EFFECTIVENESS OF LOW VOLTAGE ELECTRIC FIELD USAGE FOR ANAEROBIC FERMENTATION OF MANURE, STRAW AND PAPER DUST

Imants Plume, Vilis Dubrovskis
Latvia University of Life Sciences and Technologies, Latvia
imants.plume@llu.lv, vilisd@inbox.lv

Abstract. Intensification of the biomass anaerobic fermentation (AF) process by help of electric field may be of great significance for improvement of biogas quality and for increase of methane output from biomass. This new way for advancement of anaerobic fermentation is less investigated for anaerobic treatment of different agricultural or industrial waste biomass. Experimental studies on low voltage (below 1.0 V) influence on the anaerobic fermentation process of manure, straw and paper dust was provided using 2 sets of laboratory bioreactors in volume of 0.75 L in batch mode at temperatures 38 ºC or 40 ºC. The first experiment consists of 16 laboratory bioreactors for anaerobic fermentation of manure and paper dust with and without influence of low voltage (0.60 and 0.47 V) electric field at temperature 38 ºC. The second experiment consists of 12 bioreactors for anaerobic fermentation of manure and wheat straw with and without influence of low voltage (0.60 V) electric field at temperature 40 ºC. The first experiment shows increase of the specific methane volume by 37.3 % or 2.4 % from substrates with cow manure or paper dust substrate, respectively, if the low voltage electric field was applied. The second experiment shows increase of the specific methane volume by 55.3 % or 8.5 %, if the low voltage electric field was applied to substrates with straw or straw-manure mixture, respectively. The investigated average current density was 33.2 or 19.7 Am^{-2} for supply voltage 0.60 or 0.47 V on the bioreactor electrodes, respectively.

Keywords: anaerobic digestion, methane, microbial electrolysis cell, manure, straw.

Introduction

Alternative energy sources should to be used instead of fossil fuels both to meet the current energy needs and to reduce environmental problems caused by global warming. The benefits of biogas production in the anaerobic digestion (AD) process is clearly justified by a team of Hungarian researchers, investigating the performance of 0.637 MW biogas power plant utilising manure from a pig farm (6000 pigs) and plants (sorghum, vetch, medick, hay and energy grasses). In 2013, the power plant produced 4347.21 MWh electric energy and 4607.89 MWh thermal energy. The carbon footprint of the complete energy production life cycle was 208173 kg CO2 equivalents (CO(2)e). If the regular Hungarian energy structure produced such a quantity of energy, GHG emissions would be 15 times higher [1].

Usage of straw for biogas production could reduce the carbon footprint both due to substitution of energy plant biomass feedstock and due to minimisation of the methane emissions from cereal fields by straw removing. Methane emissions from rice paddy soils were reduced by 95 % for a conventional rice variety and 96 % for a high biomass-yielding rice variety when the straw was removed rather than returned to the fields [2].

However, biodegradability of straw is low due to lot of cellulose, hemicelluloses and lignin, and straw should be pre-treated by chemical, thermo-chemical ad/or thermo-mechanical means prior to anaerobic digestion [3].

Scientists reported results of wheat straw pre-treatment through a thermo-mechanical process, by the application of high temperature (140 ºC) and pressure (2.75 bar) in autoclave at different retention times (0, 30, 60 and 90 minutes). WS samples were placed in a 500 mL bottles and deionized water was added in order to obtain a solid content of 35 % (w/v). After heating treatment, a rapid pressure drop followed until atmospheric pressure was reached.The pre-treatment did not affect the ultimate methane potential, which varied between 241 and 279 mL $CH4 \cdot g^{-1}$ VS atorganic load rate (OLR) of 4 kg VS/m3 applied. At an OLR of 8 kg $VS \cdot m^3$, only the 60 min pre-treatment time affected the ultimate biomethane potential, which increased by ~9 %, compared to the untreated substrate [4].

To further improve the AD process of agricultural biomassthe energy content in the produced biogas should be increased by increasing of hydrogen and/or methane content in biogas. Researchers reported possibilities to use microbial electrolysis cells (MEC) in the AD process for increasing of the hydrogen or methane content in gases released from wastewater. Using a single-chamber MEC with a graphite-fiber brush anode, hydrogen gas was generated at 0.9-1.0 $m^3 \cdot m^{-3} \cdot day^{-1}$ H_2 using a fullstrength or diluted swine wastewater. The gas produced was up to 77 ± 11 % hydrogen, with overall recoveries of up to 28 ± 6 % of the COD in the wastewater as hydrogen gas. Methane was also produced at a maximum of 13 ± 4 % of total gas volume. The efficiency of hydrogen production, based on the electrical energy needed (but excluding the energy in the wastewater) compared to the energy of the hydrogen gas produced, was as high as 190 ± 39 % in 42-h batch tests with undiluted wastewater, but was lower in longer batch tests of 184 h (91 ± 6 %) [5].

Other researchers investigated the use of spiral MEC electrode with acetate and dairy wastewater for methane production in the AD process. With acetate as the substrate and increasing applied voltages from 0.7 to 1.3 V, the average current density and CH4 production rate increased from 46 to 132 $A \cdot m^{-3}$ and from 0.08 to 0.17 m^3/m^3 d, respectively. With the increasing applied voltages, the energy efficiencies decreased from 157 % to 69 %, while the COD removal rates increased from 0.31 to 0.69 kg $COD \cdot m^{-3}$ d. The optimal applied voltage of the spiral-wound-electrode MEC was about 0.95 V. Fed with dairy wastewater, the MEC also showed good performance with the average current density of 24 $A \cdot m^{-3}$, CH4 production rate of 0.03 $m^3 \cdot m^{-3}$ d, energy efficiency of 66 %, and COD removal rate of 0.20 kg $COD \cdot m^{-3}$ d. [6].

Microbial electrolysis cell (MEC) in combination with alkali-pre-treated biomass is a promising approach for production of transport biofuel biohytane or mixture of biohydrogen and biomethane in the AF process.The alkali-pretreated sludge fed MECs (AS-MEC) showed the highest biohythane production rate of 0.148 $L \cdot L^{-1}$-reactor$\cdot$day^{-1}, which is 40 and 80 % higher than raw sludge fed MECs (RS-MEC) and anaerobic digestion (open circuit MEC, RS-OCMEC). Current density, metabolite profiles, and hydrogen-methane ratio results all confirm that alkali-pre-treatment and microbial electrolysis greatly enhanced sludge hydrolysis and biohythane production [7].

Purposes of the current study are to investigate enhancement of methane production in anaerobic fermentation of cow manure, paper dust and wheat straw by use of low voltage electric field applied to electrodes immersed in substratesin laboratory bioreactors.

Materials and methods

For microbial electrolysis experimental study, each 0.75 L round shaped bioreactor was provided with 3 anode and 3 cathode electrodes made from graphite. Every graphite electrode has dimensions 40x15x2 mm. All 6 electrodes were placed inside the bioreactor to form a circle with 60 mm inside diameter. All cathode and anode electrodes in the bioreactor were connected in parallel to increase the contact area and current density. The cathode and anode were connected to a low voltage 0.3-0.8 VDC power supply unit.

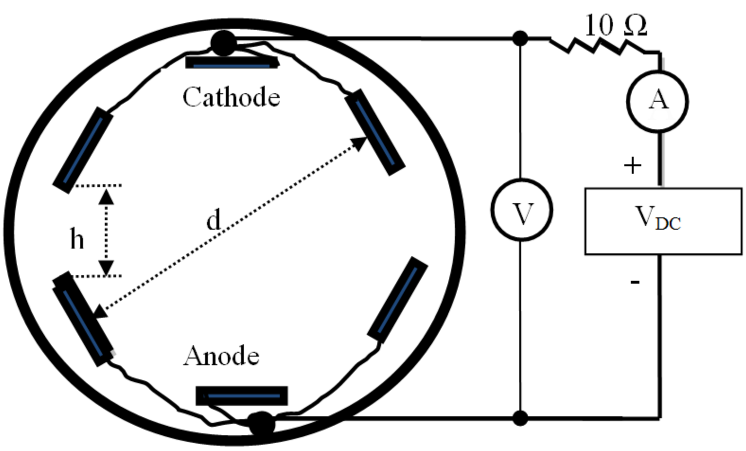

Fig. 1. **Scheme of power supply and position of electrodes in MEC bioreactor:**
d – diameter of the circle for positioning of electrodes in the bioreactor;
h – closest distance between the anode and cathode

Paper dust material was obtained from air cleaning filters installed in an enterprise processing paper products. Particle size of paper dust was less than 1.0 mm and, therefore, no pre-treatment was provided for this raw material, Fig. 2. Wheat straw was chopped, milled and sieved through a 2 mm mesh sieve to obtain small 2-3 mm straw particles, Fig. 3.

Fig. 2. **Paper dust material**

Fig. 3. **Wheat straw biomass**

Before anaerobic fermentation, inoculums, cow manure, paper dust and wheat straw biomass were analysed for the total solids (TS) and dry organic matter (DOM) content forcalculationof acceptableorganic load rate in bioreactors.

Total solids (TS) content in samples was determined by drying of the material in dryer-weights (typeMOC-120H, accuracy ± 0.001 g) at 105 ºC. Dry organic matter content (DOM) was determined by aching of dry samples in the oven (model Memmert) at 550 ºC according to a standard aching cycle. Standard mathematical operations were used for calculation of the sample TS and DOM content. Based on the above analyzes, an experimental design was worked out for 2 sets of bioreactors.

The first experiment involved anaerobic fermentation of cow manure and paper dust in 16 bioreactors with a volume of 0.75 L. Fresh manure 20 g was added in every bioreactor R2-R9 and paper dust 5 g was added in R1-R15. Bioreactors R1 and R16 were filled with inoculums 500 g only to provide blank (control) yield to be retracted from biogas (methane) volumes obtained from bioreactors R2-R15 to calculate the biogas (methane) potential for specific added biomass only.

Half of the bioreactors within the group of similar added biomass were equipped with electrodes, and the other half of bioreactors were processed without electrodes to ensure the statistical reliability. Low voltage 0.60 V_{DC} or 0.47 V_{DC} was supplied to electrodes in the microbial electrolysis cell (MEC) reactors with cow manure or paper dust respectively.

The second experiment involved anaerobic fermentation of cow manure and wheat straw biomass in 12 bioreactors based on the same method described above. Inoculums (fermented cow manure) 500 g was filled in every reactor for initiation of the anaerobic fermentation process. Wheat straw biomass 15 g was added in bioreactors R2-R5 and cow manure 20 g + wheat straw 10 g were added in bioreactors R10-R55. Half of the bioreactors within groups of similar added biomass were equipped with electrodes (with applied low voltage 0.60 V), and the other half of bioreactors were processed without electrodes. Design and implementation of the experimental plan is based on standard experimental method developed by German researchers [8].

All bioreactors filled with substrates were positioned in the thermostat to provide anaerobic fermentation at temperature 38 ± 0.5 ºC for the first experimental setup and at temperature 40 ± 0.5 ºC for the second experimental setup. Anaerobic fermentation of substrates was provided, until biogas (methane) release from the substrates ceases.

Gas bags were positioned outside the thermostat, for gas collection connected through plastic pipes to bioreactors, providing the gas volume and composition analyses at room temperature. Gas volume was measured by a flow meter (Ritter drum-type) and the composition was measured by help of a gas analyser (model Gasboard3200L).

Substrate pH value was measured in the bioreactor before and after the AF process, using the pH meter (model HI 8424, accuracy ± 0.01). Substrate weight before and after the AF cycle was determined by scales (type KFB 16KO2,accuracy ± 0.2 g). Electric voltage and current were measured by a multimeter model FLUKE AUTO-V Lo2 (accuracy ± 0.001 mV; ± 0.001 mA). After the gas emission ceases, the total solids and dry organic matter content in the digestate was determined using standard methods and common mathematical operations [8].

Average biogas and methane volumes obtained from blank (control) reactors (R1; R16) with inoculums only were subtracted from biogas and methane volumes from the bioreactors with added biomass to calculate the biogas and methane volumes obtainable from added biomass only.

Results and discussion

Composition of substrates, weight and content of organic matter and degradation rate of organic matter in substrates before and after anaerobic digestion within the first experiment are shown in Table 1.

Table 1

Results of analyses of substrates before and after finishing of anaerobic fermentation

Bioreactors	Component weight, g	S_{OM}, g	F_{OM}, g	DM, g	DM_{ad}, g	DM_{ad}, %
R1; R16	IN500	6.240	2.129	4.111	0.000	0.0
R2-R5	IN500 + CM20 + e0.60 V	8.623	3.278	5.345	1.234	51.8
R6-R9	IN500 + CM20	8.623	2.700	5.923	1.812	76.0
R10-R12	IN500 + PD5	9.946	3.004	6.942	2.831	76.4
R13-R15	IN500 + PD5 + e0.47V	9.946	2.717	7.229	3.118	84.1

Note: IN – inoculums; CM – cow manure; PD – paper dust; e – electric field applied; S_{OM} – dry organic matter of substrate at the start; F_{OM} – dry organic matter of digestate at the finish; DM – degraded organic matter of substrate during AF cycle; DM_{ad} – degraded organic matter of added biomass during AF cycle; R1;R16 – bioreactors with inoculums blank (control); R2-R5– group of bioreactors filled in with similar substrates and processed at similar conditions.

Raw substrate analyses show that the paper dust (PD) biomass has higher organic matter content compared to cow manure (CM) at the start of anaerobic fermentation.

Digestate analyses show that the average percentage of organic matter degradation in reactors with added cow manure at applied low voltage 0.6 V decreases by 24.2 %, and average percentage of organic matter degradation in reactors with paper dust at applied low voltage 0.47 V increases by 7.8 % compared to the bioreactors within respective groups without applied low voltage electric field.

Biogas and methane yields obtained in the AF process from all reactors with added biomass in the experiment 1 are shown in Fig. 4.

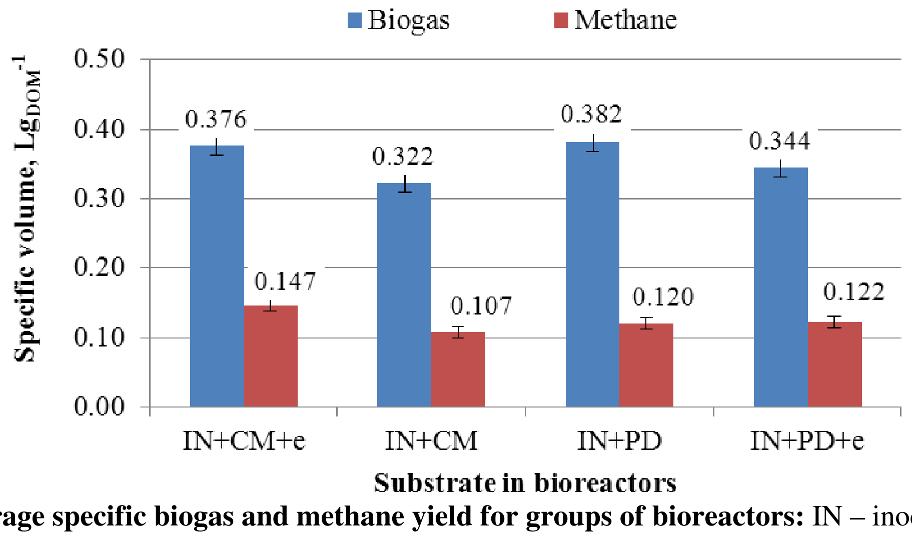

Fig. 4. **Average specific biogas and methane yield for groups of bioreactors:** IN – inoculums; CM – cow manure; PD – paper dust; e – electric field applied

Experimental data show higher biogas and methane yields in bioreactors with applied low voltage electric field, and lower biogas and methane yields in bioreactors without electric field. Higher increase of the specific methane content by 37.3 % was obtained from the cow manure mixture with applied voltage (0.60 V) compared to the cow manure mixture without the electric field. This increase in the specific methane content is in line with increase of methane production by 76.2 % from MEC reactors with activated sludge digestion at 0.6 V on electrodes [9].

Methane content in biogas from bioreactors is shown in Fig. 5.

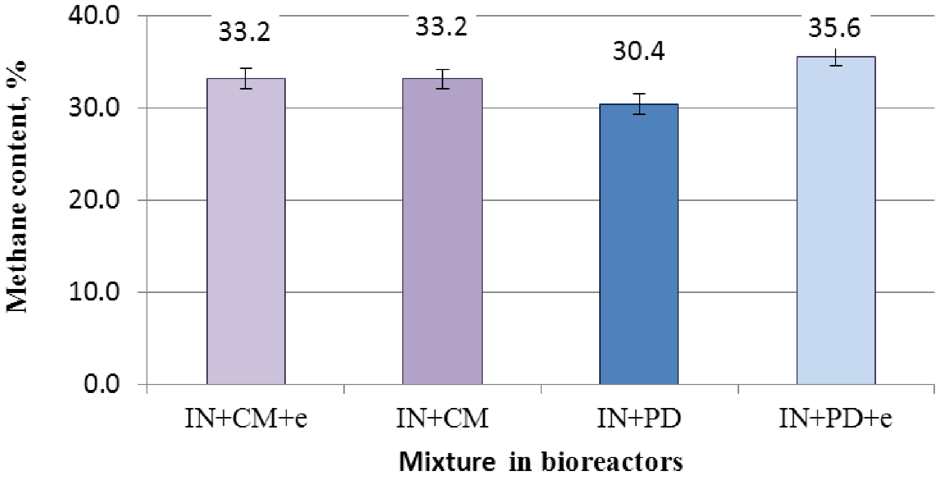

Fig. 5. **Average percentage of methane in biogas for groups of bioreactors:**
IN – inoculums; WS – wheat straw; e – electric field applied; PD – paper dust

Composition of substrates, weight and content of organic matter and the degradation rate of organic matter in substrates before and after anaerobic digestion in experiment 2 are shown in Table 2.

Table 2

Results of analyses of substrates before and after finishing of anaerobic fermentation

Reactors	Component weight, g	S_{OM}, g	F_{OM}, g	DM, g	DM_{ad}, g	DM_{ad}, %
R1; R16	IN500	10.08	8.20	1.88	0.0	0.0
R2-R3	IN500 + WS15	22.646	13.227	9.419	7.539	60.0
R4-R5	IN500 + WS15 + e0.60V	22.646	14.594	8.052	6.172	49.1
R10-R12	IN500 + CM20 + WS10	18.167	12.049	6.118	4.238	52.4
R13-R15	IN500 + CM20 + WS10 + e0.60V	18.167	12.995	5.172	3.291	40.7

Note: *IN – inoculums; WS – wheat straw; CM – cow manure; e – electric field applied;* S_{OM} *– dry organic matter of substrate at the start;* F_{OM} *– dry organic matter of digestate at the finish; DM – degraded organic matter of substrate during AF cycle;* DM_{ad} *– degraded organic matter of added biomass during AF cycle; R1;R16 – bioreactors with inoculums blank (control); R2-R3 –group of bioreactors filled in with similar substrates and processed at similar conditions.*

Increase in methane production in all groups of reactors with applied 0.6 V was accompanied by decrease of biodegradation rates within all groups of reactors with applied 0.6 V compared to biodegradation rates in the respective groups without applied electricity. Such the evidence can be explained by biosynthesis of new substances, e.g. acetate, methane and others in substrates in MEC reactors with applied 0.6 V electric field [10].

Specific biogas and methane volumes per unit of added biomass dry organic matter (DOM) obtained in experiment 2 are given in Fig. 6.

Investigated average specific methane from fermentation of wheat straw withoutapplied electric field is lower by 30.6 % compared to the specific methane yield 0.285 $L \cdot g^{-1}_{DOM}$ obtained from wheat straw pellets in our previous research. However, if the electric field 0.6 V is applied,the specific methane yield is by 7.9 % higher compared with the specific methane obtained from wheat straw pellets in our previous research [9]. Use of the electric field 0.6 V in MEC bioreactor increases the average specific methane production by 55.3 % from straw substrates vs. the average specific methane production from wheat straw substrates without electricity. This increase is similar to increase of specific methane production by 54.8 % obtained by other researchers for anaerobic fermentation of waste activated sludge (WAS) at applied 0.8 VDC between the cathode and anode in MEC bioreactor [12].

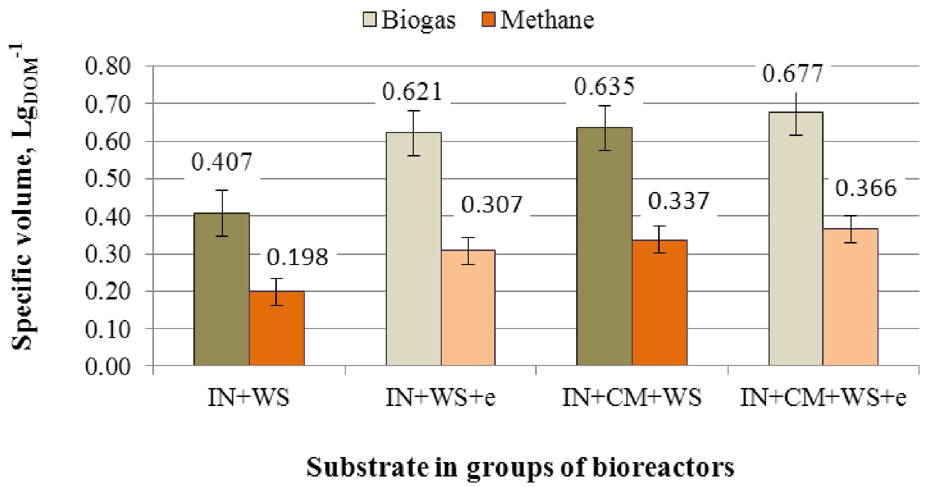

Fig.6.**Average specific biogas and methane volumes for groups with similar substrates:** IN – inoculums; WS – wheat straw; CM – cow manure; e – electric field applied

Methane content in biogas from bioreactors with added biomass with or without low voltage electric field is shown in Fig.7.

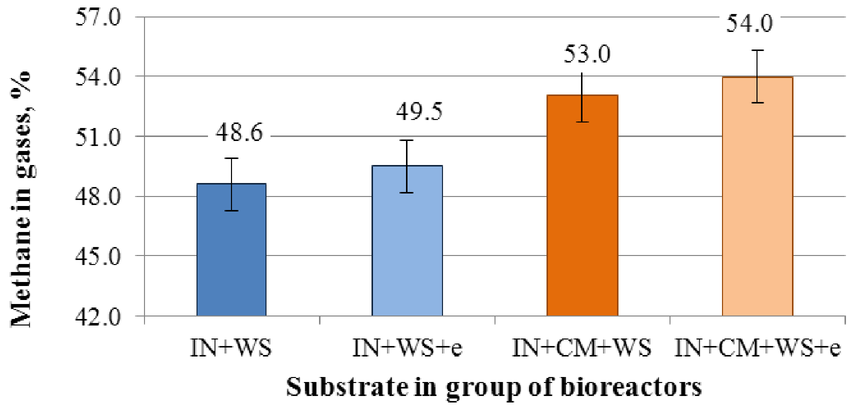

Fig.7. **Average percentage of methane in biogas for groups of bioreactors:** IN – inoculums; WS – wheat straw; CM – cow manure; e – electric field of low voltage (0.60 V) applied

Average methane content was higher by 1.0 % in biogas from bioreactors with low voltage electric field applied. This can be explained due to the stimulating effect of low voltage electricity on the activity of methanogenic bacteria in the substrate.

Conclusions

1. All experiments show increased methane production and methane content in biogas, if the low voltage electric field was applied to the investigated substrates.
2. Increase in methane production was 37.3 % or 2.4 %, if the low voltage (0.60 V or 0.47 V) electric field was applied to the substrate with cow manure or paper dust, respectively.
3. Increase in methane production was 55.3 % or 8.5 %, if the low voltage electric field (0.60 V) was applied to substrates with straw or straw-manure mixture, respectively.
4. Increase in methane production in all groups of reactors with applied 0.6 V was accompanied by decrease of biodegradation rates in these reactors compared to the biodegradation rates in respective groups without applied electricity. Such the evidence can be explained by ongoing biosynthesis of new organic matter along with traditional biodegradation of organic matter within substrates in MEC reactors with applied 0.6 V electricity.

5. Average current densities were 33.2 or 19.7 $A \cdot m^{-2}$ for supply voltage 0.60 or 0.47 V on electrodes (anode and cathode), respectively.

Acknowledgements

The research was supported by a grant from Latvia University of Life Sciences and Technologies for the internal project “Studies on the effectiveness of the anaerobic fermentation process of biomass”, theme G4.

References

[1] Szabó G., Fazekas I., Szabó S., Szabó G., Buday T., Paládi M., Kisari K., Kerényi A. The carbon footprint of a biogas power plant. Environmental Engineering and Management Journal, vol.13(11),2014, pp. 2867-2874.

[2] Koga N., Tajima R. Assessing energy efficiencies and greenhousegas emissions under bioethanol-oriented paddy rice production in northernJapan. J. Environ. Manage. 92, 2011, pp. 967–973.

[3] Amin R., Khalid H., Zhang H., Rahman S., Zhang R, Liu G., Chen C. Pretreatment methods of lignocellulosic biomass for anaerobic digestion.AMB Expr, 7:72, 2017, p. 12.

[4] Fernandes TV., Bos G.J., Zeeman G., Sanders J.P., van Lier J.B. Effects of thermo-chemical pre-treatment on anaerobic biodegradability and hydrolysis of lignocellulosic biomass. Bioresour. Technol., vol. 100, 2009, pp. 2575–2579.

[5] Wagner R.C., Regan J.M.., Oh S.E., Zuo Y., Logan B.E. Hydrogen and methane production from swine wastewater using microbial electrolysis cells. Water Research, vol. 43 (5), 2009, pp. 1480-1488

[6] Hou Z., Zhang R., Luo H., Liu G., Kim Y., Yu S., Zeng J. Microbial electrolysis cell with spiral wound electrode for wastewater treatment and methane production. Process Biochemistry, vol. 50(7), 2015, pp. 1103-110.

[7] Zhiong Q, Ren Z. J., Huang C ., Liu B., Ren N., Xing D. Multiple syntrophic interactions drive biohythane production from waste sludge in microbial electrolysis cells.Biotechnology for Biofuels, vol. 9, 2016, article number: 162.

[8] Kaltschmitt M. Methodenhandbuch, Leipzig, 2010, 93 p. (In German).

[9] Chen Y., Yu B., Yin C., Zhang C., Dai X., Yuan H., Zhu N. Biostimulation by direct voltage to enhance anaerobic digestion of waste activated sludge. RCS advances, vol. 6(2), 2016, pp. 1581-1588.

[10] Marshall C.W., Ross D.E., Fichot E.B., Norman R.S., May H.D. Electrosynthesis of Commodity Chemicals by an Autotrophic Microbial Community. Appl. Environ. Microbiol. 2012, 78(23):8412.

[11] Dubrovskis V., Plume I., Straume I. Anaerobic co-fermentation of molasses and oil with straw pellets. Agronomy Research, 16(3), 2018, pp. 688-695.

[12] Liu W., Cai W., Guo Zv., Wang L., Yang C., Varrone C.,Wang A.Microbial electrolysis contribution to anaerobic digestion of waste activated sludge, leading to accelerated methane production, Renewable Energy, vol. 91, 2016, pp. 334-339.