INTEGRATED USE OF BIOENERGY CONVERSION TECHNOLOGIES IN AGROECOSYSTEMS
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КОМПЛЕКСНЕ ВИКОРИСТАННЯ ТЕХНОЛОГІЙ БІОЕНЕРГЕТИЧНОЇ КОНВЕРСІЇ У АГРОЕКОСИСТЕМАХ

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ABSTRACT
The paper substantiates the mechanical and technological principles of formalizing the structure of agroecosystems on the basis of optimizing the interdependence between the elements of the agroecosystem within a specified range of conditions. The equipment for the production of bioenergy resources is improved by means of minimizing its energy capacity with all qualitative indices of the technological processes preserved.

РЕЗЮМЕ
У статті обґрунтовано механіко-технологічні основи для формалізації структури агроекосистем на основі оптимізації взаємозв'язків між елементами агроекосистеми у визначеному діапазоні умов. Удосконалено обладнання для виробництва біоенергоресурсів шляхом мінімізації його енергоємності при збереженні якісних показників технологічних процесів.

INTRODUCTION
There is no doubt that every measure proposed for implementation in agroecosystems should not only provide soil fertility, but favour the expanded fertility renewal. Therefore, the important task is to determine the amount of plant biomass, which can be used in heating without any harm to soil fertility recovery. It should also be taken into account that the use of technological processes with high mechanization level does not always lead to higher economic production indices because of increased deductions in production costs for technical servicing and repair of technical equipment, as well as deductions for depreciation, which are not compensated by additional production profits.

Oil-bearing crop production takes one of the leading positions in the structure of plant growing and in the whole system of agricultural production in Ukraine. In the structure of total agricultural output, 35% of total production volumes in all farm categories are due to these crops. The main producers of these products manufacture 60% of oilseed products *(***Agricultural Ukraine, 2015)*. In terms of food security, the volumes of domestic production fully satisfy domestic demands in these products, leaving some bulk for export and raw materials for biofuels.

The experience of using biogas plants was completely analysed by the Agency for renewable resources in Germany *(***Guide to biogas, 2012)*. The authors of the analysis indicate that in the absence of biomass mixing in the reactor, after a while there is a separation of biomass with layer forming due to the difference in density of certain mineral and organic components, as well as to flotation of particles while yielding gas. Thus, the biggest part of the anaerobic bacteria biomass is situated at the bottom of the reactor and the organic part of the biomass substrate accumulates at the top of the reactor. As a result, the contact zone of anaerobic bacteria with biomass substrate is limited by a boundary layer of mentioned parts of the reactor. Floating crust of solid organic substances also blocks biogas yield. Facilitation of anaerobic bacteria contact with substrate biomass is provided by mixing the substrate, but intensive mixing should be avoided because it can cause stopping of anaerobic fermentation at the expense of disturbance of acetogenic and methanogenic bacteria symbiosis. In practice, a compromise is achieved by slow rotation of agitators or by their work within a short period of time. Part of the solid mineral inclusions contained in substrates based on manure is released in the process of biological decomposition inside the reactor. Mineral sediment reduces the useful volume of the reactor (*Gouxa X. et al, 2016; Satjaritanuna P. et al, 2016).*

MATERIALS AND METHODS

Structural diagram for the biological conversion of organic material in agricultural ecosystems with production of outputs and biofuels was developed on the basis of typical crop rotation for intensive farming in the Forest-Steppe zone using the calculation of the balance of humus and compost mixture formulation through agrochemical balances. The amount of straw for combustion was calculated as the difference between the total quantity of straw and the priority needs of its use. Heat generation ability of different types of straw was calculated on the basis of DSTU 3581-97 Energy efficiency. We used the methods of measurement and calculation of combustion heat. Biodiesel production resources were determined on the basis of statistical indicators of Ukrainian agricultural sector. Estimated volume of the produced biogas was determined on the basis of the intensity of organic biomass decomposition during its fermentation.

RESULTS

Biological energy conversion

With due regard to well-known regularities and research results it is developed the structural diagram and simulation model of diversified manufacturing of products with biological energy conversion of organic raw materials for 6-field crop rotation with a total area of 300 hectares (fig. 1).

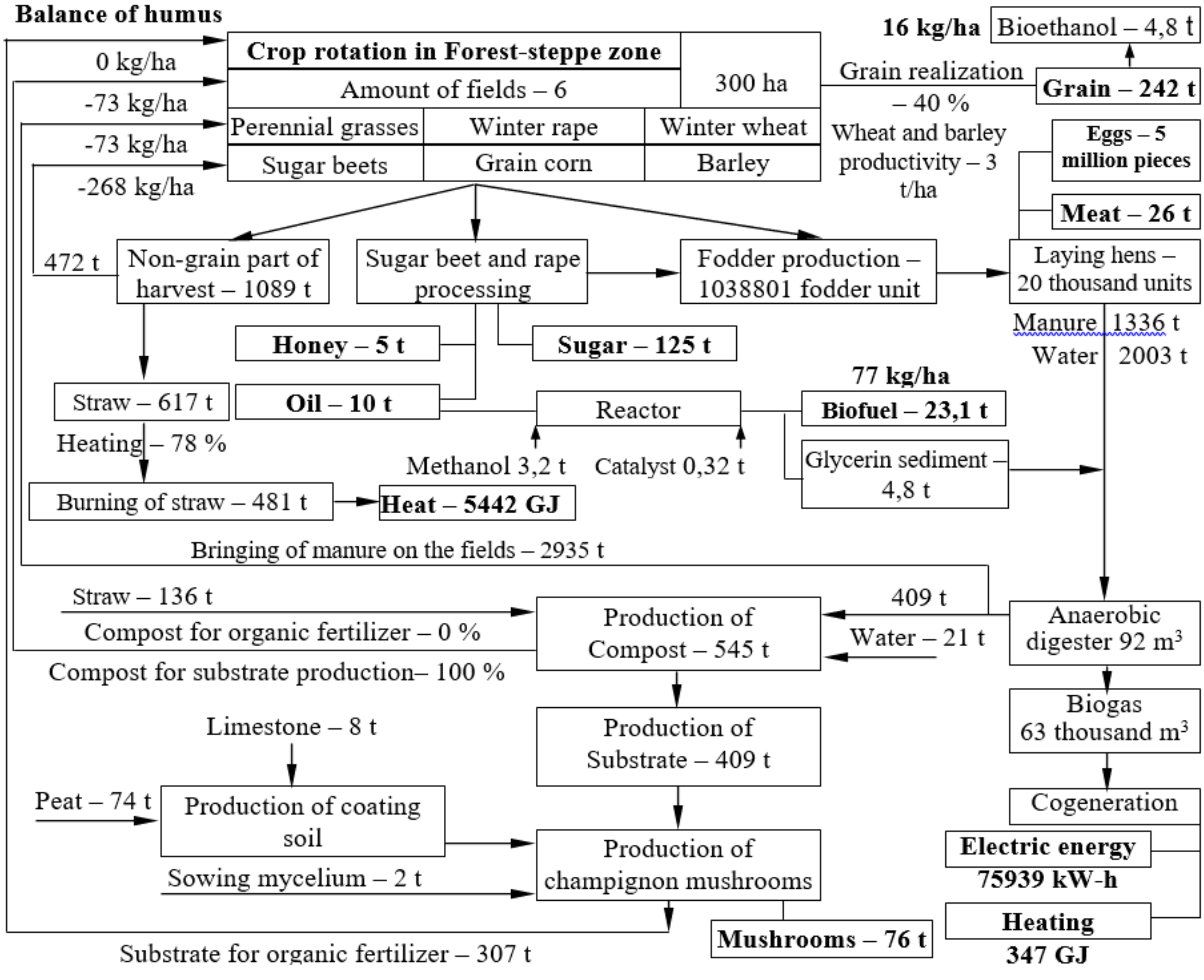

Fig. 1 – Structural diagram for the manufacturing of production and energy on the basis of biofuels

Structural diagram of diversified manufacturing of agricultural products and energy envisages: growing of rotation field crops with production of grain and sugar beets; harvesting of crop straw and rape stalks; leaving of shredded corn stalks in the field as mulch; feed production for poultry; manufacturing of poultry products; methane (anaerobic) fermentation of poultry manure with production of heat and electric power from biogas; the preparation and use of grain crop straw and rape stalks for heating needs in the form of briquettes, rolls or chaff; usage of grain crop straw, rape stalks and fermented manure for compost production; production of substrate for champignon growing in compost and champignon production;

production of biodiesel from rape seeds; use of glycerine residue for heating needs or its anaerobic fermentation.

On the basis of the introduced scheme it was defined the balance of humus in crop rotation using the well-known equation:

$$B = \frac{1}{\sum_{i=1}^{n} S_i}\left[-\sum_{i=1}^{n} S_i M_i + \sum_{i=1}^{n} S_i U_i k_{DWi} k_{Hi} + \sum_{j}^{m} OB_j \left(1-\frac{W_j}{100}\right) k_{Hj}\right], \quad (1)$$

where:

B – the annual balance of humus in crop rotation, kg/ha;

S_i – the area under the i rotation crop, ha; M_i – mineralization of humus by the i rotation crop, kg/ha;

U_i – the productivity of the i rotation crop, kg/ha;

k_{DWi}, k_{Hi} – output coefficients of dry weight of residues and their humification for the i rotation crop, rel. units.;

OB_j – annual organic biomass volume of the j species (non-seed biomass of agricultural crops remaining in the fields, manure, compost, substrate and biomass of weeds, green manure, etc.), which enters the field during a year, kg;

W_j – relative humidity of organic biomass of the j species, %;

k_{Hj} – humification coefficient of dry organic biomass of the j species, rel. units.;

n, m – the number of rotation fields and the number of organic biomass species respectively, units.

Computer simulation model allows determining the quotient of straw, which can be used for heating needs individually for separate farm. Thus, under the conditions shown in the figure, it can be reserved 78 % of straw for heating needs, and the part of the gathered straw in amount of 136 tons should be used for humus deficiency compensation in order to compensate humus losses completely. This can be done by two methods – either to leave some chopped straw in the fields or to develop on its basis compost or substrate for growing champignons.

Straw combustion

On the basis of existing indicators, which characterize agricultural production in Ukraine during recent years in general, there were also made the calculations on defining the straw volume limits used for heating needs. This dependence defined as a percentage of the total amount of straw is as follows:

$$C^{\%} = -0{,}57D + 48{,}66 \quad (2)$$

where:

$C^{\%}$ is the straw amount limit from the total amount which can be used for heating needs, %;

D – annual humus deficiency, kg/ha.

It should be mentioned, that in the case of the total humus deficiency in the range of 80 to 90 kg/ha, the use of straw for heating needs is impossible because of soil fertility preserving terms. The maximum amount of straw which can be used for heating needs with zero humus balance is about 50%.

To ensure use of corn and sunflower tops for heating needs, as well as of rape stems, there remain unsolved technical issues of this plant biomass storage, that’s why nowadays it is usually crushed and left in the fields.

When summarizing the data of chemical composition of straw it was assumed that the nitrogen-sulphur ratio in cereal straw is 5 units (in legume straw – 10 units), and the hydrogen-sulphur ratio is 56 units, which correspond to the averaged data according to (*Barotfy I., Rapan P., 1988*). The carbon-nitrogen ratio was taken as medium in volume, according to the data in (*Shkarada M., 1985*). On the basis of the generalized data, introduced in table 1, were received empirical calculation dependences for determination of heat of different straw combustion types.

While calculations performed to prove the use of plant biomass for specific region or whole country, the heat of straw combustion should be determined by the equation which takes into account the importance of the volumes of a particular straw type. For example, it is known that the main volumes of grain crop straw in Ukraine are presented by wheat straw (from 40 to 60%), barley straw (from 20 to 30%), rye straw (from 3 to 6%) and legume straw (from 2 to 8%). In recent years, it began to increase specific weight of rape straw, which reached values from 4 to 6%.

It is well-known that grain crops, vegetative mass major producers, traditionally occupy from 40 to 55% in the structure of sowed crops. It should also be mentioned that with livestock decrease straw consumption for feeding and litter decreased as well, and the surplus straw is usually burned in fields. Using straw in existing volumes would allow natural gas saving in the range from 4.5 to 14.3 billion m^3.

Table 1

Composition and calculation of straw combustion heat

Field crop – the straw producer	Content of dry weight, %								Calculation formula, MJ/kg
	Ash	Organic matter	Nitrogen, N	Carbon, C	Hydrogen, H	Oxygen, O	Sulphur, S	C/N	
Wheat	4.65	95.35	0.52	44.43	5.86	44.43	0.11	85	$Q_H^p = 16.261-0.1876W$
Rye	4.65	95.35	0.43	45.02	4.80	45.02	0.09	105	$Q_H^p = 15.309-0.1781W$
Barley	4.65	95.35	0.59	44.03	6.58	44.03	0.12	75	$Q_H^p = 16.914-0.1941W$
Oats	6.98	93.02	0.51	43.35	5.71	43.35	0.10	85	$Q_H^p = 15.865-0.1836W$
Corn	4.65	95.35	0.63	43.80	7.01	43.80	0.13	70	$Q_H^p = 17.304-0.1980W$
Rape	5.88	94.12	0.66	42.96	7.40	42.96	0.13	65	$Q_H^p =17.520-0.2002W$
Grain legumes	6.98	93.02	1.64	41.02	9.19	41.02	0.16	25	$Q_H^p =18.915-0.2141W$

It is necessary to mention the appropriateness and availability of rolled straw storage, because this technology allows quick removal of straw from fields and is realized by means of simple and reliable technical equipment.

According to our estimations, while annual volume of straw combustion at the rate of 30 million tons, the total amount of natural gas yielded will be 10.9 billion m^3. In these conditions, additional investments for preparation and combustion of straw will be 14.6 billion UAH, and their payback period will be from 1.2 to 1.3 years.

The effectiveness of straw combustion on the basis of comparison to heat generation by natural gas burning dependence from the heat production efficiency of straw when compared to gas heating and changing of straw cost.

Biodiesel

In Ukraine there are many cases of usage by agricultural producers of rapeseed oil in mixture with diesel for diesel tractors which have exceeded their service life.

We found that rapeseed oil production for usage as biodiesel can be economically reasonable in terms of agricultural production, when compared to rapeseed selling if the total cost of production is high and close to the average selling price of rapeseeds, or if the price of realization is low and similar to the total cost of rapeseeds.

Using biodiesel to replace diesel, it is necessary to heat biodiesel in the fuel lines of low pressure up to the temperature which provides the determined level of biodiesel filtration (*Man X. et al, 2015; Corsini A. et al, 2015)*. To increase efficiency and temperature range of biodiesel use, we have designed and made a two-stage heating system, which allows using biodiesel under any values of environment temperature and provides an increase in completeness of fuel combustion. The second stage of fuel heating is made in the fuel pump-injector section for its better spraying and increase of speed and combustion completeness.

Fuel prices are constantly increasing, and faster than those for agricultural products, which significantly affects production cost, realization price and farmers' profit. The analysis shows (fig. 2) that in 2000 farmers had to sell 4.6 tons of wheat to buy 1 ton of diesel, in 2006 it was necessary to sell 8.1 tons of wheat, in 2008 – 9.1 tons. Over the past 11 years the price of wheat increased 2.74 times and of diesel – 4.73 times.

On the basis of statistical data about consumption of diesel in agriculture and rape gross harvest, we have evaluated the capacity of replacing diesel to biodiesel while processing of whole rape harvest.

The largest consumption of diesel in agriculture for the observed period was noticed in 2001, 2002, 2000, and the lowest – in 2006, 2007, 2008; in 2011 it was observed the tendency of diesel use increase when compared to 2010 from 1201.4 thousand tons to 1349.7 thousand tons. Rape gross yield increase is being observed since 2004, and in 2009 was noticed production decline. The volume of biodiesel production while processing the whole rape harvest was to be the highest for the investigated period in 2008 – 900.6

thousand tons of biodiesel, in 2009 – 587.3 thousand tons, in 2010 – 460.8 thousand tons, in 2011 – 387.9 thousand tons, and the lowest – in 2003 – 15.8 thousand tons, as well as in 2002 – 19.1 thousand tons. The quotient of diesel which can be substituted to biodiesel while processing whole rape harvest was the largest in 2008 – 64.7%. At the same time, as it is predicted, production and use of biofuel in 2020 will not exceed 100 thousand tons per year (*Geletukha G.G., Zheleznaya T.A., 2012*).

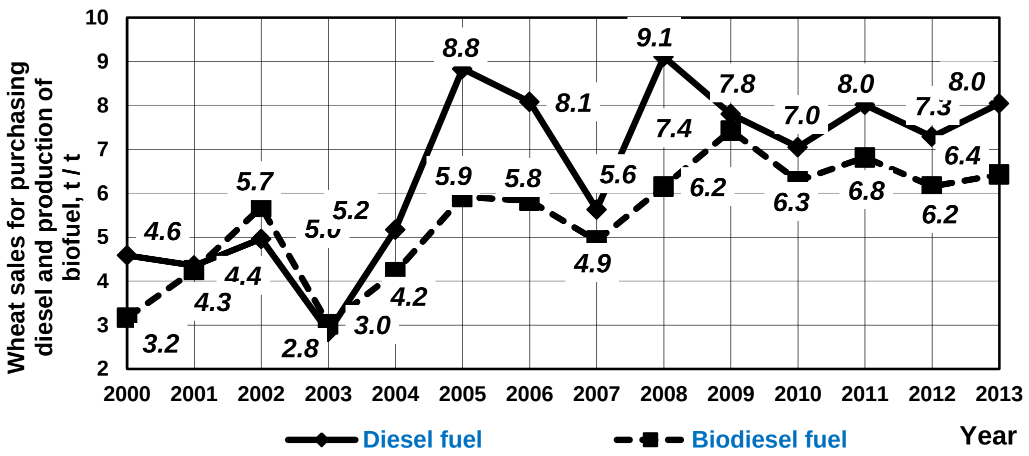

Fig. 2 – Change dynamics of required wheat sale volumes to buy diesel or produce biodiesel

Farms can produce biodiesel after harvesting oilseeds, i.e. in autumn. In autumn-winter period diesel is limitedly used in agricultural production – in animal husbandry only (*Ivanova B., Stoyanov S., 2016; Baskar G., Aiswarya R., 2016*). The produced biodiesel is stored in warehouses for oil products till the beginning of spring field work. When stored in sealed containers, biodiesel does not lose its properties during the year, unlike rapeseeds and rape oil. Prices for fossil diesel are constantly increasing, especially at the beginning of spring, but the cost of produced biofuels in the previous year remained unchanged, that is one of the cost saving provisions in agriculture.

The profitability of production of rapeseeds, rapeseed oil and based on it biodiesel is affected by a number of factors including: the cost and selling price of rapeseeds, production capacity of equipment which was used for production of oil and biofuels, the price situation in the diesel market. Profitability of rapeseed oil production was higher than the one of rapeseed production for the entire studied period, except of 2001, 2002 and 2010. Profitability of biodiesel production was lower than the one of oil and rapeseeds in 2000-2004, 2006, 2008, 2009, 2011 and 2012. Profitability of biodiesel production in 2005, 2007, 2010 and 2013 was greater than the one of rapeseed production, which can be explained by reducing of rapeseed realization cost.

Stable high demands, formed by the world market, and high prices provide highly profitable rapeseed production and are very attractive to investors. Profitability of rapeseed production was increasing till 2004 and reached 69%, and starting from 2005 up to 2007 it tended to decrease, and stabilized at 17-35%. Profitability of rapeseed oil production was increasing till 2004 and reached 81%, from 2005 to 2010 – it was decreasing (except in 2008, when there was the highest index – 86%) and stabilized at the level of 8-17%. Analysing the profitability of biodiesel production, it should be mentioned, that by 2002 biodiesel production was not profitable, due to the relatively high cost of its production and a fairly low price of diesel. However, with the rising cost of fossil fuels, the profitability of biodiesel production has significantly increased, and from 2004 to 2007 exceeded even the profitability of crop production, confirming the effectiveness of investment and the need to develop the biofuel production branches.

The analysis of interest rates on deposits of banks of Ukraine shows that for the 2000-2011 the interest rate for individuals ranged from 12.6 to 20.4%, for legal entities – from 6.6 to 13.8% (*National Bank of Ukraine*). However, investing money into biodiesel production, investor derives much greater profit. So, in 2004 the average interest rate on bank deposits for individuals was 15.7%, for entities – 8.9%, while the profitability of biofuel production was 40%, in 2007 respectively – 14.1 and 8.9%, and biofuel profitability – 38%, in 2010, rates of banks – 18.8% and 13.7%, while biofuel production – 27%. Raising funds to produce biodiesel is probable not only to improve the efficiency of invested capital, but also to make contribution for improving the environmental situation of the country and for ensuring power independence industry, as well as the country as a whole.

BIOGAS

Experience of using biogas reactors showed that there are reactors already half-filled with mineral sediment, which can be removed only with an excavator after total stopping of fermentation process. Floating layers, especially based on fibrous substrates, often form a crust and if it is not mixed, the reactor must also be stopped to remove it.

Thus, the improvement of biogas reactor work to ensure the mixing of biomass substrate layers requires new technical solutions, one of which is mixing by rotation of the suspended reactor submerged into water. We have developed and patented several designs of modular anaerobic digesters of rotational type (*Patent Ukraine №110077, 2015*); the design of one of those is shown in fig. 3.

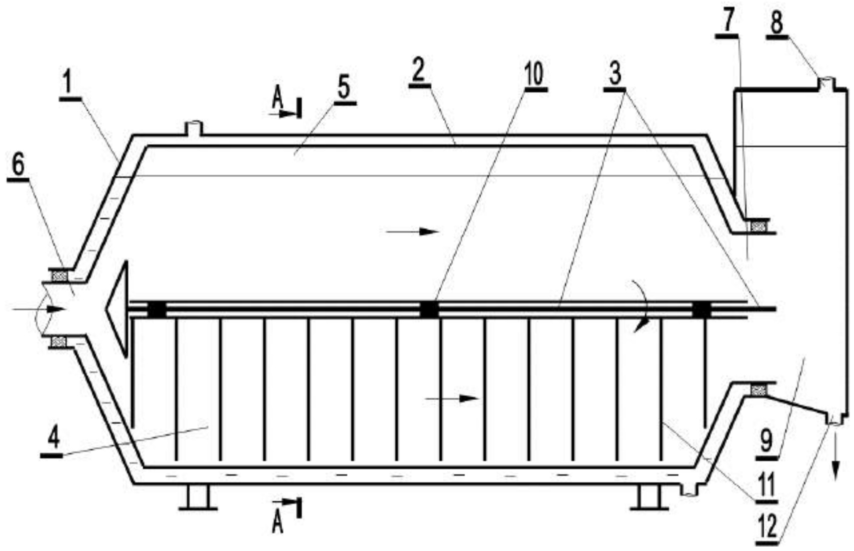

Fig. 3 – Construction of anaerobic digester immersed into thermostatic liquid

1 – horizontal outer casing, 2 – cylindrical reactor 3 – longitudinal bulkhead, 4, 5 – fermentation chambers, 6, 7 – tubes for cart and removal of organic matter, 8 – pipe for biogas runoff, 9 – unloading camera, 10 – joints 11 – mixing fingers, 12 – pipe for organic matter removing

Our calculations showed that the microbiological decomposition while anaerobic fermentation of 1 kg of organic matter is accompanied by about 0.4 kg of methane yield and by 0.7 kg of carbon dioxide yield.
Assuming that the volume of produced biogas is determined by the intensity of organic matter decomposing during organic biomass fermentation, biogas yield while fermentation in terms of normal conditions can be defined as follows:

$$V_{BG} = \rho_{BM}\left(1 - \frac{W_{BM}}{100}\right) k_{OM} k_{OM}^{D} \frac{m_{BG}}{\rho_{BG}^{N}}, \quad (3)$$

where:

V_{BG} is a specific biogas yield from the reactor under normal conditions, m^3_{BG}/m^3_{BM} per day;

ρ_{BM} – biomass density, kg_{BM}/m^3_{BM};

W_{BM} – biomass humidity, %;

$\left(1 - \frac{W_{BM}}{100}\right)$ – dry matter content in relation to the total biomass, kg_{DM}/kg_{BM};

k_{OM} – organic matter content in relation to the volume of the total dry weight in fermenting biomass, kg_{OM}/kg_{DM};

k_{OM}^{D} – the number of decomposed organic matter per day in relation to the total organic mass, kg_{DOM}/kg_{OM} per day;

M_{BG} – biogas yield per unit of decomposed organic matter, kg_{BG}/kg_{DOM} ;

ρ_{BG}^{N} – biogas density under normal conditions, kg_{BG}/m^3_{BG}.

Table 2

Calculation of the specific release of biogas and biomethane

Indicator	Measurement	Values
Manure density	kg_{BM} / m^3_{BM}	1062
Humidity	%	90
Water content	kg_W / kg_{BM}	0.9
Dry weight	%	10
	kg_{DM} / kg_{BM}	0.1
Organic matter content	%	80
	kg_{OM} / kg_{DM}	0.8
The intensity of organic matter decomposing	% per day	**3.0**
	kg_{DOM} / kg_{OM} per day	**0.03**
	kg_{DOM}/m^3_{BM} per day	**2.55**
Biogas yield from decomposed organic matter under normal conditions	kg_{BG}/ kg_{DOM}	1.1
	m^3_{BG}/ kg_{DOM}	0.92
Biogas yield from the reactor under normal conditions	m^3_{BG}/m^3_{BM} per day	**2.34**
Biomethane yield under normal conditions	m^3CH_4/ m^3_{BM} per day	**1.666**
The maximum level of organic biomass decomposing	%	38
	kg_{POM} / m^3_{BM}	32.5
Fermentation time	days	**12.74**

At the same time, specific biomethane yield will be:

$$V_{CH_4} = V_{BG} k_{CH_4}, \tag{4}$$

where:

V_{CH_4} – is specific biomethane yield from the reactor under normal conditions, $m^3_{CH^4} / m^3_{BM}$ per day;

k_{CH_4} – volume of biomethane content in biogas, $m^3_{CH^4} / m^3_{BG}$.

With the parameters introduced in table 2, the relations between the intensity of organic matter decomposing and specific biomethane and biogas yields, and fermentation time, will take the form shown in fig. 4.

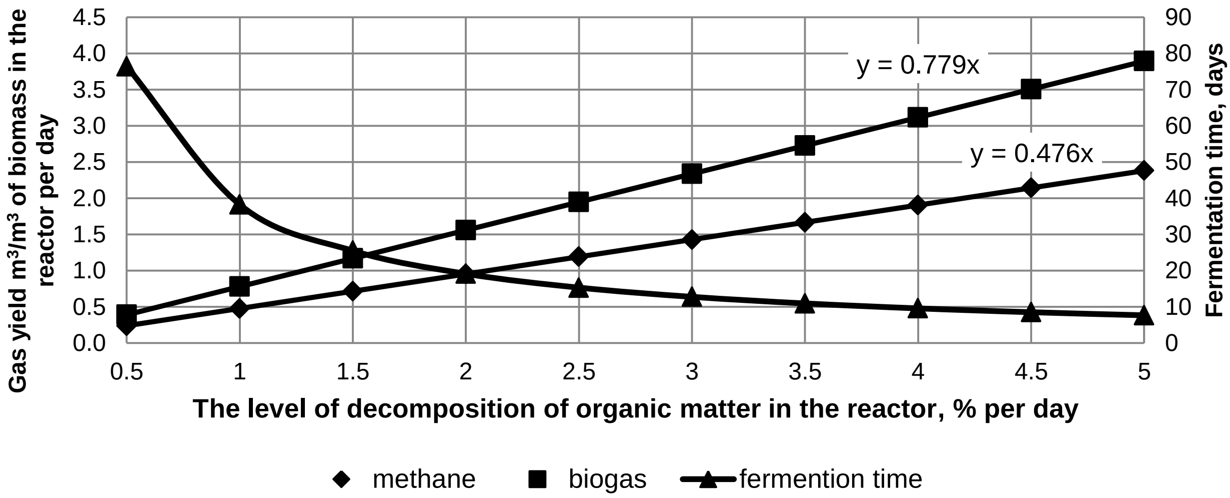

Fig. 4 – The effect of organic matter decomposing intensity on the specific yield of biomethane, biogas and fermentation time

Biogas and biomethane yields increase proportionally with increasing the level of organic biomass decomposing in the reactor, and the fermentation time decreases exponentially until it reaches 38% fermentation level.

CONCLUSIONS

Biological and energetic conversion of organic agrocenosis raw materials with energy production can ensure energy autonomy of agroecosystems in total energy balance. Though, it is impossible to do it according to the types of fuels and energy, since there is a limit on the possibility of autonomous production of electric power and gasoline. However, production of biodiesel and heat energy can be redundant. The source of raw materials that would meet the needs of agricultural production under centralized bioethanol production is sufficient. At the same time, to implement such systems, first of all, it is necessary to change the basic principles of society existence, regarding manufacturing of environmentally friendly production and biological diversity preserving.

The heat of straw combustion reduces down to 0.18 to 0.21 MJ/kg for each percent of its humidity increase. Energy efficiency is increased while burning straw in the compressed form (briquettes, pellets). Baled straw should be burned in boilers equipped with cameras for post-combustion of volatile compounds. Non-pressed straw should be burned in crushed form by using eddy chambers.

The main direction in manure fermentation process intensification is the increase of organic matter decomposition at the cost of creation of appropriate conditions for the development of anaerobic microflora. This can be achieved by creating stable fermentation temperature conditions and, what is more important, by providing quality biomass mixing, which, on the one hand, must not disturb the symbiosis of acetogenic and methanogenic bacteria, and, on the other hand, prevent the exfoliation of biomass in the reactor to mineral sediment and floating organic layer.

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