sludge, then for a mixture with food waste it can already reach 85%) [2; 3].

Food waste is well suited for biogas production, as it usually contains around 73% biodegradable mass. University and hospital [2] canteen food waste can have a low C:N ratio, with pH typically in the range of 4.42-6.80 [3].

Fermentation of food and paper waste has been carried out by several researchers [4; 5]. In the dry fermentation process, when the concentration of total solids was varied from 14 to 20%, the best results were achieved at 14% and feed material to yeast ratio (S/I) of 0.5 – fermenting food waste 402 $mL_{CH4}\cdot g_{VS}^{-1}$ and fermenting paper waste 229 $mL_{CH4}\cdot g_{VS}^{-1}$ [4]. By co-fermenting cattle slurry with different types of cardboard products – 29.6% corrugated cardboard, 62.5% cardboard packaging and 7.9% other cardboard. Co-fermentation of food waste with cattle manure in 4-liter bioreactors produced biogas with a methane content of 62.7% and a specific methane yield of 0.306 $m^3\cdot kg_{VS}^{-1}$, which was achieved with a ratio of food waste and cattle manure of 60:40 and an organic load of 4 kg $(m^3\cdot d)^{-1}$. In co-fermentation of food waste with cardboard in 4-liter bioreactors, the maximum value of the specific methane yield was at an organic load of 3 $kg\cdot(m^3\cdot d)^{-1}$ – 0.315 $m^3\cdot kg_{VS}^{-1}$ [5].

The use of electricity in promoting the potential of biogas has taken place in different directions – starting with the use of a pulsed electric field in the pre-treatment of the input material [6] and ending with the placement of microbial electrolysis cells (MEC) in the bioreactor itself [7; 8]. Methane productivity from pulsed electric field (PEF) pre-treated silage increased by 20.1% compared to the untreated control. The highest biogas output from PEF pre-treated samples was 535.57 $L\cdot kg_{VS}^{-1}$, while the highest biogas output from microwave pre-treatment substrates was 487.18 $L\cdot kg_{VS}^{-1}$ [6]. During the 9 days of a fed-batch cycle, biohythane (biomethane and biohydrogen) production of

0.667 ± 0.054 $L\cdot L_{reactor}^{-1}$ (based on three fed-batch cycles) in alkali-pre-treated sludge fed MECs was obtained, compared to 0.451 ± 0.030 $L\cdot Lr_{eactor}^{-1}$ in raw sludge fed MEC and 0.383 ± 0.027 $L\cdot L_{reactor}^{-1}$ in raw sludge fed open circuit MEC [7]. In another study, glucose and sewage sludge were fermented. Three studies were performed for each study group – control (without electric field), with electric field – 0.3 V, and with an electric field of 0.6 V. When fermenting glucose, the biogas yield increased by 9.7% from 0.546 L to 0.599 L, and when fermenting sewage sludge, the biogas yield increased by 12.6% from 1.93 to 2.19 L respectively. Methane content in biogas increased as follows – when fermenting glucose, it increased by 9.4% (from 0.315 L to 0.347 L) and by 8.5% when fermenting sewage sludge (from 1.215 L to 1.322 L) [8].

When studying the utilization of coffee processing waste for charcoal production, it was found that during the carbonization process, at a higher temperature (above 500 ºC), the flue gas had a higher concentration of volatile substances [9]. They contained a lot of methane that could be used as fuel [10]. Ulcido's research group investigated the potential of biogas from coffee husks. The tests were carried out using one-litre laboratory bioreactors, which were operated for approximately 40 days, in two temperature regimes – 37 ºC and 52 ºC. At 37 ºC the specific yield of biogas was 241.31 ± 10.29 $mL\cdot g_{VS}^{-1}$ and methane – 131.67 $mL\cdot g_{VS}^{-1}$ compared to 57 ºC: biogas – 239.7 ± 12.97 $mL\cdot g_{VS}^{-1}$ and methane – 124.63 $mL\cdot g_{VS}^{-1}$ [11].

The aim of this study is to compare the biogas potential from food leftovers and lignocellulosic materials such as willows. Also, the effect of the electric field and lower temperature on the fermentation process will be clarified in this investigation.

Materials and methods

The food leftovers from uneaten food in one day in the hospital and cafeteria were 9.307 and 5.768 kg, respectively. The food leftovers of the hospital consist of white bread, sweet and sour bread, oatmeal porridge, rice with carrots, pasta, tomatoes, mashed potatoes, courgettes, fresh cucumber and paprika. The food leftovers of the cafeteria consist of sponge cake, potato skins, salad, pickles, cabbage, carrots, pork, toast salad, potatoes, coffee. The food leftovers from uneaten food in a household, 3.833 kg created in four days. Ingredients: Pickled cucumbers, beets, potato skins, onions and apples (damaged), fish, onion skins, tomatoes, carrots.

Before feeding the food leftovers into the bioreactors, they were ground, creating a homogeneous mass. The pre-treatment of willows and their preparation has been discussed in previous studies conducted in bioenergy laboratories [12].

The bioreactors were filled with the following raw materials:

- R1, R21, R37, R53 – 500g inoculum (IN);
- R2- R4 – 500g IN and 25g food leftovers from hospital;
- R5-R7 – 500g IN, 19g food leftovers from cafeteria and 6g coffee grounds;
- R8-R10 – 500g IN and 25g food leftovers from household;
- R11-R13 – 500g IN, 23g all three of the above and 2g coffee grounds;
- R14-R16 – 500g IN, 20g all three of the above and 5g paper dust;
- R17-R18 – 500g IN, 20g all three of the above and 5g paper dust, as well as were added electrodes with a potential of 0.0 V.
- R19-R20 – 500g IN, 20g all three of the above and 5g paper dust, as well as electrical field was added with a potential of 0.7 V.
- R22-R24; R38-R40; R54-R56 – 500 g IN and 20 g willow pellets;
- R25-R27; R41-R43; R57-R59 – 500 g IN, 10g willow pellets and 10 g food leftovers;
- R28-R30; R44-R46; R60-R63 – 500 g IN, 20g willow pellets and 1g bentonite clay;
- R31-32; R47-R48; R65-R66 – 500 g IN, 20 g willow pellets and electrical field;
- R33-R34; R49-R50; R67-R68 – 500g IN, 20g willow pellets and 0.2g coffee charcoil;
- R35-R36; R51-R52; R69-R70 – 500g IN, 20g willow pellets, 1g bentonite clay and 0.2g coffee charcoil (coffee charcoil (CC) was produced by heating of coffee grounds at temperature 550 ºC without presence of oxygen).

Fermented cattle manure (from a 120 L bioreactor working in continuous mode) was used as the inoculum. Batch mode food waste and paper waste AD process was ongoing at temperature 38 ± 0.5 ºC. The willow pellet AD process was ongoing at temperature 28 ± 0.5 ºC (R22-R36), 33 ± 0.5 ºC (R37-R52) and 38 ± 0.5 ºC (R53-R70).

The four bioreactors (R17-R20) were involved in the experiment with electrodes and application of the electric field. Electrodes were installed according to the scheme used in the previous research [13]. Two bioreactors (R17, R18) were equipped with electrodes, but voltage was not supplied. In the microbial electrolysis cell reactors (R19, R20; R31, R32; R47, R48; R63, R64), the electrodes were supplied with a low voltage of 0.7 V direct current. The method of placing the electrodes in the bioreactor has been discussed in previous studies [13].

Biogas released was collected in gas bags for further measurements of the gas volume and elemental composition. Biogas and methane volumes and gases composition were measured during the AD process at regular time intervals. The AD process was provided until biogas emission ceases. The design and conduct of the experiments were based on the standard experimental methodological manual developed by German and Latvian scientists [12-14].

Results and discussion

The analyses of the input material show that the content of organic matter in willows and paper dust is the highest among all input materials – 88.71 and 78.72%, respectively. Therefore, considering the organic matter content in input materials, the highest concentration of dry organic substances was in the reactors when co-fermenting willows with food residues, coffee grounds and bentonite clay 5.42, 6.76 and 6.74%. The results of the analysis are shown in Table 1.

Table 1

Food leftover and paper dust physical properties before AF process

Bioreactors	Raw materials	Weight, g	TS, %	Ash, %	DOM, g	DOM, %
R1, R21	IN	500	4.62	1.15	17.35	3.47
R2-R4	FLH	25	17.08	1.11	3.99	15.97
R5-R7	FLC	19	26.49	1.54	4.74	24.95
R8-R10	FLHH	25	16.61	1.61	3.75	15.01
R11-R13	FLCO	23	20.95	1.49	4.48	19.46
R14-R20	FLCO	20	20.95	1.61	3.00	15.01
-	CG	6	39.36	0.55	2.33	38.81
-	CG	2	39.36	0.55	0.78	38.81
-	PD	5	97.61	21.85	3.94	78.72
R2-R4	500IN + 25FLH	525	5.22	1.15	21.35	4.07
R5-R7	500IN + 19FLC + 6CG	525	5.81	1.16	24.42	4.65
R8-R10	500IN + 25FLHH	525	5.19	1.17	21.10	4.02
R11-R13	500IN + 23FLCO + 2CG	525	5.47	1.16	22.61	4.31
R14-R16	500IN + 20FLCO + 5PD	525	6.13	1.36	24.29	4.63
R22-R24	WIL	20	90.44	1.73	17.74	88.71
R25-R27	WIL	10	90.44	1.73	8.87	88.71
R25-R27	FLCO	10	20.95	1.49	1.95	19.46
R33-R34	CC	0.2	100	100	0	0
R22-R24	500IN + 20WIL	520	7.92	1.17	35.09	6.75
R25-R27	500IN + 10WIL + 10FLCO	520	6.59	1.17	28.17	5.42
R28-R30	500IN + 20WIL + 1BC	521	7.91	1.17	35.09	6.74
R33-R34	500IN + 20WIL + 0.2CC	520.2	7.94	1.17	35.17	6.76
R35-R36	500IN + 20WIL + 1BC + 0.2CC	521.2	5.23	0.30	35.17	6.75

IN – inoculum; *FLH – food leftovers from hospital*; *FLC - food leftovers from cafeteria*; *FLHH - food leftovers from household*; *FLCO - food leftovers, combo*; *CG – coffee grounds*; *PD – paper dust*; *EL – electrode*; *EF electric field*., *WIL – willow*; *BC – bentonite clay*; *CC – coffee charcoal*.

As a result of the study, the following results were obtained, which are presented in tables and figures. The highest yield of biogas was co-fermenting food leftovers with paper dust. On average, 9.08 ± 0.195 litres of biogas were produced from one bioreactor within the group of reactors R2-R20.

The largest specific biogas yield was observed in fermentation of food leftovers from household – 1.987 ± 0.014 $L \cdot g_{DOM}^{-1}$ (Fig.1).

The highest methane content in biogas was in fermentation of food leftovers from household – 42.8%, thus the specific methane yield was – 0.850 ± 0.138 $L_{CH4}\ g_{DOM}^{-1}$.

Addition of paper dust to food leftovers reduced the specific methane yield compared to that from food leftovers. This may be justified by higher content of slowly degradable lignocellulosic substance in paper dust.

In co-fermentation of food leftovers and paper dust, the specific methane yield was reduced by 50% in reactors with installed electrodes without application of low voltage field and by 75% with application of a low voltage (0.7 V) electric field to those electrodes. These results are controversial to that reported in the previous research, where application of the electric field (0.47 or 0.60 V) increased the specific methane yield in substrates with paper dust, cow manure or wheat straw [13].

On the other hand, the highest specific methane yield was obtained in fermenting food leftovers together with paper dust and food leftovers (combo) with 2 grams of coffee grounds – 0.46 $L_{CH4} \cdot g_{DOM}^{-1}$. These research results are compared with other conducted studies [4; 5], where when fermenting both food waste and food waste with paper cardboard, the results were 0.402 and 0.306 $L_{CH4} \cdot g_{DOM}^{-1}$, respectively.

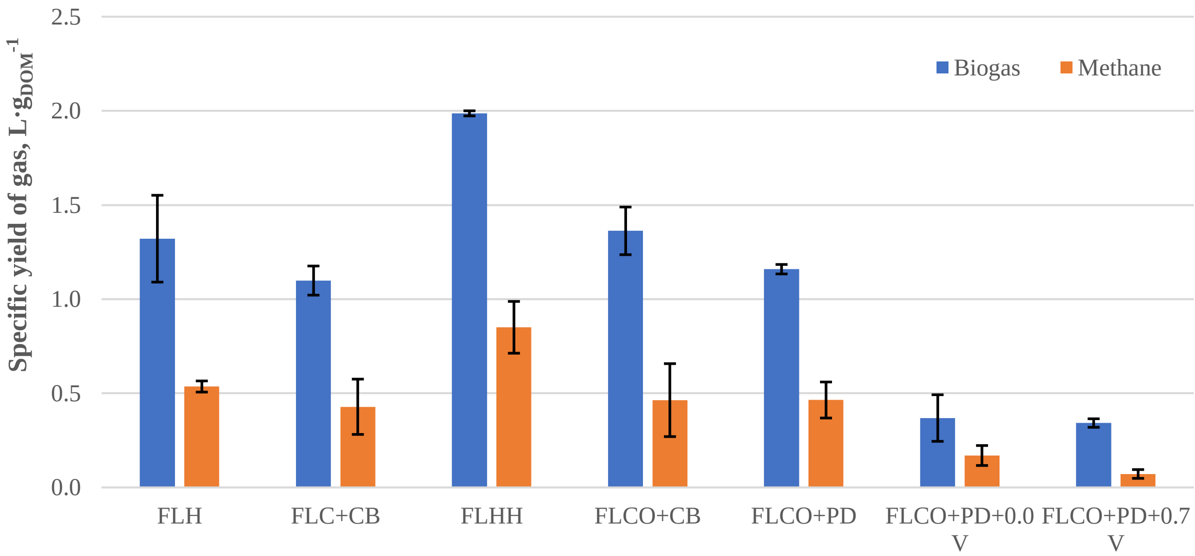

Fig.1. **Specific yield of biogas and methane from food leftovers**

Fermenting of willow at different mesophilic temperatures (28 ºC, 33 ºC, 38 ºC), the highest biogas yield was achieved in fermentation of willows at a temperature of 38 ºC – 6.39 ± 0.31 litres of biogas. High yield of biogas at lower temperature (33 ºC) was achieved by co-fermentation of willows with bentonite – 5.85 ± 0.46 litres per reactor.

The highest specific biogas yield was obtained by co-fermenting willows with food residues at any temperature, but the maximum specific biogas yield was achieved at 38 ºC temperature – 0.558 ± 0.065 and at 33 ºC – 0.535 ± 0.009 $L \cdot g_{DOM}^{-1}$.

The highest concentration of methane in biogas was during fermentation of willows – 53.71%. The specific methane yield was also achieved by co-fermenting willows with food leftovers – 0.268 ± 0.033 (33 ºC) and 0.259 ± 0.044 (38 ºC) $L_{CH4} \cdot g_{DOM}^{-1}$ (Fig.2.). Compared to previous studies in our laboratory with willow pellets [12] – 0.22 $L_{CH4} \cdot g_{DOM}^{-1}$ without applying an electric field to the substrate, the results have been similar (0.25 $L_{CH4} \cdot g_{DOM}^{-1}$). With the effect of an electric field on the substrate, the results of the study were not as successful as before – 0.074 vs. 0.36 $L_{CH4} \cdot g_{DOM}^{-1}$. This can be explained by the fact that there were probably not enough microorganisms in the substrate that would react to the electric field and produce hydrogen.

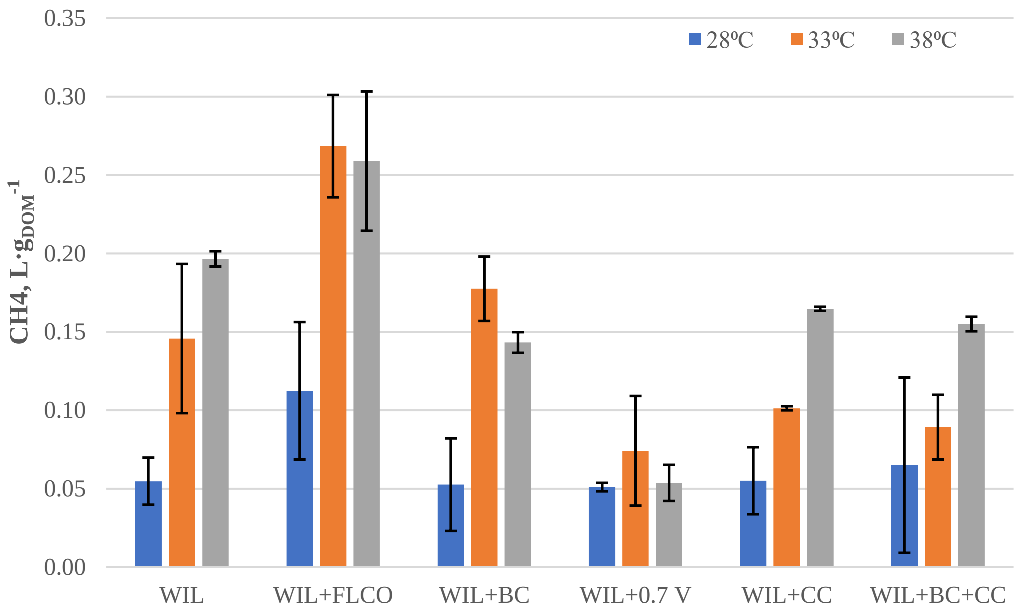

Fig. 2. **Specific methane yield from willow and willow co-fermentation with food leftovers, coffee charcoal and bentonite clay**

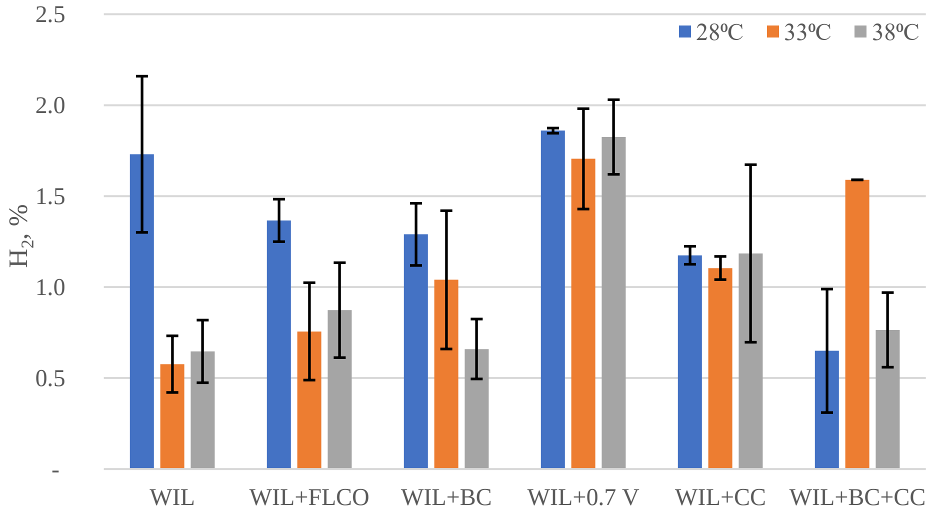

Fig. 3. **Concentration of obtained hydrogen in biogas from substrates with willow biomass**

Application of low voltage (0.7 V) electric field to substrate with willow and food leftovers has zero (at 28 ºC) or negative (at 33 ºC and 38 ºC) effect on methane output compared to reactors without application of the electric field. However, high hydrogen yield (hydrogen content 1.71-1.86% in biogas) - 0.164 L was observed from willow substrates with application of the electric field, that was by 92.7% higher compared to compared to substrates without application of the electric field (Fig.3.). This means that released hydrogen from bioreactors should be considered in calculation of the process efficiency in fermentation of substrates under influence of the electric field.

Conclusions

1. The largest cumulative amount of biogas was observed during the co-fermentation of food leftovers with paper dust – 9.08 litres, which was 26.6% more than when fermenting only homogeneously mixed food leftovers from canteens (7.17 litres).

2. The specific methane yield, which is decisive in all biogas potential studies, reached the highest value when fermenting food leftovers from household – 1.987 $L \cdot g_{DOM}^{-1}$. It was by 44.6% more than fermenting food leftovers from a cafeteria – 1.099 $L \cdot g_{DOM}^{-1}$. Also, compared to the best result from willow fermentation (0.558 $L \cdot g_{DOM}^{-1}$), the biogas yield from household leftovers was higher by72%.
3. Methane concentration in biogas had the highest values when fermenting willows – 53.71%. The concentration of methane was relatively high in co-fermentation of willows with bentonite clay and coffee charcoal – 51.27%. and 51.07%, respectively.
4. The maximum specific methane yield was observed in the fermentation of household food leftovers – 0.85 $L_{CH4} \cdot g_{DOM}^{-1}$, which was higher by 45.8% and 76.1% compared to paper dust (0.46 $L_{CH4} \cdot g_{DOM}^{-1}$.) and willow (0.268 $L_{CH4} \cdot g_{DOM}^{-1}$), respectively.
5. Good specific methane yields 0.165 $L_{CH4} \cdot g_{DOM}^{-1}$ were obtained in co-fermentation of willow with coffee charcoal at temperature 38 ºC. This specific methane yield was higher by 6.1%, 13.3% or 67.2%, compared to the methane yield from willow with bentonite clay and coffee charcoal, willow with bentonite clay or willow with low voltage field.
6. Low voltage electric energy input for maintenance of 0.7 V electric field was from 1.03 to 1.22 Wh per reactor during the whole anaerobic fermentation (AF) process. Installation of graphite electrodes and application of 0.7 V electric field in reactors resulted to zero (at 28 ºC) or negative (at 33 ºC and 38 ºC) effect to methane output compared to reactors without application of the electric field. Further investigations should be provided on possibilities of the enhancement of the AF process using the electric field with different voltage and electrode configuration.

The released hydrogen from bioreactors should be considered to provide fair estimation of the process efficiency in fermentation of substrates under the influence of the electric field.

Author contributions

The contribution of each author. Conceptualization, I.S.; methodology, V.Du.; software, I.S.; validation, I.S. and I.P; formal analysis, I.S.; investigation, I.S., I.P., V.Dr. and E.Z.; data curation, I.S., I.P., V.Dr. and E.Z.; writing – original draft preparation, I.S.; writing – review and editing, I.P. and V.Du.; visualization, I.S. All authors have read and agreed to the published version of the manuscript.

References

[1] Ngoc Bao Dung Thi, Kumar G., Lin C.Y. An Overview of Food Waste Management in Developing Countries: Current Status and Future Perspective. Journal of Environmental Management, 157. 2015, pp. 220-229.

[2] Kanger K. Biogas Production under Co-Digestion of Food Waste with Sewage Sludge. University of Tartu. 2013. 37 p.

[3] Development of Food Waste Processing Conditions for Their Further Processing Using Biotechnology (in Latvian). Biedrība "Latvijas Atkritumu saimniecības asociācija". 2016. p.67

[4] Jansson A.T., Patinvoh R.J., et.al. Dry Anaerobic Digestion of Food and Paper Industry Waste at Different Solid Contents. Fermentation. 2019.5(2), doi:10.3390/fermentation5020040.

[5] Zhang Y, Banks C.J, Heaven S. Co-digestion of Source Segregated Domestic Food Waste to Improve Process Stability. Bioresour Technology. 2012. 114. pp.168-178. DOI: 10.1016/j.biortech.2012.03.040

[6] Szwarc D., Nowicka A., Glowacka K., Cross-Comparison of the Impact of Grass Silage Pulsed Electric Field and Microwave-Induced Disintegration on Biogas Production Efficiency. Energies. 2022. 15. 5122. 10 p. DOI: 10.3390/en15145122

[7] Liu Q., Ren J.Z., et.al. Multiple Syntrophic Interactions Drive Biohythane Production from Waste Sludge in Microbial Electrolysis Cells. Biotechnology for Biofuels. 2016. 9. 162. 10 p.

[8] Shashikant G., Yuxi H. et.al., Methane Production Improvement and Associated Methanogenic Assemblages in Bioelectrochemically Assisted Anaerobic Digestion. Biochemical Engineering Journal. 2017. 117. pp.105-112.

[9] Srisang S., Phetpan K., et.al. Charcoal Briquette Production from Waste in the Coffee Production Process Using Hydrothermal and Torrefaction Techniques: A Comparative Study with Carbonization Technique. Journal of Cleaner Production. 2022. 372. 133744. 12 p. DOI: 10.1016/j.jclepro.2022.133744

[10] Sawadogo M., Tanoh S.T., et.al. Cleaner Production in Burkina Faso: Case Study of Fuel Briquettes Made from Cashew Industry Waste. Journal of Clean. Production. 2018. 195. pp.1047-1056

[11] Ulside M.D., Zaleke G., Li M. Biogas Potential Assessment from Coffee Husk: an Option for Solid Waste Management in Gidabo Watershed of Ethiopia. Proceedings of 15. International conference "Engineering for Rural Development", May 25-27, 2016. pp.1348-1354.

[12] Plume I., Dubrovskis V., Klavins M., Improvement of Anaerobic Fermentation of Mechanically Pretreatment Lignocellulosic Biomass. Proceedings of 21th International Scientific Conference Engineering for Rural Development, May 25-27, 2022. pp. 80-85.

[13] Plume I., Dubrovskis V., Effectiveness of Low Voltage Electric Field Usage for Anaerobic Fermentation of Manure, Straw and Paper Dust. Proceedings of 19th International Scientific Conference Engineering for Rural Development, May 20-22, 2020. pp.1907-1913.

[14] Kaltschmitt M. Methodenhandbuch (Method manual), Leipzig, 2010, 93 p. (In German).