Increasing the efficiency of organic waste conversion into biogas by mechanical pretreatment in an electromagnetic mill

Yury Litti¹, Dmitry Kovalev², Andrey Kovalev², Inna Katraeva³, Yulia Russkova¹ and Alla Nozhevnikova¹

¹ Winogradsky Institute of Microbiology, Federal Research Center "Fundamentals of Biotechnology" Russian Academy of Sciences, Moscow, 119071, Russia
² Federal Government Budgetary Institution of Science "Federal scientific agroengineering centre VIM" Moscow, 109428, Russia
³ NNGASU, Nizhny Novgorod, 603950, Russia

litty-yuriy@mail.ru

Abstract. The article studies the feasibility of using an electromagnetic mill (EM) for mechanical pretreatment of organic waste prior to anaerobic digestion in the laboratory conditions. Pretreatment in an EM led to the significant improvement in the characteristics of subsequent anaerobic digestion of the simulated organic fraction of municipal solid waste. The specific biogas and methane yield increased by 25% and 80%, respectively. The rate of methane production increased by 50%. The degree of volatile solids destruction increased on average by 16%. Economically feasible time to treat the substrate in an EM was shown to be no more than half a minute.

1. Introduction
In recent years a lot of attention has been paid to the two inextricably connected problems: rational use of natural resources and protection of the environment from anthropogenic pollution. High level of consumption of natural fuel reserves, restricted construction of hydro- and nuclear power plants have drawn interest to the renewable energy sources, particularly, to the huge mass of organic waste generated in agriculture, industry, urban public utilities. Consequently, methods of biological conversion of organic wastes to produce biogas and high-quality organic fertilizers while simultaneously protecting the environment from pollution are quite promising [1].

Hydrolysis of biopolymers is one of the rate-limiting steps during the anaerobic digestion of the organic waste. The hydrolysis rate depends greatly on the size of substrate particles that determines their availability for hydrolytic microorganisms, which require direct contact with the surface of the hydrolysable substances. Pre-treatment of substrate by various methods, among which the most common are thermal [2]; mechanical [3, 5]; and chemical [3, 4, 7] methods, including ozonation [8], is beneficial for increasing the bioavailability and efficiency of mass transfer between substrate particles and hydrolytic microorganisms. Chemical and thermal pretreatment methods are effective and thoroughly studied, but often decrease the potential of the methane production due to inhibition by products of hydrolysis and/or recrystallization of organic compounds [3, 4]. Mechanical methods are almost free of the aforementioned drawbacks.

Substrate treatment in an electromagnetic mill (EM) is one of the mechanical methods. An EM is a pipe of 50 mm to 150 mm diameter made of stainless steel and placed instead of the rotor in the stator of...
an induction motor. Initial mixture of components is affected by the electromagnetic field created by the stator windings, and intensively and randomly moving ferromagnetic bodies in the pipe; movement direction changes with the same frequency as the frequency of the current. A vortex layer is formed in those areas of the pipe where electromagnetic fields emerge. Mill feed in the vortex layer is affected by all kinds of mechanical action, such as impact, abrasion, cavitation, even electrolysis occurs if there is water in the system [9]. The aim of the study is to determine a feasibility of using an EM for pretreatment of organic waste and the efficiency of subsequent methanogenic fermentation. It has not yet been studied despite the fact that EM has been used in industry for a long time [10-12].

2. Materials and methods

2.1. Electromagnetic mill

An experimental setup: an electromagnetic mill with a vortex layer was made in the laboratory of the bioenergetic and supercritical technologies of the Federal Government Budgetary Institution of Science "Federal scientific agroengineering centre VIM" for the pretreatment of organic waste. A general view and schematic diagram of the experimental setup are given in Figure 1.

![Figure 1. General view (A) and schematic diagram (B) of the experimental setup for pretreatment of organic waste in an electromagnetic mill prior to anaerobic digestion:](image)

1 –inductor; 2 –working chamber; 3 –steel needles; 4 –discharge pipe; 5 –air cooling fan; 6 –control unit with frequency converter; 7 –peristaltic pump; 8 –influent tank; 9 –effluent tank.

The setup works as follows: liquid organic waste is loaded into the influent tank 8, peristaltic pump 7 pumps mixture at a rate of 2 l/min through the working chamber 2. The working chamber is equipped with steel needles 3 (an abradable element), which make rotational and oscillatory motions under the action of the magnetic field created by the inductor 1 (the stator of the electric motor). The magnetic field rotates at an increased frequency (100–120 Hz) due to the use of a speed converter mounted in the control unit 6. The inductor is cooled by the air cooling fan 5. Pretreated effluent is discharged into tank 9 through the discharge pipe 4. Technical characteristics of the experimental setup are given in Table 1.

A mixture of the simulated organic fraction of municipal solid waste (granulated feedstuff K-65) and tap water in a ratio of 300 g/l was used as the substrate for pretreatment in the EM. The substrate was prepared as follows: warm (45°C) tap water was poured into a weighted portion of granulated substrate, after that the granules were allowed to swell for 2 hours at room temperature. Treatment in an EM was performed with a different retention time of the water and feedstuff K-65 mixture in the apparatus, namely 0.5, 1.0, 2.0 and 4.0 min. The frequency of the magnetic field rotation was constant and equal to 120 Hz. Pretreated substrate was stored in a refrigerator at a temperature of 4°C for 7 days prior to setting up the anaerobic digestion experiment.
Table 1. Technical characteristics of the setup.

| Name                        | Measurement unit | Value |
|-----------------------------|------------------|-------|
| Voltage                     | V                | 380   |
| Volume of the chamber       | l                | 0.5   |
| Material of the chamber     | -                | Polypropylene |
| Mass of the steel needles   | g                | 100   |
| Diameter of the needles     | mm               | 2     |
| Length of the needles       | mm               | 20    |
| Maximum frequency of field rotation | Hz | 120 |
| Capacity                    | l/ min           | 2     |
| Hydraulic retention time    | s                | 15    |
| Rated power                 | kW               | 1.3   |

2.2. Experiment on the anaerobic digestion of organic waste pretreated in an EM

Experiment on the anaerobic digestion (AD) of the pretreated in the EM and native (without pretreatment) substrate was carried out under thermophilic conditions (55°C), in 250 ml batch reactors, in which 140 ml was occupied by fermentation mixture and 110 ml by gas phase. Thermophilically digested sewage sludge from the Lubertetsk wastewater treatment plant (Moscow) was used as inoculum (a source of methanogenic microorganisms). Some characteristics of inoculum and substrate are shown in Table 2.

Table 2. Substrate and inoculum characteristics.

| Parameter          | Measurement unit | Inoculum | Substrate pretreatment time in an EM, min |
|--------------------|------------------|----------|------------------------------------------|
|                    | g/g              | 0.0393   | 0.0829 0.0811 0.0890 0.0873 0.0809       |
| Total solids (TS)  | g/g TS           | 0.459    | 0.920 0.921 0.922 0.913 0.918           |
| Volatile solids    | % TS/TS          | 9.9      | 15.3 13.3 10.7 12.8 12.3                |
| pH                 | -                | 7.96     | 5.27 5.36 5.52 5.81 5.92                |

The inoculum to substrate ratio in terms of total volatile solids (VS) content in all mixtures was 57/43. Control mixture (CM) consisted only of the inoculum without substrate. Moisture content of the mixtures was 98.6%, which was adjusted by adding required amount of tap water. Mixture components were added under nitrogen flow, the bottles were sealed with rubber stoppers and metal caps. Incubation was carried out with constant stirring by a rotary shaker at a speed of 85 rpm. Methane, carbon dioxide and hydrogen in the gas phase, pH and the volatile fatty acids in digestate were analyzed regularly. All the experiments were done in duplicate.

2.3. Analytical methods

The total solids weight was determined after drying the sample to constant weight at 105°C. Nonvolatile solids content was determined by combustion of dry sample in a muffle furnace to constant weight at 650°C. Volatile solids content was calculated as the difference in weights between the total and nonvolatile solids. pH was measured with a pH meter FE20 (Mettler Toledo, Switzerland) equipped with InLab® Micro electrode (Mettler Toledo, Switzerland). C/N ratio was measured on an element analyzer Vario EL cube (Abacus Analytical Systems GmbH, Germany). The concentration of methane, carbon dioxide and hydrogen in the gas phase and volatile fatty acids (VFA) in the liquid phase was analyzed by a gas chromatograph Crystal 5000.2 (Chromatec, Russia)

3. Results and discussion

The results of the experiment on the anaerobic digestion of the pretreated organic waste (simulated organic fraction of municipal solid waste) are presented in Figures 2 and 3 as well as in Table 3.
From the dynamics of the specific methane and biogas production (Figure 2), it can be seen that on the first day of the experiment, a higher rate of methane production was observed in all mixtures containing substrate pretreated in the EM than in mixtures containing untreated (native) substrate. The rates of biogas production in the first day were comparable. However, in the mixtures with untreated substrate, biogas consisted mainly of carbon dioxide and hydrogen, which indicated the instability of AD process. In all the studied mixtures, accumulation of volatile fatty acids (VFA) was low on the first day of the experiment. The total concentration of VFA (C2–C5) was the highest in the first 1–2 days of the experiment and did not exceed 0.4–0.6 g/l (data not shown). Only trace amounts (no more than 0.03 g/l) of acetate (C2) remained in the digestate after 5-6 days, which indicated the stability of the methanogenic community.

The inoculum used in the work was characterized by low biodegradability; the amount of methane released after the month of incubation did not exceed 20 ml/g of the initial volatile solids. The data on the production of methane and biogas (the sum of methane and carbon dioxide) in the control batches containing only inoculum were used further to calculate the yield of methane and biogas from the substrate according to the method described in [13]. Figure 3 and Table 3 show that the maximum methane yield was achieved in the mixtures after 4 minutes pretreatment in an EM and was about 136 ml per g VS of substrate. The lowest methane yield, about 72.3 ml per g VS of substrate, was observed in the untreated mixture. The specific biogas yield was also maximal in the mixtures after 4 minutes pretreatment in the EM and was 238.6 ml per g VS of substrate. Biogas and methane yields from the substrate with a shorter pretreatment time were lower, but not significantly, by about 5–6% (Table 3).

It should be mentioned that the methane to carbon dioxide ratio, which characterizes the calorific value of the biogas, was the highest in the mixture after 2 minutes pretreatment in an EM (except for control mixture without any substrate). In that mixture the produced biogas contained about 71% of methane. In the mixture without pretreatment, CH₄/CO₂ ratio was the lowest, the content of the methane in biogas was only about 43%.

Consequently, the pretreatment of substrate in the electromagnetic mill (EM) increased significantly the specific yield of biogas (by 25%), and especially the specific yield of methane (by 80%), compared to the substrate not subjected to the pretreatment. The methane production rate during anaerobic digestion of the pretreated substrate was approximately 50% higher than without pretreatment, and the rate of biogas production was virtually independent of the pretreatment in the EM.

It should be stated that the degree of substrate VS degradation after its treatment in the EM increased on average by 16%. This is also confirmed by a lower carbon to nitrogen ratio in the digestate after the end of AD process (Table 3).

Despite a sufficiently long incubation time under anaerobic conditions (one month), untreated substrate could not be converted effectively into biogas. This indicates insufficient bioavailability and efficiency of mass exchange between substrate particles and hydrolytic microorganisms, and hence usefulness of the substrate pretreatment. According to the obtained results on the anaerobic digestion of the simulated organic fraction of municipal solid waste, economically feasible time to treat the substrate in an EM is considered to be no more than half a minute, since the increase in methane yield with a longer pretreatment time is not significant.
Figure 2. Dynamics of methane (A) and biogas (B) production per g VS of mixture (both substrate and inoculum): CM –control mixture (only inoculum); 0 min, 0.5 min, 1.0 min, 2.0 min and 4.0 min –time of the substrate pretreatment in an EM.
Figure 3. Dynamics of methane (A) and biogas (B) production per g VS of substrate: 0 min, 0.5 min, 1.0 min, 2.0 min and 4.0 min – time of the substrate pretreatment in an EM.
Table 3. Parameters of the anaerobic digestion of the substrate pretreated in an EM.

| Parameter          | Measurement unit | Control (inoculum) | Substrate pretreatment time in an EM, min |
|--------------------|------------------|--------------------|-----------------------------------------|
| VS<sub>mixture</sub> destruction | %                | 9.2                | 30.2 33.9 31.3 36.2 33.4                |
| VS<sub>substrate</sub> destruction | g/g TS           | –                  | 56.0 64.6 59.9 70.4 64.2                |
| C/N<sub>final</sub> | % TS/% TS        | 9.3                | 11.8 9.0 8.9 8.9 9.7                   |
| pH                 | –                | 7.29               | 6.96 6.89 6.77 6.77 6.84                |
| Methane yield      | ml/g VS<sub>substrate</sub> | –                  | 72.3 128.2 128.4 129.6 136.3            |
| Biogas yield       | ml/g VS<sub>substrate</sub> | –                  | 191.1 224.7 225.0 222.5 238.6           |
| CH<sub>4</sub>/CO<sub>2</sub> | vol%/vol%        | 1.52               | 0.67 1.35 1.35 1.41 1.36                 |

4. Conclusion

The work studied the feasibility of using an electromagnetic mill for the mechanical pretreatment of simulated organic fraction of municipal solid waste and of increasing the efficiency of subsequent anaerobic digestion. The principle of operation of electromagnetic mill consists in using ferromagnetic particles as a working unit, which, under the influence of an electromagnetic field, rotate in the working zone at a speed close to that of the magnetic field rotation. At the same time, each ferromagnetic particle serves as a stirrer, what leads to rapid mixing and fine dispersion of the substrate components, improves its rheological properties, promotes partial hydrolysis of complex organic compounds, increases the availability of nutrients for microorganisms and provides heating.

Pretreatment in an EM resulted in the significant improvement of the characteristics of the subsequent AD of pretreated substrate. For instance, the specific biogas yield was increased by 25% and methane yield – by 80%. Substrate VS degradation degree after its treatment in an EM increased by 16% on average. The methane production rate was increased by 50% during anaerobic digestion of the pretreated substrate.

Thus, pretreatment in an electromagnetic mill is an effective way to increase the efficiency of anaerobic digestion of organic waste. Based on obtained results, economically feasible time to treat the substrate in an EM should not exceed half a minute, since the increase in methane yield with a longer pretreatment time is not significant.

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References

[1] Nozhevnikova A N, Kallistova A Yu, Litti Yu V and Kevbrina M V 2016 Biotekhnologiya i mikrobiologiya anaehroboj pererabotki organicheskikh kommunalnyh othodov: kollektivnaya monografiya (Moscow: Universitetskaya kniga) p 320 [In Russian]
[2] Carrère H, Bougrier C, Castets D and Delgenès J P 2008 Impact of initial biodegradability on sludge anaerobic digestion enhancement by thermal pretreatment J. Environ. Sci. Health 43 1551–5
[3] Luste S, Luostarinen S and Sillanpää M 2009 Effect of pre-treatments on hydrolysis and methane production potentials of by-products from meat-processing industry J. Hazard. Mater. 164 247–55
[4] Salminen E, Einola J and Rintala J 2003 The methane production of poultry slaughtering residues and effects of pre-treatments on methane production of poultry feather Environ. Technol. 24 1079–86
[5] Izumi K, Okishio Y, Nagao N, Niwa C, Yamamoto S and Toda T 2010 Effects of particle size on anaerobic digestion of food waste Int. Biodeter. Biodeg. 64 601–8
[6] Raynal J, Delgenès J P and Moletta R 1998 Two-phase anaerobic digestion of solid wastes by a multiple liquefaction reactors process Bioresour. Technol. 65 97–103
[7] Yiyings J, Huan L, Bux M R, Zhiyu W and Yongfeng N 2008 Combined alkaline and ultrasonic pretreatment of sludge before aerobic digestion J. Environ. Sci. 21 279–84
[8] Yeom I T, Lee K R, Ahn K H and Lee S H 2002 Effects of ozone treatment on the biodegradability of sludge from municipal wastewater treatment plants Water Sci. Technol. 46 421–5
[9] Web site of Apparat-NN LLC (http://apparat-nn.ru/) [accessed 30.06.2018]
[10] Mishchenko M V, Bokov M M and Grishaev M E 2015 Aktivaciya tehnikolicheskikh processov obrabotki materialov v apparatah s vrashchayushchimsya ehlektromagnitnym polem Fundamentalnye issledovaniya 2 3508–12 [In Russian]
[11] Kochetov O C 2009 Sistema utilizacji mokryh uglerodsoderzhashchih othodov (Patent for an invention) RUS 2385438 [In Russian]
[12] Seliverstov GV and Titov D P 2017 Need of utilization the ashes and slag waste with use of the processing machinery on the principles of devices of a vortex layer Ground transport-technological complexes and means (Materials of the International Scientific and Technical Conference) ed Merdanov Sh M pp 276–8 [In Russian]
[13] Angelidaki I and Sanders W 2004 Assessment of the anaerobic biodegradability of macropollutants Rev. Environ. Sci. Biotechnol. 3 117–29