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Study of the anaerobic destruction of post-alcohol distillery waste by mateen

Abstract. Post-alcohol distillery waste is an environmental pollutant, which determined the relevance of its disposal. One of the ways to utilise post-alcohol distillery waste is through its anaerobic methane destruction in biogas plants. The research aims to determine the optimal amount of post-alcohol distillery wastes to be added to the substrate to achieve maximum biomethane yield. The research was conducted on a laboratory biogas plant consisting of a 30-litre digester and a gas holder in a mesophilic mode at a substrate temperature of 40°C with a periodic substrate loading mode. It was found that the highest biogas yield of 5.369 l/(h·kg DOM) was obtained by anaerobic methane mono-degradation of post-alcohol distillery waste. However, the methane content in the biogas is in the range of 48-52%. During the anaerobic methane destruction of a mixture of post-alcohol distillery waste with cow manure, the methane content in biogas increases to 70-76%, but the biogas yield is lower and is 4.577 l/(h·kg DOM) at 36% post-alcohol distillery waste content in the substrate, 3.294 l/(h·kg DOM) at 27%, 2.960 l/(h·kg DOM) at 18%, 1.538 l/(h·kg DOM) at 9%. The optimum content of post-alcohol distillery waste in the substrate, at which the biomethane yield will be maximum (3.821 l/(h·kg DOM)), is 46.7% of the substrate content and 100% of the organic part of the substrate. The results of this study can be used in planning the composition of the substrate of biogas plants and designing and building new biogas plants near distilleries

Keywords: biomethane; biogas plant; digester; fermenter; bioreactor; digester

INTRODUCTION

For biogas production, the main substrate is traditionally cow manure, which already contains methane-producing bacteria and has an optimal C/N ratio (Rogovskii *et al.*, 2020). However, the biogas yield from the anaerobic methane destruction of cow manure is relatively low. Therefore, to increase the biogas yield from livestock by-products, substrates are used – waste from processing and agricultural production. This eliminates the need for their disposal. Such concentrates include vegetable oil

sludge, granulated straw, substandard flour, and biodiesel production waste: crude glycerine – a by-product of biodiesel production, and soap stock – a by-product of biodiesel neutralisation. However, these co-substrates cannot undergo anaerobic methane degradation on their own, so biogas plants are often limited to corn silage, poultry manure, pig manure and cattle manure as feedstock. One of the co-substrates for biogas production, which can also undergo mono-degradation, is post-alcohol distillery waste.

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Post-alcohol distillery waste is the final by-product of brew distillation in the production of ethanol from sugar and starch crops or cellulosic material. E. Carrilho *et al.* (2016), I. Syaichurrozi (2016) determined that it consists of 93% water and 7% solids. For every litre of ethanol produced in the sugar industry, 15 litres of distillery waste can be produced. This residue contains high levels of salt and organic matter and has a low pH. Every year, 22.4 gigalitres of post-alcohol distillery waste are produced worldwide (Parsaee *et al.*, 2019). As argued by A.M. Rosales *et al.* (2022), it is an environmental pollutant that is difficult to dispose of. It is disposed of in filtration fields, but there is an unpleasant odour in the vicinity of filtration fields. Disposal of post-alcohol distillery waste in soils and water bodies causes serious environmental problems, mainly due to soil salinity and changes in pH.

The post-alcohol distillery waste can be utilised by processing it into biogas, with no foul odour from distillery waste decomposition and the resulting biogas being an energy-valuable product.

The anaerobic methane degradation of post-alcohol distillery wastes can generate significant amounts of biogas that can be used for electricity or biomethane production. Biomethane can be injected into the natural gas network or used as a substitute for petroleum fuels (Neto *et al.*, 2019).

Nevertheless, following G. Kulichkova *et al.* (2020), post-alcohol distillery waste has a low carbon-to-nitrogen ratio. Therefore, additional substances, such as animal manure, organic industrial waste, and lime fertilisers, should be added to increase the biogas yield. R. Yuliasni *et al.* (2021) concluded that post-alcohol sugarcane distillery waste has an acidic pH (3.5-5.0) and a high concentration of sulphuric acid (over 150 mg/l).

G. Kulichkova (2022) argued that the thickened distillery waste obtained after sugar beet alcohol production is more suitable for anaerobic methane degradation than liquid distillery waste.

A. Calvo *et al.* (2019) investigated the co-digestion of anaerobic methane degradation of post-alcohol sugarcane distillery waste with sludge from oxidation and cooling lagoon. A concentration of 90% of the distillery waste was found to give the highest yield (674.5 ml of biogas over 18 days in a 400 ml working volume). N. Golub *et al.* (2019) describe the results of a study of the one-stage combined anaerobic methane destruction of post-alcohol distillery waste and poultry manure in a dry organic matter (DOM) ratio of 1:1.7. To ensure the utilisation of the post-alcohol distillery waste, one-sixth of the reactor volume was replaced daily with post-alcohol distillery waste with a pH of 3.7, without adding new portions of poultry manure. The research has shown that a ratio of dry organic material of poultry manure to post-alcohol distillery waste of less than 1:1 leads to a decrease in biogas yield and methane content. Periodic daily replacement of the fermented part of the substrate with post-alcohol distillery waste without disturbing the stabilisation of the process is possible at a pH value of at least 6.5. Manure utilisation

leads to the establishment of a steady state after 20 days, which is maintained for at least 10 days. In the work of K. Jaman *et al.* (2023) studied the co-degradation of cow manure and molasses distillery waste at different ratios and changes in the organic load rate (OLR). The studies were conducted from OLR 1 g/l/day to OLR 7 g/l/day. At OLR of 7 g/l/day, signs of methanogen inhibition began to appear. The optimal OLR was found to be 5 g/l/day. At the same time, the biomethane yield was 1.24 l/g volatile solids (VS). In this case, the best model of biomethane yield was the first-order model with a determination coefficient of $R^2=0.94035$.

Thus, the literature review shows that post-distillation distillery waste can be used for biogas production. However, it is acidic and contains chemicals (molasses distillery waste, sugar cane distillery waste – sulphuric acid salts, sulphates) that are added to the mash in the process of ethanol production from sugar-containing raw materials and remain in the post-distillation distillery waste. These chemicals cause inhibition of methane-forming bacteria, making methane formation impossible, so it is recommended to add molasses distillery waste to the substrate in small amounts, diluting it with water. However, the reviewed literature does not mention how anaerobic methane destruction of post-alcohol distillery waste is carried out without the presence of harmful impurities.

The research aims to determine the optimal amount of post-alcohol distillery waste in a substrate based on cow manure to obtain maximum biomethane yield.

MATERIALS AND METHODS

The influence of post-alcohol distillery waste on biomethane generation was studied at a laboratory biogas plant at the National University of Life and Environmental Sciences of Ukraine (Fig. 1), which consists of a 30-litre fermenter and a gas holder.



Figure 1. Laboratory biogas installation
Source: compiled by the authors

The dynamics of the biomethane yield rate were carried out under the periodic mode of fermenter loading during the mono-degradation of cow manure, during the mono-degradation of post-alcohol distillery waste and

the combined anaerobic destruction of cow manure and post-alcohol distillery waste in different proportions. The content of substrate components in the study of biogas yield dynamics is given in Table 1.

Table 1. Content of substrate components in the study of biogas yield dynamics

The content of the post-alcohol distillery waste to:		Substrate components, kg		
substrate contents, %	water organic matter percentage in the substrate, %	water	post-alcohol distillery waste	cow manure
0	0	4.5	0	3.5
9	20	4.5	0.7	2.8
18	40	4.5	1.4	2.1
27	60	4.5	2.1	1.4
36	80	4.5	2.8	0.7
47	100	4.5	3.5	0

Source: compiled by the authors

A total of 8.0 kg of substrate was loaded. The temperature mode of the digester during the study was $40 \pm 0.5^\circ\text{C}$ and was set using a TRC02 “Universal” thermostat manufactured by the Zhytomyr plant “Promprylad” (Ukraine). The biomethane content in biogas was determined by a GEM-500 gas analyser manufactured by LANDTEC (USA). The post-alcohol distillery waste had a pH of 4.8, which was determined by a pH meter PH-009 manufactured by Kelilong Electron (China).

The graphical dependences of the dynamics of biogas and biomethane yields, and accumulated biogas and biomethane yields over time were constructed on a computer using the EXCEL spreadsheet processor. The analytical model of the maximum biomethane yield during anaerobic methane destruction of the substrate with different content of post-alcohol distillery waste was obtained by approximating the maximum biomethane yield on a computer using the EXCEL spreadsheet processor at different content of the organic part of the post-alcohol distillery waste in the substrate.

The coefficient of determination (Foerster & Roenz, 1979) was used to assess the extent to which the regression function is described by the determinants:

$$R^2 = 1 - \frac{\sigma_z^2}{\sigma^2}, \quad (1)$$

where R^2 – determination coefficient; where σ^2 – general dispersion; σ_z^2 – remaining (group internal) dispersion.

The general dispersion is determined by the formula (Foerster & Roenz, 1979):

$$\sigma^2 = \sum_i (y_i - \bar{y})^2, \quad (2)$$

where y_i – actual values of time series levels; \bar{y} – arithmetic mean of the actual values of the time series levels.

The remaining dispersion is determined by the formula (Foerster & Roenz, 1979):

$$\sigma_z^2 = \sum_i (y_i - \hat{y}_i)^2, \quad (3)$$

where \hat{y}_i – estimated values of the time series levels obtained by the approximated expression.

The higher the coefficient of determination R^2 is close to one, the better the regression is defined.

To make a statistical conclusion about the presence or absence of a correlation between the variables under study, it is necessary to check the significance of the coefficient of determination. Since the reliability of statistical characteristics, including the coefficient of determination, depends on the sample size, a situation may arise when the value of the coefficient of determination is entirely due to random fluctuations in the sample based on which it is calculated. The significance of the paired coefficient of determination is assessed by Fisher’s criterion (Foerster & Roenz, 1979):

$$F = \frac{R^2 \cdot (n-2)}{1-R^2}, \quad (4)$$

where F – Fisher’s criterion; R^2 – determination coefficient; n – measurements, pcs.

The value of Fisher’s criterion calculated by formula (4) was compared with the critical values of Fisher’s criterion given in (Foerster & Roenz, 1979) at a given level of significance and the corresponding number of degrees of freedom. If $F > F_{cr}$, then the calculated coefficient of determination is significantly different from zero. This conclusion is ensured with a probability of $1-\alpha$. The determination of the coefficient of determination and Fisher’s test was carried out on a computer using the EXCEL spreadsheet processor.

By studying the function $w_{bm} = f(Vin)$ for the extremum $w_{bm} \rightarrow \max$, the optimal content of post-alcohol distillery waste in the substrate was determined, at which the biomethane yield would be maximised. The study of the function $w_{bm} = f(Vin)$ for the extremum $w_{bm} \rightarrow \max$ was carried out on a computer in MATHCAD using the built-in optimisation function Maximize, which includes the algorithm of the “gradient descent” method.

RESULTS AND DISCUSSION

The dynamics of biogas yields from anaerobic mono-degradation of cow manure, anaerobic mono-degradation

of post-alcohol distillery waste and combined anaerobic methane degradation of cow manure and post-alcohol distillery waste in different proportions are shown in Figure 2.

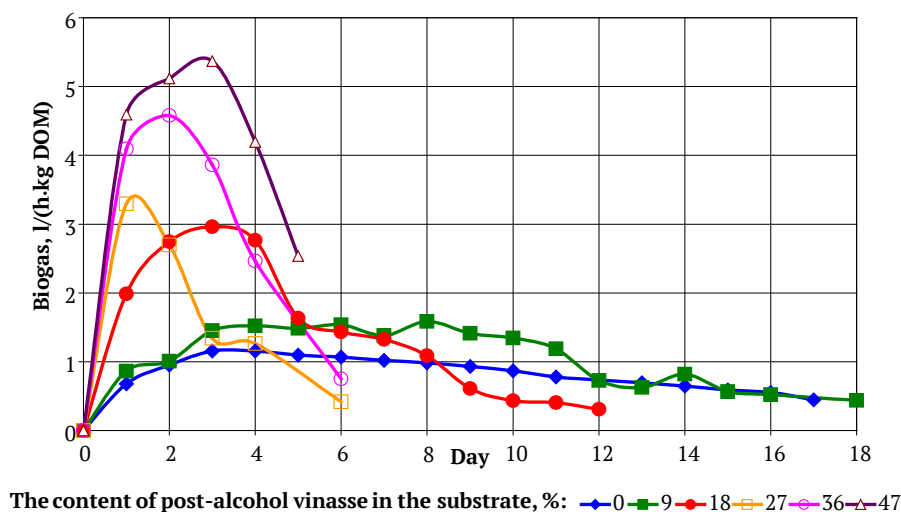


Figure 2. The dynamics of biogas yields from anaerobic mono-degradation of cow manure, anaerobic mono-degradation of post-alcohol distillery waste and combined anaerobic methane degradation of cow manure and post-alcohol distillery waste in different proportions

Source: compiled by the authors

As can be seen from Figure 2, the dynamics of biogas yield correspond to all phases of microbial development. Initially, a logarithmic phase is observed when anaerobes, in the presence of a nutrient medium (freshly added substrate to the digester), actively multiply, producing more and more of their vital product – biogas. The logarithmic phase gradually turns into a short stationary phase, when the number of anaerobes is in dynamic equilibrium with the availability of nutrients. At this time, the maximum biogas yield is observed. After that, the substrate nutrients begin to be depleted due to their active consumption by the anaerobic biomass, which has grown to a significant size. The active reproduction of anaerobes stops, and their gradual death begins due to a lack of nutrients in the substrate. The phase of dying off begins. At the same time, the biogas yield gradually decreases. Both during the anaerobic mono-degradation of cow manure, anaerobic mono-degradation of post-alcohol distillery waste, and combined anaerobic methane degradation of cow manure and post-alcohol distillery waste in different proportions, the phase of anaerobes getting used to a new substrate (lag phase) was not observed. No diauxia was observed, which is typical for multicomponent substrates, when methane-forming bacteria first consume one, in their opinion, the most palatable component of the substrate. After its exhaustion, methanogens switch to another component of the substrate. In this case, there are two peaks of maximum biogas yield, i.e., two stationary phases (Malinin *et al.*, 2021).

Moreover, with the increase of post-alcohol distillery waste content in the substrate, the duration of the logarithmic phase and the die-off phase decreases, resulting in a shorter period of anaerobic methane destruction. Thus, if the maximum biogas yield at 18%, 27%, and 36% of the post-alcohol distillery waste content in the substrate and during the mono-degradation of post-alcohol distillery waste is observed on day 2-3 of anaerobic methane destruction, at 9% of the post-alcohol distillery waste content in the substrate and during the mono-degradation of cow manure – on day 4-8.

At the same time, the maximum biogas yield increases with the increase in the content of post-alcohol distillery waste in the substrate. Thus, during the mono-degradation of cow manure, the maximum biogas yield is 1.157 l/(h·kg DOM), with the content of post-alcohol distillery waste in the substrate of 9% – 1.538 l/(h·kg DOM), at 18% – 2.960 l/(h·kg DOM), at 27% – 3.294 l/(h·kg DOM), at 36% – 4.577 l/(h·kg DOM). The maximum biogas yield of the post-alcohol distillery waste is 5.369 l/(h·kg DOM), which is 4.6 times higher than the maximum biogas yield of cow manure mono-digestion.

Accumulated biogas output yields from anaerobic mono-degradation of cow manure, anaerobic mono-degradation of post-alcohol distillery waste and combined anaerobic methane degradation of cow manure and post-alcohol distillery waste in different proportions are shown in Figure 3.

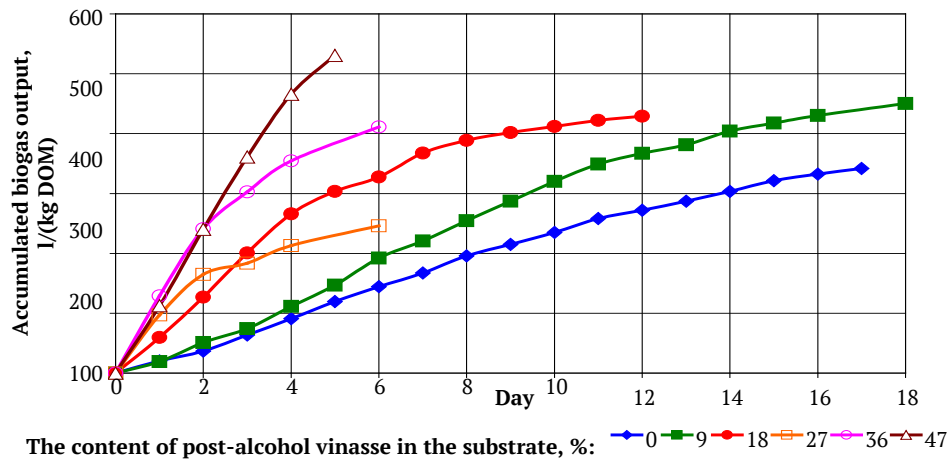


Figure 3. Accumulated biogas output yields from anaerobic mono-degradation of cow manure, anaerobic mono-degradation of post-alcohol distillery waste and combined anaerobic methane degradation of cow manure and post-alcohol distillery waste in different proportions

Source: compiled by the authors

Figure 3 shows that with an increase in the content of post-alcohol distillery waste in the substrate, the slope of the curve of the accumulated biogas yield increases, which indicates a more intensive biogas yield. Thus, already on the fifth day, the accumulated biogas yield during the mono-degradation of post-alcohol distillery waste is 530.6 l/(kg DOM), with the content of post-alcohol distillery waste in the substrate of 9% – 382.8 l/(kg DOM), 18% – 303.3 l/(kg DOM), 27% – 229.6 l/(kg DOM), 36% – 146.9 l/(kg DOM), and with the mono-degradation of cow manure – 119.4 l/(kg DOM). The accumulated biogas yield on the fifth day of mono-degradation of post-alcohol distillery waste is higher than the accumulated biogas yield on the 18th day of mono-degradation of cow manure.

The methane content in biogas produced during anaerobic methane destruction of the substrate with 9% and 18% post-alcohol distillery waste on the first day of anaerobic methane destruction is insignificant (biogas does not burn), and a persistent hydrogen sulphide smell is felt. On

the second day of anaerobic methane digestion, the methane content in biogas increases to 65%, and on the next day and subsequently stabilises at 70-72%. With the content of post-alcohol distillery waste in the substrate of 27% and 36% on the first day of anaerobic methane digestion, the methane content in biogas is 58-60% and subsequently increases to 74-76%. During anaerobic methane digestion of the substrate without cow manure (post-alcohol distillery waste content 46.7%), the methane content in biogas from the first day ranges from 66-68%. The methane content in biogas during the mono-degradation of cow manure without the addition of post-alcohol distillery waste is lower than when using post-alcohol distillery waste and is in the range of 48-52%.

The dynamics of biomethane yields from anaerobic mono-degradation of cow manure, anaerobic mono-degradation of post-alcohol distillery waste and combined anaerobic methane degradation of cow manure and post-alcohol distillery waste in different proportions are shown in Figure 4 (Bulhakova, 2022).

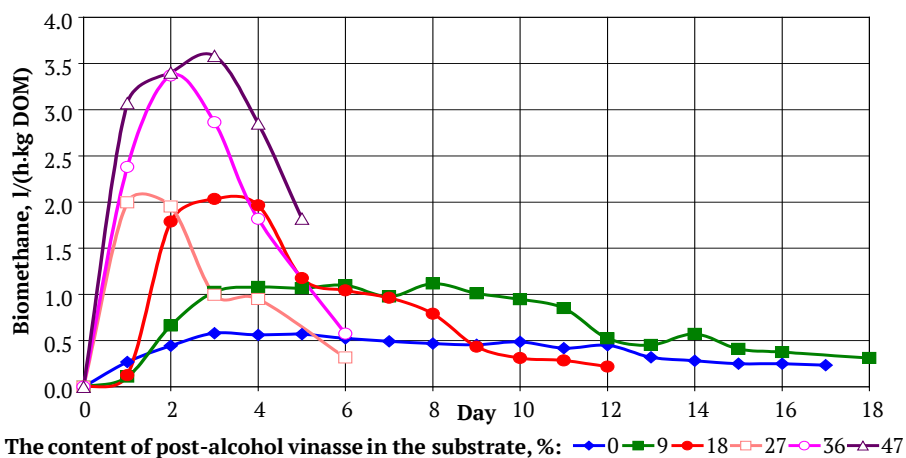


Figure 4. The dynamics of biomethane yields from anaerobic mono-degradation of cow manure, anaerobic mono-degradation of post-alcohol distillery waste and combined anaerobic methane degradation of cow manure and post-alcohol distillery waste in different proportions

Source: compiled by the authors

The maximum biomethane yield during anaerobic mono-degradation of cow manure is 0.58 l/(h·kg DOM), during the combined anaerobic methane degradation of cow manure and post-alcohol distillery waste at the content of post-alcohol distillery waste to the substrate of 9% – 1.118 l/(h·kg DOM), 18% – 2.033 l/(h·kg DOM), 27% – 1.997 l/(h·kg DOM), 36% – 3.371 l/(h·kg DOM), with anaerobic mono-destruction of post-alcohol distillery waste – 3.582 l/(h·kg DOM).

The maximum biomethane yield during anaerobic mono-degradation of post-alcohol distillery waste and com-

combined anaerobic methane degradation of cow manure and post-alcohol distillery waste (18%, 27% and 36%) is observed already on day 1-3 of methane fermentation, while during combined anaerobic methane degradation of cow manure and 9% of post-alcohol distillery waste – on day 8.

Accumulated biomethane output yields from anaerobic mono-degradation of cow manure, anaerobic mono-degradation of post-alcohol distillery waste and combined anaerobic methane degradation of cow manure and post-alcohol distillery waste in different proportions are shown in Figure 5.

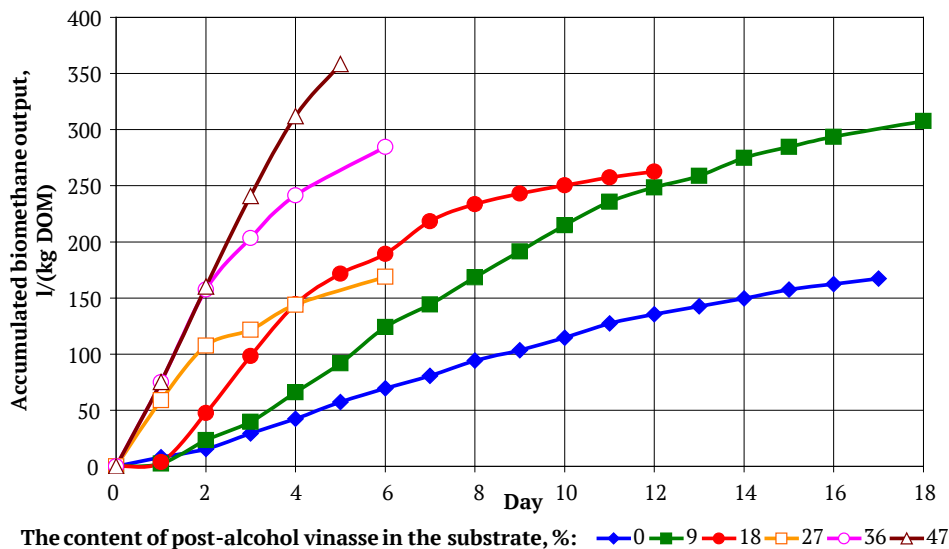


Figure 5. Accumulated biomethane output yields from anaerobic mono-degradation of cow manure, anaerobic mono-degradation of post-alcohol distillery waste and combined anaerobic methane degradation of cow manure and post-alcohol distillery waste in different proportions

Source: compiled by the authors

Figure 5 shows that the curves of the accumulated biomethane yields follow the curves of the accumulated biogas yields. The only difference between them is that the biomethane yield is lower than the biogas yield per biomethane content in the biogas and that at the initial stage of anaerobic methane degradation at a certain content of post-alcohol distillery waste in the substrate, biogas does not contain methane, so some curves of the accumulated biomethane yield start to grow from the next day after the start of anaerobic methane degradation.

The fermenter of the biogas plant, where experimental studies of anaerobic destruction of substrates based on cow manure with the addition of post-alcohol distillery waste were carried out, is suitable for batch loading of the substrate. At the same time, due to the peculiarities of biogas yield during batch loading of the substrate, when the biogas yield increases sharply to the maximum and then

decreases, it is impossible to obtain the maximum biogas yield for a rather significant period. Therefore, industrial biogas plants use a semi-continuous mode of fermenter loading, when the substrate is added in small portions over a short period (about 10 minutes). In this case, the constant biogas yield with a semi-continuous fermenter loading system used in industrial bioreactors will be close to the maximum biomethane yield with a batch loading system (Polishchuk *et al.*, 2021). Therefore, based on the data of the maximum biogas yield with batch loading of the substrate into the fermenter, a model of constant biogas yield with a semi-continuous mode of substrate loading into the fermenter used in industrial biogas plants can be obtained.

The maximum biomethane yield during the anaerobic methane degradation of a substrate with different post-alcohol distillery waste content is shown in Figure 6.

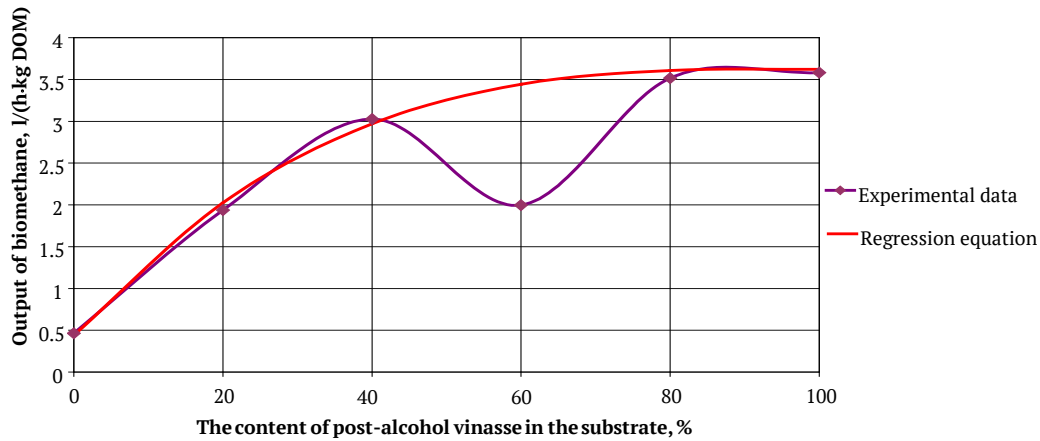


Figure 6. The maximum biomethane yield during the anaerobic methane degradation of a substrate with different post-alcohol distillery waste content

Source: compiled by the authors

The modelled biomethane yield rate can be represented as a third-order Newtonian polynomial:

$$w_{bm} = 0.0000036 \cdot Vin^3 - 0.001 \cdot Vin^2 + 0.0978 \cdot Vin + 0.4412, \quad (5)$$

where w_{bm} – is the biomethane yield rate, l/(h·kg DOM); Vin – is the content of post-alcohol distillery waste in the substrate, %.

The coefficient of determination of expression (5) is 0.7445 due to the loss of the biomethane yield point at 60% of the post-alcohol distillery waste content in the substrate from the overall process dynamics.

The significance of the coefficient of determination of the function $w_{bm} = f(Vin)$ according to Fisher's criterion (Fisher's calculated criterion is 11.7, Fisher's critical criterion at $\alpha = 5\%$ – 225 (Foerster & Roenz, 1979)).

When studying the function $w_{bm} = f(Vin)$ for the extremum $w_{bm} \rightarrow max$ using the gradient descent method, the optimal content of post-alcohol distillery waste in the substrate at which the biomethane yield will be maximum (3.821 l/(h·kg DOM)) was found to be $Vin = 46.7\%$.

Thus, this study shows that post-alcohol distillery waste can be successfully subjected to anaerobic methane degradation both without and with the addition of other substrates (in this case, cow manure). The highest biomethane yield is achieved during the mono-degradation of the post-alcohol distillery waste and is 3.582 l/(h·kg DOM), or 86 l/kg DOM per day. This daily biomethane yield can be achieved in a quasi-continuous mode of digester loading (used in large industrial biogas plants) when small portions of the fresh substrate are fed into the digester continuously at short intervals (from 10 minutes to 1 hour). When the substrate is periodically loaded into the digester, the biomethane yield is lower. Thus, during the mono-fermentation of post-alcohol distillery waste, the average biomethane yield during 5 days of anaerobic methane destruction (it is irrational to subject this substrate to destruction for more time since the biomethane yield decreases sharply) is 2.939 l/(h·kg DOM), or 71 l/kg DOM per

day, or 355 l/kg DOM per day for the entire fermentation period (5 days). Taking into account that the DOM content in the DM of the post-alcohol distillery waste is 5%, the biomethane yield from the mono-degradation of the post-alcohol distillery waste in the batch mode of loading is 187 l/kg DM for the entire fermentation period, which is slightly lower than the result obtained by J.C. de Carvalho *et al.* (2023), which is 215-324 l/kg DM during the anaerobic methane degradation of post-alcohol distillery waste, and S.S. Hashemi *et al.* (2022) – 425 ml/g VS during the anaerobic methane degradation of the substrate in the ratio of post-alcohol distillery waste to whey 25:75, which was used for cultivation of fungi at pH = 6.5. At the same time, J.C. de Carvalho *et al.* (2023) and S.S. Hashemi *et al.* (2022) do not specify the time to which the results refer. As for the quasi-continuous mode of the digester loading, the biogas yields reported in these works can be achieved on the 3-5th day of anaerobic methane degradation, while the HRT for a digester is usually taken at the level of 20-25 days. However, our results are close to the results (380 ± 20 cm³/g DOM, methane content in biogas – 70 ± 2%) obtained in N. Golub & M. Potapova (2018), where the co-digestion of anaerobic methane degradation of wastewater, post-alcohol distillery waste and poultry manure in a ratio of 0.2:1:7 in a two-stage mode was studied. N. Golub & M. Potapova (2018) noted that the problem of anaerobic methane destruction of post-alcohol distillery waste in its pure form is its low pH and insufficient content of nitrogen compounds, which are necessary for the development of microorganisms-destroyers and producers of methane. It is to neutralise these problems that methane destruction was carried out in conjunction with poultry manure. To maximise the conversion of pollutants into biogas, the liquid fraction is fermented in a second fermenter after the solid residue is separated. The concentration of dry organic urea in the first reactor did not exceed 10%, the temperature of the reactor was 40 ± 2°C, the stirring speed was 100 rpm, and the final pH of the substrate – 7.0 ± 0.5.

The methane content in biogas during the mono-destruction of the post-alcohol distillery waste is in the range of 48-52%, which is lower than the value of 77% for the hydraulic retention time (HRT) of 21 days reported by S. Belhamidi *et al.* (2021), but correlates with the methane content in biogas (42.89-58.06%) reported by I. Utami *et al.* (2016) and 57.21% reported by N. Harihastuti *et al.* (2020) and 50-55% during the anaerobic methane degradation of post-alcohol distillery waste from the production of miscal (an alcoholic beverage obtained by distillation of fermented agave sucrose) in combination with activated sludge in a ratio of 3: 7 (Santos *et al.*, 2019). The obtained methane content in biogas from anaerobic methane digestion of post-alcohol distillery waste and cow dung substrate is 70-76%, which correlates with 70% methane in biogas from anaerobic methane digestion of post-alcohol distillery waste and cow dung substrate at a hydraulic retention time of 20 days, as reported in C.E. de Farias Silva & A.K. de Souza Abud (2017), and 81% for anaerobic methane digestion of a substrate consisting of post-alcohol distillery waste from the production of miscal and cow manure, as reported by L.V. Santos *et al.* (2020). Thus, based on our research and comparison with the results reported in the literature, it can be stated that the methane content of biogas is lower in the case of mono-degradation of post-alcohol distillery waste than in the case of combined anaerobic methane degradation of post-alcohol distillery waste with cow manure.

The results differ significantly from the conclusions presented by W. Romaniuk *et al.* (2022), which state that anaerobic mono-degradation of molasses distillery waste yields significant biogas, but it contains almost no methane and consists mainly of carbon dioxide. Only when cow manure is added to the substrate in large quantities does methane appear in the biogas and the lower calorific value of biogas reaches 16.5-20.5 MJ/m³. This difference can be explained by the peculiarities of the ethanol production technology from molasses distillery waste when sulphuric acid is required. As a result, sulphuric acid salts are formed – sulphites, which harm methane formation during molasses biodegradation. The addition of cow manure to the substrate significantly improves the biodegradation process with methane production. By the way, as noted in A. Calvo *et al.* (2019), the same problem as in the biodegradation of molasses distillery waste is observed in the biodegradation of post-alcohol distillery waste from sugar cane.

C.R. Tunes *et al.* (2016) found that the biogas yield from post-alcohol sugarcane distillery waste in an 87-litre reactor over 15 days was 1160 litres with a methane concentration of 48-57%. B. Budiyo *et al.* (2013) modelled the biogas yield from anaerobic methane degradation of post-alcohol distillery waste according to the Gompertz model. The maximum biogas yield according to this model is 83.982 ml/(kg DOM).

In general, cow manure is considered to be an ideal substrate for anaerobic methane fermentation, but,

unfortunately, the yield of biogas, and, accordingly, biomethane, is low. Thus, the study of the efficiency of biomethane production using anaerobic methane destruction of cow manure and post-alcohol distillery waste with different content showed a reduction in the period of biomethane production with an increase in the content of post-alcohol distillery waste

CONCLUSIONS

In the case of combined anaerobic methane destruction of cow manure and post-alcohol distillery waste with periodic loading of the digester with an increase in the content of post-alcohol distillery waste, the effective period of biomethane production is reduced. If the effective period of biomethane production is 10-12 days with a post-alcohol distillery waste content of 9%, then with a post-alcohol distillery waste content of more than 9%, it is reduced to 4-5 days, after which the biomethane yield decreases significantly.

With an increase in the content of post-alcohol distillery waste in the substrate, the maximum biomethane yield increases and exceeds the biogas yield from cow manure mono-degradation by 4 times at a post-alcohol distillery waste content of 9%, and by 6-7 times at a post-grain distillery waste content of more than 9%.

The modelling of the constant biomethane yield at quasi-continuous substrate loading into the digester was carried out based on studies of the maximum biomethane yield at periodic substrate loading. The dependence of biomethane yield on the content of post-alcohol distillery waste in the substrate is described by a third-order Newton polynomial with a determination coefficient of 0.7445. As a result of studying this dependence at the extremes, it was found that the optimal way to obtain the maximum biomethane yield is to use anaerobic mono-destruction of post-alcohol distillery waste. In this case, the biogas yield will be 3.821 l/(h·kg DOM).

Mathematical models of the digester functioning during the anaerobic mono-degradation of post-alcohol distillery waste and the combined anaerobic methane degradation of cow manure and post-alcohol distillery waste are planned to be developed in the future. These models will describe the dynamics of changes in the concentration of nutrients in the substrate, the concentration of methane-forming bacteria biomass (considering the growth of the methanogen population according to the Mono equation and their death according to the Kolpikov equation) and biogas generation depending on different concentrations and modes of loading the digester. These mathematical models will be compared with the results of experimental studies and, if deviations are found, the coefficients of the mathematical models will be adjusted.

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CONFLICT OF INTEREST

None.

REFERENCES

- [1] Belhamidi, S., Elkhedime, H., Omar Elrhaouat, O., Sarra Kitanou, S., Taky, M., & Elmidaoui, A. (2021). Biogas production from vinasse derived from ethanol manufacturing using a continuous stirred tank reactor pilot plant. *Desalination and Water Treatment*, 240, 216-224. doi: 10.5004/dwt.2021.27763.
- [2] Budiyo, B., Syaichurrozi, I., & Sumardiono, S. (2013). Biogas production kinetic from vinasse waste in batch mode anaerobic digestion. *Malaysian Journal of Science*, 32(2), 2-14. doi: 10.22452/mjs.vol32no2.1.
- [3] Bulhakova, A. (2022). Mass spectrometric studies of valine molecules by electron shock in the gas phase. *Scientific Herald of Uzhhorod University. Series "Physics"*, 51, 9-17. doi: 10.54919/2415-8038.2022.51.9-17.
- [4] Calvo, A., Ravelo, R., Cadavid, P., Andrés, C., & Jhoan, D. (2019). Biogas production evaluation and reduction of vinasse organic load by anaerobic digestion. *Revista Colombiana de Biotecnología*, 21(2), 118-130. doi: 10.15446/rev.colomb.biote.v21n2.79555.
- [5] Carrilho, E.N.V.M., Labuto, G., & Kamogawa, M.Y. (2016). Destination of vinasse, a residue from alcohol industry: Resource recovery and prevention of pollution. *Environmental Materials and Waste Resource Recovery and Pollution Prevention*, 21-43. doi: 10.1016/B978-0-12-803837-6.00002-0.
- [6] de Carvalho, J.C., de Souza Vandenberghe, L.P., Sydney, E.B., Karp, S.G., Magalhães, A.I., Martinez-Burgos, W.J., Medeiros, A.B.P., Thomaz-Soccol, V., Vieira, S., Letti, L.A.J., Rodrigues, C., Woiciechowski, A.L., & Soccol, C.R. (2023). Biomethane production from sugarcane vinasse in a circular economy: Developments and innovations. *Fermentation*, 9(4), article number 349. doi: 10.3390/fermentation9040349.
- [7] de Farias Silva, C.E., & de Souza Abud, A.K. (2017). Influence of manure concentration as inoculum in anaerobic digestion of vinasse. *Acta Scientiarum. Biological Sciences*, 39(2), 173-180. doi: 10.4025/actasciobiolsci.v39i2.34007.
- [8] Foerster, E., & Roenz, B. (1979). *Methods of correlation and regression analysis*. Berlin: Verlag Die Wirtschaft.
- [9] Golub, N., & Potapova, M. (2018). [Technology of biogas production from distillery spent wash](#). *Scientific and Applied Journal Vidnovluvana Energetika*, 2(53), 70-78.
- [10] Golub, N., Potapova, M., & Karpenko, Yu. (2019). Mathematical modeling of the biogas production process from the distillery spent wash on the first stage. *Scientific and Applied Journal Vidnovluvana energetika*, 3(2), 96-104. doi: 10.20535/ibb.2019.3.2.166429.
- [11] Harihastuti, N., Yuliasni, R., Djayanti, S., Irnaning, H.N., Rame, R., & Prasetio, A. (2020). Hybrid Upflow-Anaerobic Filter (HU-AF) Integrated technology for bio-methane generation from vinasse with shorter hydraulic retention time. *E3S Web of Conferences*, 202, article number 10008. doi: 10.1051/e3sconf/202020210008.
- [12] Hashemi, S.S., Karimi, K., & Taherzadeh, M.J. (2022). Valorization of vinasse and whey to protein and biogas through an environmental fungi-based biorefinery. *Journal of Environmental Management*, 303(5), article number 114138. doi: 10.1016/j.jenvman.2021.114138.
- [13] Jaman, K., Idrus, S., Wahab, A.M.A., Harun, R.; Daud, N.N.N., Ahsan, A., Shams, S., & Uddin, M.A. (2023). Influence of molasses residue on treatment of cow manure in an anaerobic filter with perforated weed membrane and a conventional reactor: variations of organic loading and a machine learning application. *Membranes*, 13, article number 159. doi: 10.3390/membranes13020159.
- [14] Kulichkova, G. (2022). Comparative characteristics of native (liquid) and concentrated up to 40% vinasse as a raw material for anaerobic fermentation. *Eureka: Life Sciences*, 6, 25-35. doi: 10.21303/2504-5695.2022.002692.
- [15] Kulichkova, G.I., Ivanova, T.S., Köttner, M., Volodko, O.I., Spivak, S.I., Tsygankov, S.P., & Blume, Ya.B. (2020). Plant feedstocks and their biogas production potentials. *The Open Agriculture Journal*, 14, 219-234. doi: 10.2174/1874331502014010219.
- [16] Malinin, A.N., Molnar, K.B., & Malinina, A.O. (2021). [Parameters of gas-discharge plasma of barrier discharge on mixtures of vapours of diiodide, dibromide and mercury dichloride with helium](#). *Scientific Herald of Uzhhorod University. Series "Physics"*, 50, 9-14.
- [17] Neto, J.V.S., Gallo, W.L.R., & Nour, E.A.A. (2019). Production and use of biogas from vinasse: Implications for the energy balance and GHG emissions of sugar cane ethanol in the Brazilian context. *Environmental Progress & Sustainable Energy*, 39(1), article number 13226. doi: 10.1002/ep.13226.
- [18] Parsaee, M., Kiani Deh Kiani, M., & Karimi, K. (2019). A review of biogas production from sugarcane vinasse. *Biomass and Bioenergy*, 122, 117-125. doi: 10.1016/j.biombioe.2019.01.034.
- [19] Polishchuk, V.M., Shvorov, S.A., Zablodskiy, M.M., Kucheruk, P.P., Davidenko, T.S., & Dvornyk, Ye.O. (2021). Effectiveness of adding extruded wheat straw to poultry manure to increase the rate of biogas yield. *Problemele Energeticii Regionale*, 3(51), 111-124. doi: 10.52254/1857-0070.2021.3-51.10.
- [20] Rogovskii, I.L., Titova, L.L., Sivak, I.M., Vyhovskyi, A.Yu., Polishchuk, V.M., Drahnev, S.V., & Voinash, S.A. (2020). [Study of biogas during fermentation of cattle manure using a stimulating additive in form of vegetable oil sediment](#). *ARNP Journal of Engineering and Applied Sciences*, 15(22), 2652-2663.

- [21] Romaniuk, W., Rogovskii, I., Polishchuk, V., Titova, L., Borek, K., Shvorov, S., Roman, K., Solomka, O., Tarasenko, S., Didur, V., & Biletskii, V. (2022). Study of technological process of fermentation of molasses vinasse in biogas plants. *Processes*, 10(10), article number 2011. doi: [10.3390/pr10102011](https://doi.org/10.3390/pr10102011).
- [22] Rosales, A.M., Montalvo-Romero, N., Santamaría, L.E.G., Herazo, L.G.S., Bautista-Santos, H., & Lambert, G.F. (2022). Post-industrial use of sugarcane ethanol vinasse: A systematic review. *Sustainability*, 14(18), article number 11635. doi: [10.3390/su141811635](https://doi.org/10.3390/su141811635).
- [23] Santos, L.V., Ramos, M.V., Morales, E.J.R., & Hensel, J.A. (2019). Inoculum adaptation for the anaerobic digestion of mezcal vinasse. *Revista Internacional de Contaminación Ambiental*, 35(2), 447-458. doi: [10.20937/rica.2019.35.02.15](https://doi.org/10.20937/rica.2019.35.02.15).
- [24] Santos, L.V., Ramos, M.V., Morales, E.J.R., & Hensel, J.A. (2020). Effect of inoculum source on the anaerobic digestion of mezcal vinasse at different substrate-inoculum ratios. *Revista Internacional de Contaminación Ambiental*, 36(1), 81-95. doi: [10.20937/RICA.2020.36.53276](https://doi.org/10.20937/RICA.2020.36.53276).
- [25] Syaichurrozi, I. (2016). Review – biogas technology to treat bioethanol vinasse. *Waste Technology*, 4(1), 16-23. doi: [10.12777/wastech.4.1.16-23](https://doi.org/10.12777/wastech.4.1.16-23).
- [26] Tunes, C.R., de Moraes, P.P., Caeser, A., Portella, F., De Souza Aguiar, R.W., da Silva, A.R., Bis, D.P., & Scheidt, G.N. (2016). [Biogas production from anaerobic digestion of vinasse in upflow anaerobic sludge blanket reactor](#). *International Journal of Current Research*, 8(9), 38699-38703.
- [27] Utami, I., Redjeki, S., Astuti, D.H., & Sani. (2016). Biogas production and removal COD – BOD and TSS from wastewater industrial alcohol (Vinasse) by modified UASB bioreactor. *MATEC Web of Conferences*, 58, article number 01005. doi: [10.1051/matecconf/20165801005](https://doi.org/10.1051/matecconf/20165801005).
- [28] Yuliasni, R., Yuliasuti, R., & Setianingsih, N.I. (2021). Biogas production from sugarcane vinasse: A review. *Jurnal Riset Teknologi Pencegahan Pencemaran Industri*, 12(2), 34-44. doi: [10.21771/jrtppi.2021.v12.no2.p34-44](https://doi.org/10.21771/jrtppi.2021.v12.no2.p34-44).

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Дослідження анаеробної метанової деструкції післяспиртової барди

Анотація. Післяспиртова барда є забруднювачем довкілля, тому проблема її утилізації є актуальною. Одним із способів утилізації післяспиртової барди є її анаеробна метанова деструкція на біогазових установках. Метою цього дослідження було визначити оптимальну кількість післяспиртової барди, яку необхідно додати до субстрату, щоб досягти максимального виходу біометану. Дослідження проводились на лабораторній біогазовій установці, яка складається із дайджестера об'ємом 30 л і газгольдера, в мезофільному режимі за температури субстрату 40°C при періодичному режимі завантаження субстрату. Встановлено, що найвищий вихід біогазу в 5.369 л/(год·кг DOM) отримується при анаеробній метановій монодеструкції післяспиртової барди. Однак вміст метану в біогазі при цьому знаходиться в межах 48-52 %. При анаеробній метановій деструкції суміші післяспиртової барди з коров'ячим гноєм вміст метану в біогазі зростає до 70–76 %, однак вихід біогазу менший і становить: 4.577 л/(год·кг DOM) при вмісті післяспиртової барди в субстраті 36 %, 3.294 л/(год·кг DOM) – при 27 %, 2.960 л/(год·кг DOM) – при 18 %, 1.538 л/(год·кг DOM) – при 9 %. Оптимальний вміст післяспиртової барди в субстраті, при якому вихід біометану буде максимальним (3,821 л/(год·кг DOM)), становить 46,7 % від вмісту субстрату і 100% від вмісту органічної частини субстрату. Результати даного дослідження можуть бути застосовані при плануванні складу субстрату біогазових установок, проектуванні і будівництві нових біогазових установок поблизу спиртзаводів

Ключові слова: біометан; біогазова установка; метантенк; ферментатор; біореактор; дайджестер