Energy Efficiency of the Extrusion Process and its Effect on Output of Biogas during the Fermentation of Maize and Rape Straw

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Abstract. The purpose of the research is determining the influence of pre-treatment by extrusion of rape and maize straw on the output of biogas and the energy efficient mode of the extrusion process. The set goal is achieved by solving the following problems: pre-treatment of rape and maize straw by grinding and various versions of extrusion; carrying out experimental researches of the fermentation of rape and maize straw in the mesophilic mode of fermentation for 42 days; carrying out numerical modeling to determine the power inputs on the process of extrusion during change the frequency rotation of screw conveyer of the extruder. The most significant results: it was experimentally proven that the output of biogas from rape and maize straw increases when the size of their particles is reduced to a certain value, which is reached after 2-times extrusion, and further reduction of the size of the particles does not give a positive effect and, vice versa, reduces gas release. Extrusion provides not only grinding, but also thermo-baro processing, which additionally grinds lignin-cellulosic raw material. It was determined that the energy efficient mode of operation, the necessary level of pressure and temperature in the die, which exclude the burning of organic raw materials, is ensured at the rotation frequency of screw conveyer of the extruder at 110 r/pm. The significance of the obtained results is that the extrusion with the proposed technological and mode parameters of the extruder can be used as an effective method of pre-treatment of lignin-cellulosic raw material to increase the productivity of bioreactors and biogas output.
Keywords: substrate, biogas, extrusion, energy efficiency, simulation model.

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Eficiența energetică a procesului de extrudare și impactul acestuia asupra producției de biogaz în timpul fermentației paielor de porumb și rapiță

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Rezumat. Scopul cercetării este determinarea influenței pretratării prin extrudarea paielor de rapiță și porumb asupra producției de biogaz și a modului eficient energetic al procesului de extrudare. Scopul stabilit este atins prin rezolvarea următoarelor probleme: pretratarea paielor de rapiță și porumb prin măcinare și diverse versiuni de extrudare; efectuarea de cercetări experimentale de fermentare a paielor de rapiță și porumb în modul mezofil de fermentație timp de 42 de zile; efectuarea de modelări numerice pentru determinarea puterii de intrare în procesul de extrudare în timpul schimbării frecvenței de rotație a transportorului cu șurub al extruderului. Cele mai semnificative rezultate: s-a demonstrat experimental că producția de biogaz din paiele de rapiță și porumb crește atunci când dimensiunea particulelor acestora este redusă la o anumită valoare, care este atinsă după extrudare de 2 ori și o reducere suplimentară a dimensiunii particulele nu dă un efect pozitiv și, invers, reduce eliberarea de gaz. Extrudarea asigură nu numai măcinarea, ci și prelucrarea termo-baro, care măcina suplimentar materia primă lignină-celulozică. S-a stabilit că modul de funcționare eficient energetic, nivelul necesar de presiune și temperatură în matriță, care exclude arderea materiilor prime organice, este asigurat la frecvența de rotație a transportorului șurub al extruderului la 110 r/pm. Semnificația rezultatelor obținute este că extrudarea

cu parametrii tehnologici și de mod propuși ai extruderului poate fi utilizată ca metodă eficientă de pretratare a materiei prime lignino-celulozice pentru a crește productivitatea bioreactoarelor și a producției de biogaz.
Cuvinte-cheie: substrat, biogaz, extrudare, eficiență energetică, model de simulare.

Энергоэффективность процесса экструзии и ее влияние на выход биогаза при ферментации кукурузной и рапсовой соломы

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Аннотация. Цель исследований – определение влияния предварительной обработки экструзией рапсовой и кукурузной соломы на выход биогаза и энергоэффективный режим процесса экструзии. Поставленная цель достигается за счет решения следующих задач: предварительная обработка рапсовой и кукурузной соломы путем измельчения и различных вариантов экструзии; проведение экспериментальных исследований ферментации соломы рапса и кукурузы в мезофильном режиме брожения в течение 42 суток; проведение численного моделирования для определения энергозатрат на процесс экструзии при изменении частоты вращения шнекового конвейера экструдера. Наиболее значимые результаты: экспериментально доказано, что выход биогаза из рапсовой и кукурузной соломы увеличивается при уменьшении размера их частиц до определенного значения, которое достигается после 2-кратной экструзии, и дальнейшего уменьшения размера частиц не дает положительного эффекта и, наоборот, снижает газовыделение. Экструзия обеспечивает не только измельчение, но и термобарообработку, при которой дополнительно измельчается лигнино-целлюлозное сырье. Установлено, что энергоэффективный режим работы, необходимый уровень давления и температуры в матрице, исключающий горение органического сырья, обеспечивается при частоте вращения шнекового конвейера экструдера 110 об/мин. Значимость полученных результатов заключается в том, что экструзия с предложенными технологическими и режимными параметрами экструдера может быть использована как эффективный метод предварительной обработки лигнино-целлюлозного сырья для повышения производительности биореакторов и выхода биогаза.
Ключевые слова: субстрат, биогаз, экструзия, энергоэффективность, имитационная модель.

INTRODUCTION

The production of biogas from lignin-cellulosic biomass is complicated by the fact that this biomass is resistant to biodegradation by enzymes and microbes due to its peculiar characteristics [1, 2] and contains natural polymers such as cellulose, hemicellulose, and lignin [3, 4]. The polymers are connected to each other by a polyphenol anaerobically indecomposed compound, lignin, which gives the straw a rigid structure and makes it resistant to biological decomposition due to various mechanisms, such as lignin-carbohydrate bonds, the physical shell of cellulose and hemicellulose, also the unproductive adsorption of hydrolyzing enzymes [5]. Crystallinity of cellulose and degree of polymerization (DP), as separate of the key factors, also negatively effect on the process of degradation [6]. Therefore, when straw is used as the raw material in the process of biogas production, a low output of methane and a low level of production are expected. This can primarily be explained by difficult hydrolysis, which is the first stage of the reaction in the process of degradation, where polymers are split and dissolved into monomeric units through enzymatically catalyzed reaction with water [7]. As a rule, any type of biomass can be used as a substrate for biogas production, if it contains carbohydrates, proteins, fats, cellulose and hemicellulose as main components. However, this process must be preceded preliminary treatment, which will destroy lignin and release hemicellulose and cellulose for strengthening the fermentation of substrates [8]. Scientific sources confirm that using pre-treatment can increase the efficiency of biogas production by more than 90% for raw material such as grass, maize straw and wood [2,9]. There are such methods of preliminary treatment of lignin-cellulosic biomass as chemical, biological, mechanical and heat treatment with pressure. The use of one or another method is determined by such aspects as energy efficiency, technological effectiveness, environmental friendliness, economy.

Splitting of lignin, hemicellulose and cellulose in rape and maize straw can be carried out by extrusion, that is, the process in which combination of pressure, temperature and shearing forces that acting on the processed material is achieved, which is ductile to heating and plasticization [10, 11]. During the process, the chamber of extruder has a high temperature that can reach 200 °C, and depending on the configuration of the unit, the pressure reaches different values. The time of the process, during which the biomass stays inside chamber of the extruder , depends on the length of the plasticizing system and the speed of rotation screw conveyer of the extruder [12].

ANALYSIS OF RECENT RESEARCHES AND PUBLICATIONS

Pre-extruded maize straw, moistened to 25% and processed at 110 r/pm of screw conveyer, gave the greatest effect for production of methane and biogas (51.63%) in comparing to maize straw without pre-treatment (49.57%) [12]. After extrusion treatment, the cumulative output of biogas from wheat straw increased by 23%, and methane increased by 27% in comparing to non-extruded biomass [13]. Mechanical pre-treatment led to the destruction of structural materials in all used biomass, which was characterized by reduction in time during anaerobic fermentation and further increasing output of methane up to 22% [14]. In [15], four different mechanical methods of pre-treatment of wheat straw were studied, namely: roller grinding, extrusion, granulation, and hammer grinding. The effect of pre-treatment on anaerobic fermentation (AD) at 37 °C was analyzed from the point of view of biochemical potential of methane (BMP), maximum daily production of methane (DMP_{max}) and output of enzymatic hydrolysis (EH) as the ratio of released glucan to initial glucan content. Roller grinding generated the highest BMP -of 287 Hml $CH_4 * gVS^{-1}$,that is increasing by 21% comparatively to untreated wheat straw. Extrusion provided the highest rate of methane production (52 Hml $CH_4 * gVS^{-1} day^{-1}$). Specific analysis of the surface and EH particles by size of 0.25–1 mm showed that mechanical pre-treatment most likely effects on the physico-chemical properties of wheat straw, such as crystallinity and melting of the outer wax layer, which in turn effects differently on AD and EH processes . Grinding and extrusion of maize silage and silage of maize straw accelerates process of their anaerobic fermentation . Extrusion of silage from maize straw at 175 °C led to the highest yield of methane per dry organic matter, that is, an increase by 12.4%. Extrusion of maize silage and silage from maize straw at 150 °C increased methane yield by at least 6.4% and 9%, respectively. Grinding the substrates accelerated their fermentation and led to higher yield of methane. The largest increase output of methane, that is 38.4%, was fixed for maize silage, while the increase output of methane from silage of maize straw was only 8.3% [16]. Wheat straw (WS) and its solid digestate (WSD) were chosen to evaluate the impact of extrusion on biogas production. WS and WSD were extruded and then used for biogas production at (37 ± 1)°C. As the results showed the contents of cellulose, hemicellulose, and lignin in WS and WSD were 28.37%, 24.60%, 14.35%, and 30.20%, 24.73%, 21.58%, respectively, while the cumulative yield of WS and WSD biogas was 178.96 and 56.68 ml/g T. After extrusion, the cumulative output of biogas WS and WSD increased by 22.55% and 152.33%, respectively, while the cumulative methane yields of WS and WSD were increased by 27 .01% and 191.58%, respectively, comparatively to non-extruded biomass[17].

A single-screw conveyer extruder was used to process artichoke straw. Chopped straw, moistened to 30, 40 and 50%, was striked to the extrusion process at different rates of screw conveyer (70, 90 and 110 r/pm). The maximum efficiency and the highest disintegration were observed for the sample with 50% moisture content processed at speed of the extruder screw conveyer at 90 r/pm. The sample obtained at 30% of humidity and 90 r/pm was characterized by the lowest efficiency and viscosity of hot paste and the highest specific mechanical energy. The results showed that the process of extrusion led to desirable changes in the structure of the analyzed lignocellulosic biomass [18]. When reed straw with small lignin particle size (≤ 0.13 mm) was pre-treated, methane yield decreased by 31% in comparing to the largest size (0.6–0.9 mm). Different sizes of particles did not significantly change methane yield ($p > 0.05$) under the two AD conditions, however the size of particles ≤ 0.13 mm was positively correlated with fast decomposition rates. The highest methane yield (333 ± 0.8 ml-gVSadded−1) and rate (15.4 ± 1.1 ml-gVSadded d−1) were achieved with this size under thermophilic conditions [19]. The stalks of maize are treated with physical pre-treatment with reduction of the size of particles, biological pre-treatment with the addition of EM-4 up to 3% r/r, 5% r/r, 7%

r/r, also by adding NaOH as a chemical pre-treatment to 0.25 N, 0.50 N and 0.75 N [20]. Extrusion of the herbal raw material improved the mixing properties and reduced the formation of floating layer even at concentration of solid matter 10% (m/r). This pre-treatment also increased the biomethane potential of silage grass and fresh grass by 18 and 11%, respectively, based on fresh substance, while chopping reduced this value by 14% in comparing with fresh grass. This is explained by changes in the content volatile solids (VS) of the treated samples, as all conditions led to the same biomethane yield per ton VS, ranging from 325.5 to 337.6 Nm3 CH_4/ton VS. The income is obtained from the treatment by extrusion was from 6 to 17 euros per tonne of FM, compansate the cost of this additional stage, indicating that extrusion would be a techno-economical process of the anaerobic fermentation of grass [21]. Existing researches of extrusion pre-treatment show that it is mainly applied to crops which containing lignin, hemicellulose, and cellulose, but these conditions may be potentially suitable also for removing of pathogens from waste substrates [22].

MATERIALS AND METHODS OF RESEARCH

Researches were conducted on rape and maize straw of farm in Koziv district of Ternopil region.

As a source of methane bacteria, fermented cattle manure from the fermenter of the biogas unit of the institute, wCP-1.7%, pH-7.7% was used. Determination of dry matter DM, organic dry matter ODM, reaction of medium pH, fractional composition and content of chemical elements were carried out according to relevant standards and known methods [23].

The laboratory fermenter is a gas-tight bag made of polymer material with a capacity of 500 ml. The investigated biomass and seeding of methane bacteria were placed in the bag in a ratio of 1:4, then the bag was sealed up and its initial volume was determined by immersing it into water. The fermenter was suspended in an incubator at the temperature of +37.5^{0}C for 42 days. The volume of the biogas sample was determined every seven days by the amount of change in the volume of the fermenter by immersing it into the water with the temperature of +37.5^{0}C by the amount of displaced water. Chopped straw was obtained by grinding straw on a laboratory grinder, and extrusion was carried out on the single-screw conveyer extruder (Fig. 1) with drive from asynchronous electric motor of type AIR160S4.

When the extruder is loaded at 80-90% and frequency rotation of the screw conveyer is 130 r/pm. with the help of the measuring set K505 , the consumed current and active capacity of the electric motor were determined, which in this mode summed to 50 A and 14.5 kWt, respectively. At the same time, burning of biomass and burning out of organic matter was observed. To avoid this harmful phenomenon, water was fed into the throat of the extruder.

During the passage of straw through the extruder, not only the structural and mechanical change of the biomass occurred, but also the process of compressing the raw material to 20 MPa and its simultaneously heating to 170^{0}C was passed. After passing through the die, the pressure sharply dropped and the kind of "explosion" took place, which ensures the destruction of lignin and, thus, gives access for microorganisms to nutrients.

During extrusion, the specific energy intensity of the process was determined according to the expression [24]:

$$C_e = \frac{\sqrt{3} IU \cos\varphi}{1000G} \qquad (1)$$

where C – is specific energy intensity of extrusion process, kW·h·t^(-1); I ; I – consumed current, A; U - voltage of electrical net, V; G – mass productivity of the extruder, t·h^(-1) cosφ – power coefficient of the electric drive.

The mass productivity of the extruder is directly proportional from the rotation frequency of the screw conveyer:

$$G = 0{,}9\pi((D+2\delta)^2 - d^2)\cdot n \cdot p \cdot s_i \cdot \gamma \qquad (2)$$

where D- is the diameter of screw conveyer , m; δ– gap between the body and the screw conveyer, m; d – diameter of shaft of the screw conveyer, m; n – rotation frequency of the screw conveyer, r/pm; s_i– step winding of screw conveyer, m; ρ– specific weight, kg/m^3 ; Y– coefficient of fullness of the screw conveyer.

The duration of all stages of extrusion is approximately the same, and the loading of the extruder had a stochastic character.

According to the work [25], the drive capacity of the single-screw conveyer extruder is determined by the formula:

$$P_a = \frac{\pi^2}{2} D^2 n h_2 p \cdot tg\alpha + \pi^3 D^2 n^2 \eta L_2 \left(\frac{D}{h_2 \cos\alpha} + \frac{e}{\delta tg\alpha}\right), \quad (3)$$

where D- is the outer diameter of the screw conveyer; n - rotation frequency in the formula instead of N, insert n; h_2 – depth of thread of the screw conveyer; p – pressure; α- the angle of inclination of the helical line thread of the screw conveyer; η- the dynamic viscosity of the pressed material; L_2– length of the screw conveyer; e – thickness of the coil; δ- the gap between the wall of cylinder and the coil of the screw conveyer.

Fig. 1. Single-screw conveyer extruder for grinding maize and rape straw: 1 – loading throat; 2 – electric motor; 3 – die; 4 - screw conveyer

The author of the work [25] indicates that with accurate calculations, the second term of the right-part of formula (3) needs correction, which is connected with the fact that due to the intensive shift of the layers of material during the pressing process, the viscosity changes and is not a constant.

It follows from formula (3) that the dynamic viscosity is directly proportional to the capacity of the single-screw conveyer extruder, i.e. to minimize power inputs for pressing of solid fuel from biomass, the dynamic viscosity of the material must be minimal.

According to [26], the shift rateϒ is defined as the difference between two velocities related to the distance in the direction perpendicular to the flow of material:

$$\dot{\gamma} = \frac{2\pi R_i \omega}{R_e - R_i} \quad (4)$$

where R_i- is the diameter of screw conveyer, m; ω - angular speed of the screw conveyer, c$^-$

[1]; R_e- - the diameter of sleeve of the screw conveyer, m.

It can be seen from formula (3) that with increasing in the diameter of the inner cylinder, the increase in the speed of rotation or decrease in the coaxial gap, the shift rate increases.

The shear stress of the material -is the stress that necessary for appearing shear deformation. It depends on the twisting moment that necessary for rotation:

$$\tau = \frac{M}{2\pi R_i^2 L} \qquad (5)$$

where M- is the twisting moment applied to the screw conveyer, N·m; L- the level of the material in the coaxial gap, m.

The dynamic shear viscosity is equal to:

$$\eta = \frac{\tau}{\dot{\gamma}} = \frac{M(R_e - R_i)}{4\pi^2 R_i L\omega} \qquad (6)$$

On the basis of equation (3) in the Matlab application program package in the Simulink environment, a simulation model of the extruder was developed for the research of power inputs for grinding maize and rape straw.

The constant values of formula (3) are set by Constant blocks with the corresponding designations of the values that they display. Mathematical operations between them are performed by corresponding blocks of the Simulink library, namely: adding Subtract, multiplication Product, division Divide, raising to a power Math Function, trigonometric functions Trigonometric Function. The asynchronous electric motor of the extruder drive is reproduced by the Asynchronous Machine SI Units block, which is feeding by a frequency converter - ~3f-PWM1 block, which is started up by the Step block. Since the rotation frequency of the extruder screw conveyer effects on the power inputs, its value is removed from the output of the Bus Selector block and through the Product4 block to the Product1 and Math Function 4 blocks, which effects on the loading of the electric motor. To determine the effects of rotation frequency on the power inputs, we change the frequency and voltage of feeding in accordance with the law $\frac{U}{f} = const$ of -PWM1 block, and we take the results of the research from the Scope4 oscilloscope.

Using the simulation model (Fig. 2), the consumed current and moment of the electric drive were determined during changing the speed of rotation of the extruder screw conveyer. The rotation frequency was changed with the help of the frequency converter (PWM block), which feeds the asynchronous motor, and the results of the researches were recorded on the Scope4 block of oscilloscope.

RESEARCH RESULTS AND THEIR DISCUSSION

The results of researches of the process of biogas output over the period of 42 days for various versions for the extrusion of rape and maize straw in the mesophilic mode of fermentation are presented in Table 1 and Fig. 3,4.

Conducted researches show that preliminary processing (extrusion) of rape and maize straw contributes to increase output of biogas in the mesophilic mode of fermentation, since extrusion carries out not only mechanical grinding, but also the thermo-baro effect. When the screw conveyer feeds the moistened material into the dosing zone, high pressure (15-25 MPa) and temperature (120-150^0 C) are created in it. When passing through the die of the matrix under the action of the sharp change of pressure (from 15-25MPa to atmospheric), occur almost instantaneous evaporation of both free and part of the bound moisture.

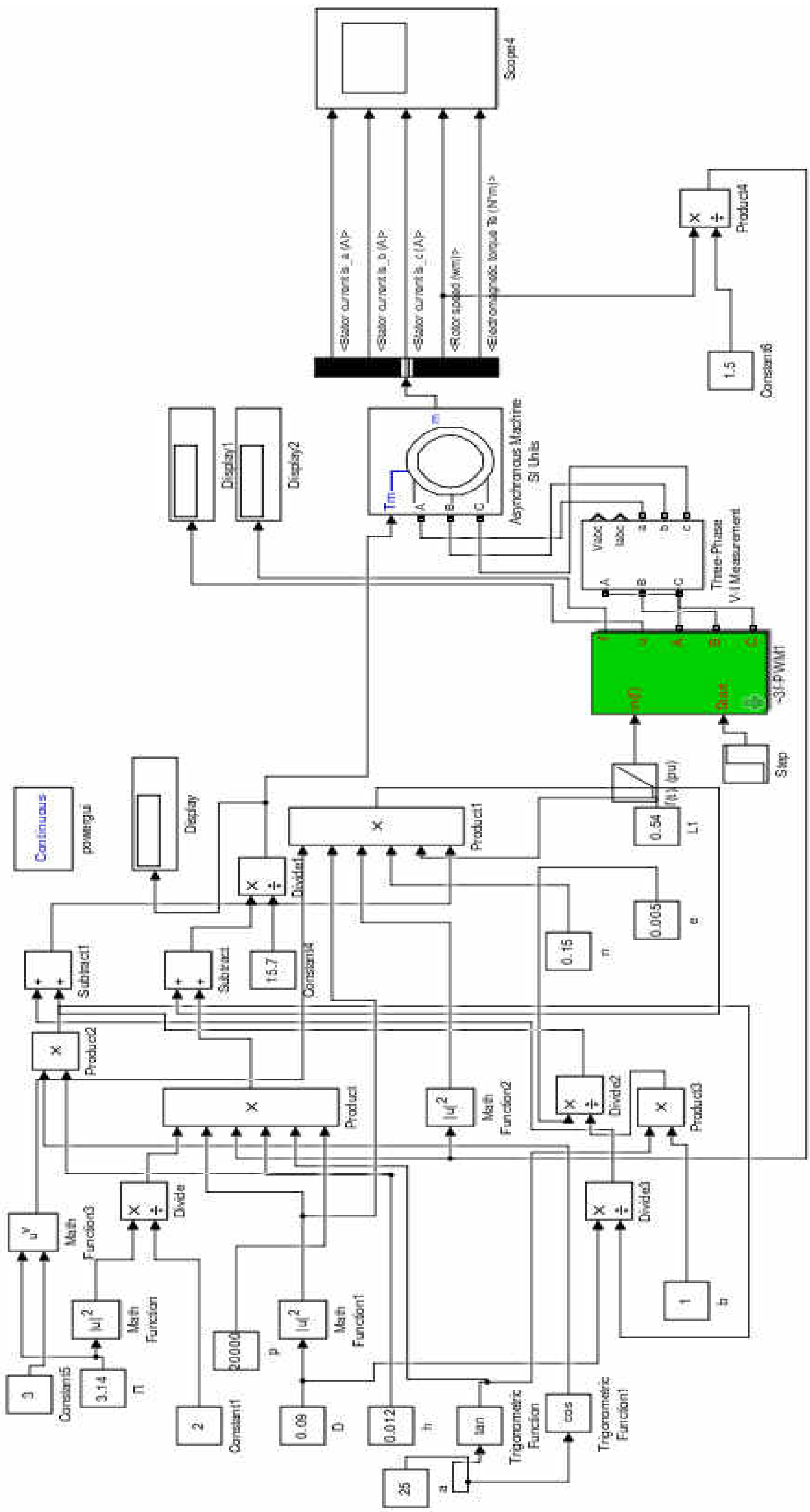

Fig. 2. A simulation model of the extruder for the study of power inputs on grinding maize and rape straw.

Table 1

Biogas output from rape and maize straw for various versions of the extrusion

№ з/п	Versions	Output of biogas m^3 /t DM					
		7	14	21	28	35	42
1	2	3	4	5	6	7	8
1	Chopped rape straw, average size 7.2 mm x 1.5 mm + seeding of methane bacteria	93	156	174	184	184	184
2	Extruded rape straw (1-time extrusion, average size 5.0 mm x 1.5 mm), which is pre-soaked for 15 minutes in water-pipe water at the temperature of (+17^{0}C), + seeding of methane bacteria	119	196	218	227	231	239
3	Extruded rape straw (2-times extrusion, average size 3.0 mm x 1.0 mm), which is pre-soaked for 15 minutes in water-pipe water at the temperature of (+17^{0}C), + seeding of methane bacteria	129	206	234	237	251	251
4	Extruded rape straw (3-times extrusion, average size 2.9 mm x 1.0 mm),which is pre-soaked for 15 minutes in water-pipe water at the temperature of (+17^{0}C), + seeding of methane bacteria	118	220	232	242	252	254
5	Extruded rape straw (4-times extrusion, average size 2.5 mm x 1.0 mm), which is pre-soaked for 15 minutes in water-pipe water at the temperature of (+17^{0}C), + seeding of methane bacteria	110	209	235	242	242	245
6	Extruded rape straw (5-times extrusion, average size 2.0 mm x 1.0 mm),which is pre-soaked for 15 minutes in water-pipe water at the temperature of (+17^{0}C), + seeding of methane bacteria	115	189	205	205	225	225
7	Flour of rape straw, average diameter d ≤0.5 mm + seeding of methane bacteria	110	163	181	181	196	211
8	Chopped straw of maize stalks, average size 28.5 mm x 8.0 mm + seeding of methane bacteria	126	305	351	356	359	359
9	Extruded maize straw (1-time extrusion, average size 9.1 mm x 2.0 mm), which is pre-soaked for 15 minutes in water-pipe water at the temperature of (+17^{0}C), + seeding of methane bacteria	147	310	343	364	364	364
10	Extruded maize straw (2-times extrusion, average size 7.3 mm x 1.2 mm), which is pre-soaked for 15 minutes in water-pipe water at the temperature of (+17^{0}C), + seeding of methane bacteria	168	323	369	371	386	388
11	Extruded maize straw (3-times extrusion, average size 6.3 mm x 1.2 mm), which is pre-soaked for 15 minutes in water-pipe water at the temperature of (+17^{0}C), + seeding of methane bacteria	143	311	348	375	388	388

Continuation table 1

1	2	3	4	5	6	7	8
12	Extruded maize straw (4-times extrusion, average size 6.2 mm x 1.2 mm), which is pre-soaked for 15 minutes in water-pipe water at the temperature of (+17^{0}C), + seeding of methane bacteria	100	286	338	370	378	378
13	Extruded maize straw (5-times extrusion, average size 4.9 mm x 1.2 mm), which is pre-soaked for 15 minutes in water-pipe water at the temperature of (+17^{0}C), + seeding of methane bacteria	100	299	345	384	384	384
14	Flour of maize straw, average diameter d ≤0.5mm + seeding of methane bacteria	133	308	360	360	365	365

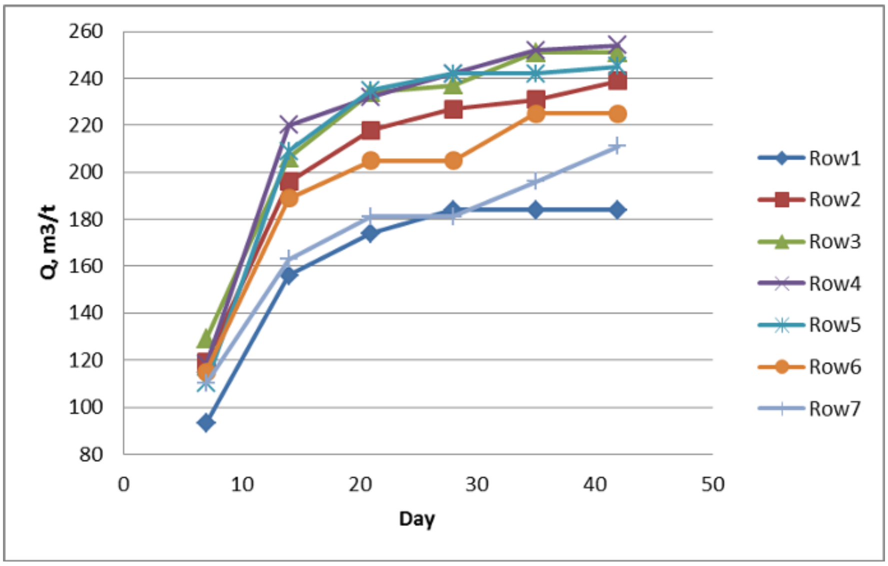

Fig. 3. Biogas output for 42 days of fermentation of rape straw depending on grinding

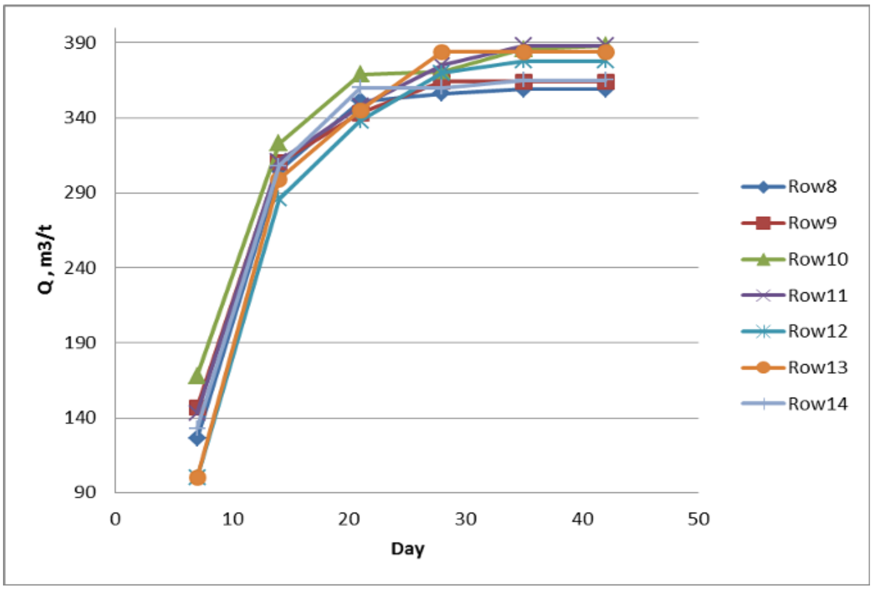

Fig. 4. Biogas output for 42 days of fermentation of maize straw depending on grinding.

There is also change in the physical structure of the plant material, namely the sharp increase in its volume and porosity, which leads to the destruction of lignin and thus gives access to food products for microorganisms. But, as the research shows, the maximum yield of biogas is at thrice repeated extrusion of rape straw with the average size of particles of 2.9 mm x 1.0 mm and is 254 m^3 at 42 days of fermentation (experiment 4). In double extrusion (experiment 3) with the average size of particles of 3.0 mm x 1.0 mm, the yield of biogas is 251 m^3, which is a slight deviation from the result of experiment 4, but the dynamics of biogas yield at the initial stage of fermentation is better. Biogas output decreases with increasing grinding. An analogy is also followed with maize straw, both with the double extrusion with the average size of particles of 7.3 mm x 1.2 mm (experiment 10) and thrice repeated extrusion with the average size of particles of 6.3 mm x 1.2 mm (experiment 11) on day 42 fermentation, the yield of biogas is 388 m^3 .This can be explained by the fact that extrusion most likely effects on other physico-chemical properties of straw, such as crystallinity or melting of the outer layer of wax, burning, which, in turn, has the different effect on fermentation processes [18]. Researches show that it is rational to carry out double extrusion of rape and maize straw and reduce the duration of fermentation to 28 days.

The specific energy intensity of one-time extrusion was experimentally determined, which is approximately 86 kW* h/t for maize straw, for rape straw - 79 kW. h//t.

The calorific facility of biogas, which was determined from the known value of the calorific facility of natural gas by multiplying the determined share of methane in the volume of biogas by 32.7 MJ/m^3. The determined calorific facility of biogas is 6.44 kW h/m^3, which corresponds to the typical composition of biogas during anaerobic fermentation, which is saturated with moisture, –6.5 kW h/m^3 [27].

With the use of the simulation model (Fig. 2), the energy parameters of the extruder electric drive were investigated. The results of the numerical experiment in the "Matlab" application program package at different frequencies current feeding of the electric motor (50 Hz, 45 Hz, 40 Hz, 35 Hz, 30 Hz) and, accordingly, feeding voltages of 220 V, 198 V, 176 V, 154 V, 132 V. The energy efficiency of extrusion and the quality of the substrate depends on the rotation frequency of the extruder screw conveyer. Since pressure and temperature increase sharply at high rotates, this leads to burning of plant material, rapid wear parts of extruder and overexpenditures of electrical energy.

In table 2 presents the results of modeling of the energy indicators of the extrusion process during adjusting the frequency of net supply. Coefficient of variation of frequency $K_f = f_1 / f_i$, where f_1=50 Hz , f_i -is the current frequency (45 Hz, 40 Hz, 35 Hz, 30 Hz).

Table 2

Energy parameters of the processs of maize straw extrusion during adjusting the frequency of net supply of the electric drive

K_f	U, V	I, A	Cos φ	Input capacity, kW	n, rpm	G, $t \cdot h^{-1}$	C_e, $kW \cdot h \cdot t^{-1}$	Coefficient of relative efficiency
1	220	49.4	0.85	16.1	155	0.095	86.0	0.9
0,9	198	44.4	0.87	13.3	142	0.087	77.2	0.88
0,8	176	34.6	0.89	9.43	125	0.077	62.0	0.83
0,7	154	30.9	0.91	7.5	110	0.067	56.4	0.77

During changing the frequency of the net supply of the electric drive from 50 to 35 Hz, decrease in mass productivity, specific energy intensity of the process, and coefficient of relative efficiency is observed. But at the frequency of 30 Hz, the specific energy intensity of the process begins to increase and the coefficient of relative efficiency is almost in twice decreased. The power coefficient cosφ increases when the frequency of the net supply of the electric drive is reduced.

So, from the point of view of energy efficiency, avoiding the burning of plant material and ensuring the quality of the substrate, the rational rotation frequency of the screw conveyer is 110 r/pm. at the frequency of current supply of the electric motor is 35 Hz. The results of the research [12] also show that the maximum yield of biogas from maize straw was observed during pre-treatment with extrusion, when the rotation frequency of the screw conveyer was 110 r/pm.

According to expression (6), during modeling the extrusion process while preservation of the design parameters at different rotation frequencies of the screw conveyer and correspondingly change of the electromagnetic moment, occurs changing of the dynamic shift viscosity of the material, which effects on the own frequency of the common structure of the screw conveyer - raw material, also the viscosity - elastic forces of friction. The presence of oscillations of the electromagnetic moment of the electric motor at the frequency of 30 Hz indicates on the rising of resonance oscillations [28], which require additional researches.

CONCLUSIONS AND PERSPECTIVES

Results of researches show that the maximum yield of biogas from rape and maize straw can be obtained if preliminary thrice repeated extrusion is carried out, but double extrusion is economically feasible.

The energy efficiency of extrusion depends on the rotation frequency of the extruder screw conveyer. At the rational mode the ratio of power inputs, productivity and quality of the obtained substrate, the rotation frequency of the extruder screw conveyer is 110 r/pm. at the frequency current supply of the electric motor of 35 Hz.

To ensure rational mode of the extruder, it is necessary to develop an automatic control system that would take into account the pressure and temperature in the die during stochastic loading of the extruder.

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