Optimisation of anaerobic digestion of agricultural waste by simulation modelling

I.Yu. Matasova [1], *Aleksey V.* Masenko [2*], *David R.* Grigoryan [2], *Anna N.* Tokareva [3], *Maria S.* Demchenko [3]

[1] Admiral Ushakov Maritime State University, Novorossiysk, 353924, Russia
[2] Kuban State Agrarian University named after I. T. Trubilin, Krasnodar, Russia
[3] Azov-Black Sea Engineering Institute – branch of Don State Agrarian University in Zernograd, Zernograd, Russia

Abstract. The article deals with the problem of agricultural waste processing, focusing on anaerobic digestion for biogas and fertiliser production. The study is devoted to the optimisation of this process on the example of poultry manure, using a simulation-statistical approach. The developed model of the biotechnological system includes waste separation into fractions, pre-digestion, methane digestion and anaerobic filtration. Substrate loading dose and substrate moisture content were found to have the greatest influence on energy release. Experiments showed that an increase in loading dose leads to an increase in biogas yield. Modelling allowed us to obtain an energy release equation that takes into account humidity, loading dose and digestion temperature. The maximum energy yield is achieved at a certain combination of these parameters. The study also showed that the use of the proposed biotechnological system can contribute to meeting part of the region's heat energy needs through the production of biogas from waste. Measures to optimise waste collection and processing, including the formation of databases and simulation modelling, have been proposed.

1 Introduction

Globally, agriculture is a major source of both organic and inorganic waste, which, if not properly managed, can have a significant negative impact on the environment. The increase in the volume of these wastes, especially in the context of growing agricultural production, requires the search for sustainable and efficient methods of their processing. At the same time, it is important to note that in order to achieve sustainable agriculture, it is necessary to consider not only recycling methods, but also the overall ways of development of the industry [1]. This can make a significant contribution to the sustainability of the agro-industrial complex and the transition to a closed-loop economy.

Currently, there are several approaches to solving the problem of processing agricultural waste, each of which has its own advantages and disadvantages. Traditional methods such as composting and direct land application have relatively low costs, but are often accompanied by nutrient loss and can be a source of environmental pollution. Thermal treatment of waste, including incineration and pyrolysis, provides energy but requires significant capital expenditure and can generate emissions. In contrast, anaerobic digestion, or methane digestion, is a promising method that not only recycles organic waste but also produces biogas, a renewable energy source, and organic fertiliser. This process, although more complex, allows a more efficient utilisation of the waste potential. However, the implementation of anaerobic technology requires detailed study, analysis and optimisation of its individual stages.

In the context of the above, the direction of solving the problem of processing organic agricultural waste through anaerobic digestion with subsequent production of biogas and organic fertilisers seems particularly relevant and important. Firstly, it allows not only to reduce the volume of waste, but also to obtain valuable products that can be used in agricultural production and energy. Secondly, the application of anaerobic technology can reduce the dependence of the agro-industrial complex on fossil fuels and chemical fertilisers, thus increasing its sustainability and competitiveness. Thirdly, anaerobic digestion contributes to the reduction of greenhouse gas emissions and other pollutants, which is in line with the goals of sustainable development and environmental safety [2, 3]. Analysing the carbon footprint of various production processes is of key importance in the transition to sustainable practices in agribusiness and other industries [4, 5]. The development of efficient and economically feasible technologies for anaerobic digestion of organic waste and their integration into production cycles is one of the key areas for achieving agricultural sustainability. In particular, it is extremely important to study the peculiarities of anaerobic digestion of various types of organic waste, as well as to analyse and model the

* Corresponding author: almasenko@yandex.ru

© The Authors, published by EDP Sciences. This is an open access article distributed under the terms of the Creative Commons Attribution License 4.0 (https://creativecommons.org/licenses/by/4.0/).

processes occurring within such a biotechnological system.

Thus, the purpose of this work is to study and model the processes of anaerobic digestion of organ-containing agricultural by-products, namely, the example of bioconversion of poultry manure, using a simulation and statistical approach. The use of mathematical models, such as neural networks, allows predicting and analysing various processes, including in the field of agro-technologies [6]. In the course of the study, a block diagram of the simulation method of statistical approximation was developed to optimise the process of anaerobic digestion and determine the most significant factors affecting the biogas yield and the quality of organic fertilizer. This will provide the knowledge necessary for the creation of effective biotechnological systems of organic waste processing.

2 Method and materials

The general plan of the experimental work carried out in this paper included several stages. At the first stage, a mathematical model of the biotechnological system describing the process of anaerobic digestion of agricultural by-products was developed. Then, a series of simulation experiments were conducted using this model. The experiments were conducted by varying various factors such as substrate moisture content and substrate loading dose into the reactor. In the next step, the results obtained were analysed using mathematical statistics techniques. At the final stage, the block diagram of the model was formed.

The main part of the experimental work was carried out through simulation modelling, where various parameters of anaerobic digestion, such as substrate composition and temperature conditions, were varied to reveal their influence on energy release. In order to create efficient systems, it is necessary to use methods for predicting the technical condition of the plants [7]. During the experiments, the dependence of biogas yield on various factors such as substrate humidity, loading dose, temperature and others was studied. Methods of mathematical statistics were used to analyse the data, which allowed us to identify significant factors and establish the structure of interrelationships between them. These methods involve the use of software tools for statistical processing of data, but the specific software is not specified. Based on the data obtained, a mathematical model describing the dependence of energy release on various parameters was constructed. The results of simulation modelling were used to analyse and optimise the anaerobic digestion process.

3 Results and discussion

An innovative biotechnological system (BTS) based on the separate treatment of solid and liquid fractions was proposed as part of the study of anaerobic digestion of organic waste from agricultural production. The experimental work was organised as follows. First, the feedstock, which was a mixture of agricultural by-products, was fed into a collection tank. Then, with the help of a faecal pump, the feedstock was directed to the first stage fractionation device. Here the separation into solid and liquid phases took place with a separation efficiency of 45-75% for the solid fraction, with a moisture content of 85-90% for the latter (Fig. 1).

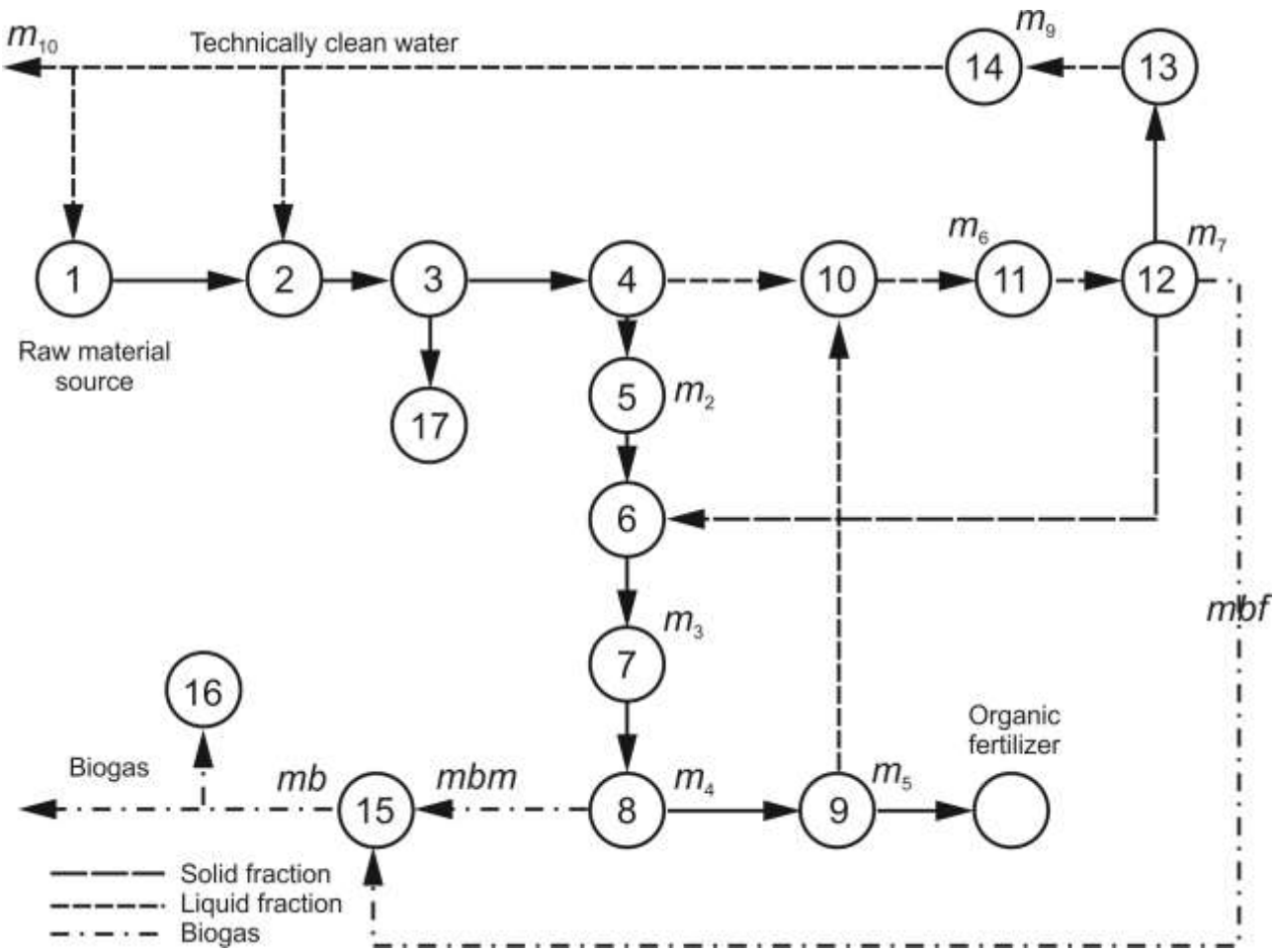


Figure 1. Schematic diagram of the technological line for processing of organ-containing agricultural by-products (biotechnological system (BTS)): 1 - raw material source; 2 - raw material collection tank; 3, 7, 10, 14 - faecal pumps; 4 - separation device into fractions of the first stage; 5 - solid fraction shredder; 6 - digester pre-digester tank; 8 - digester; 9 - second stage fractionation device; 10 - anaerobic filter precipitator tank; 12 - anaerobic filter; 13 - technical clean water tank; 15 - biogas gas holder; 16 - combined cycle power plant; 17 - sanitary storage facility.

The solid fraction was then pulverised and transferred to the digester's digestion pre-digester tank. In this tank, it was mixed with anaerobic microflora-contaminated sludge from the anaerobic filter, which helped to intensify the methane digestion process. To create optimal digestion conditions, the solid fraction was heated to the required temperature. Then, once a day, the mass was fed to the digester, where it was kept for 10-15 days. This resulted in decomposition of organic matter by 35-45% with biogas formation. The obtained sludge was fed to the second stage fractionation device, where additional separation into solid and liquid phases was performed. The solid fraction, with moisture content of 65-75% was used as fertiliser, and the liquid fraction was fed to the anaerobic filter's predigestion tank. Here, the liquid phase was mixed with the liquid fraction obtained after the first separation step and heated. The mixture was then fed into the anaerobic filter, where it was kept for one and a half to two days. In the anaerobic filter, due to the intensification of the digestion process, the degree of decomposition of organic matter increased to 75-80%. Further, the liquid went to the tank of conditionally clean water, where after purification part of the water was returned for technological needs, and the rest could be used for irrigation. The released biogas, which was a mixture of methane (about 60%) and carbon dioxide (about 40%), was collected in a gas holder and further used for energy production.

The effect of various factors on the anaerobic digestion process, in particular the moisture content of the treated substrate and the loading dose, was investigated experimentally. A non-symmetric factorised design of experiment was used for the study. As a result of statistical processing of the data, the energy release equation was derived. The study showed that the loading dose has the greatest influence on the energy release, with the biogas yield also increasing with increasing loading dose. In the energy release model (Fig. 2), in addition to substrate moisture and loading dose, a third factor was introduced, namely the temperature regime of digestion.

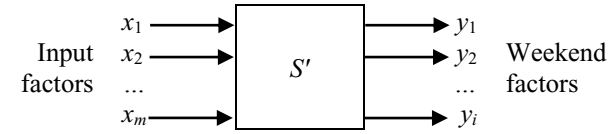


Figure 2. Cybernetic diagram of bioenergetic system connections

The system S reacts differently to the choice of different levels of factors (variables). In particular, the relationships between input and output factors can be characterised by regression models of the form [4].

$$y_{\alpha i} = \sum_{j=0}^{k} \theta_{\alpha i} x_{ji} + \sum_{\substack{j=1 \\ j<\beta}}^{k} \theta_{\alpha j \beta} x_{ji} x_{\beta i} + \sum_{\substack{\gamma=1 \\ \gamma \neq \alpha}}^{\ell-1} \theta_{\alpha(\gamma+q)} y_{ji}. \quad (1)$$

System S can also be represented as a system of equations (not always linear, one-dimensional) of the form

$$Y_1 = \begin{pmatrix} y_{i1} \\ y_{i2} \\ - \\ y_{i\ell} \end{pmatrix} = \begin{pmatrix} \theta_1^1 x_{i1} + \theta_2^1 x_{i2} + \ldots + \theta_m^1 x_{im} + \ldots + \varepsilon_{i1}^1 \\ \theta_1^2 x_{i1} + \theta_2^2 x_{i2} + \ldots + \theta_m^2 x_{im} + \ldots + \varepsilon_{i1}^2 \\ - - - - - - - - - - - - - - - - - \\ \theta_1^\ell x_{i1} + \theta_2^\ell x_{i2} + \ldots + \theta_m^\ell x_{im} + \ldots + \varepsilon_{i1}^\ell \end{pmatrix}.$$

Studies of the model confirmed that an increase in substrate moisture content promotes greater conversion of ash-free matter into biogas, and the optimal temperature regime allows to obtain the maximum energy yield. The energy release equation obtained on the basis of modelling and experiments is as follows:

$y_1 = 0{,}07 + 0{,}765\ x_2 + 0{,}136$

x_1x_2, where y_1 - energy release; x_1 - humidity of the treated substrate; x_2 - substrate loading dose into the reactor. The regression coefficient for the loading dose is 0.765, which shows its greatest influence on the energy release, it was also found that the interaction effect of humidity and loading dose is significant, it is equal to 0.136. Another obtained model describing the energy release is as follows:

$y_2 = 0{,}472x_1 + 0{,}375x_2 - 0{,}113x_3$,

where y_2 - energy yield; x_1 - substrate moisture; x_2 - loading dose; x_3 - temperature. In this case, substrate moisture has the greatest influence on energy yield with a regression coefficient of 0.472. At the same time, the maximum energy yield was calculated, which is achieved at a substrate loading dose of 5%, substrate humidity of 93% and reactor volume of 473 m3. Based on these data we can conclude that in anaerobic digestion of agricultural waste it is necessary to maintain optimal substrate humidity and temperature, as well as the optimal dose of reactor loading to achieve maximum energy yield.

Analysis of the results of the study showed that the proposed biotechnological system, as well as the obtained regression models, allow us to identify significant factors that influence the process of anaerobic digestion, as well as to establish the structure of relationships between them. This requires detailed analyses and crop planning using bibliometric analysis [8]. Moreover, the results of the work indicate the possibility of using simulation modelling to control the technological process of anaerobic digestion. This is an important advantage of the developed methodology, as it allows modelling and optimising technological processes without conducting expensive and time-consuming full-scale experiments. It is worth noting that in studies by other authors, a significant influence of loading dose and moisture content on biogas yield was also established. At the same time, in the conducted study the energy yield model was also constructed and evaluated, which takes into account not only the loading dose and substrate humidity, but also the digestion temperature, which expands the possibilities of using the obtained model in practice. For example, in a similar study it was shown that increasing the substrate moisture content from 75% to 90% increases the biogas yield by 15-20%, and increasing the temperature from 20°C to 35°C increases the biogas yield by 20-25%. It is worth noting that in our study a slightly higher biogas yield was obtained due to the use of a more efficient waste treatment technology. We also conducted studies to determine the potential volume and quality of biogas in poultry litter and effluent from the pig farm, which showed that the total potential biogas production can reach 22 million m3 per year, which allows to meet about 6% of the total heat energy demand in the region. Assessment of the impact of mountain factors on agroecological processes helps to more accurately assess the region's potential for development [9]. These results confirm the possibility of using a biotechnological system as an energy source and, importantly, allow the utilisation of agricultural by-products, simultaneously obtaining valuable fertiliser and clean water. However, in practice, there are difficulties in realising such projects, such as the collection and transportation of by-products and the need to ensure the stability of the technological process. To solve these problems, it is proposed to form balances of agricultural by-products and use regulatory bases for their formation in the sectoral and geographical context. This will allow, firstly, to effectively plan the production capacity of bioenergy plants, and secondly, to optimise the costs and logistics of raw material supply. In the future, for more effective management of the process, it is proposed to use a unified information base, which will allow planning and forecasting the development of the agro-industrial complex for the long term, as well as to use simulation models to identify inefficient elements, as well as to forecast the development of real situations. Assessment of the ecological state of agro-landscapes at the local level can provide more accurate data for planning and management [10]. This, in turn, will improve the efficiency of resource utilisation and reduce the negative impact on the environment.

4 Conclusion

The system of agro-industrial waste processing proposed in this work is based on separate treatment of solid and liquid fractions of waste. The solid fraction is subjected to grinding and methane digestion in a digester, and the liquid fraction is subjected to anaerobic filtration. At the same time, it is necessary to take into account the importance of creating organic fertilisers and ensuring soil fertility through waste utilisation [11]. Simulation modelling was used to optimise the process and identify factors affecting biogas yield.

It was found experimentally that the substrate loading dose has the greatest influence on the energy yield, and the interaction between substrate moisture and loading dose is also significant. In the course of modelling it was determined that an increase in moisture content promotes a more complete conversion of organic matter into biogas, and maintenance of optimum temperature ensures maximum energy yield. Based on the obtained data, mathematical models describing the dependence of energy release and energy yield on various process parameters were developed. The developed biotechnological system allows not only to reduce the volume of waste, but also to produce biogas, which can be used for energy production, and organic fertilisers. The creation of a model for agro-ecological assessment of an area can help in creating sustainable production systems [12]. It has also been found that the potential for biogas production from poultry manure and effluent from pig farms can provide a significant share of thermal energy needs in the region. However, there are difficulties in the implementation of such projects related to the collection and transport of by-products, as well as ensuring the stability of the process. To solve these problems, it is proposed to form balances of by-products and use a unified information base for planning and forecasting the development of the agro-industrial complex. The use of anaerobic processing technologies, in this case, correspond to the general trends in agrarian changes and adaptation to climatic changes [13]. In general, the results of the study confirm the prospectivity of anaerobic digestion of agricultural organic wastes as a sustainable and environmentally safe way of obtaining energy and valuable products. The use of simulation modelling is an effective tool for the control and optimization of such biotechnological processes.

References

1. I. Chowdhuri, S.C. Pal. Challenges and potential pathways towards sustainable agriculture crop production: A systematic review to achieve sustainable development goals (SDGs). Soil Till. Res., **248,** 106442 (2025). DOI: 10.1016/j.still.2024.106442.

2. L.S. Malyukova, V.V. Bukhtoyarov, V.Y. Konyukhov. Circular Mining Wastes Management for Sustainable Production of Camellia sinensis (L.) O. Kuntze. Sustainability (Switzerland), **15,** 11671 (2023). DOI: 10.3390/su151511671.

3. B. Aparecida da Silva, R. Evangelista de Oliveira, A. Cavalieri Sais, E. Cardoso leite. Family farmers and trees: ecological functions, ecosystem services and food production in agrarian reform settlements in Brazil. Agroecol. Sustain. Food Syst., **49,** 4-21 (2025). DOI: 10.1080/21683565.2024.2405515.

4. V. I. Silaev, R. V. Klyuev, D. V. Eremeev, T. A. Martynova, Yu. V. Danilchenko. Analysis of the carbon footprint created by mining enterprises. MIAB. Mining Inf. Anal. Bull., **11,** 265–277 (2023). DOI: 10.25018/0236_1493_2023_111_0_265.

5. A.A. Kulikova, E.I. Khabarova. Biological working agents use to reduce the carbon footprint. Sustainable Development of Mountain Territories, **16,** 311–321 (2024). DOI: 10.21177/1998-4502-2024-16-1-311-321.

6. S.N. Sorokova, E.A. Efremenkov, D.V. Valuev, M. Qi. Analysis of a Predictive Mathematical Model of Weather Changes Based on Neural Networks. Mathematics, **12,** 480 (2024). DOI: 10.3390/math12030480.

7. O. A. Kolenchukov, A. Y. Mikhaulov, K. A. Bashmur, R. B. Sergienko, V. V. Kukartsev, V. V. Tynchenko. Forecasting the technical condition of thermochemical reactor systems. SOCAR Proceedings, **2023,** 123–130 (2023). DOI: 10.5510/OGP20230100814.

8. A. Deo, N. Sawant, A. Arora, S. Karmakar. How has scientific literature addressed crop planning at farm level: A bibliometric-qualitative review. Farming Syst., **3,** 100139 (2025). DOI: 10.1016/j.farsys.2025.100139.

9. K.I. Kravtsov, T.A. Panfilova. Influence of mountain factors on salt excess and soil toxicity in mountain conditions. Sustainable Development of Mountain Territories, **15,** 784-797 (2023). DOI: 10.21177/1998-4502-2023-15-3-784-797.

10. N. A. Tursynbaev, I. V. Kuzhevskaya, L. M. Tatarintsev, A. A. Ospanova. Assessment of the environmental state and sustainability of agrolandscape at the local level. Sustainable Development of Mountain Territories, **15,** 662–671 (2023). DOI: 10.21177/1998-4502-2023-15-3-662-671.

11. V. V. Kireeva, T. G. Rasskazova, N. M. Serbulova. Maintaining soil fertility: A method for organic fertilizer production from crop farming waste. Sustainable Development of Mountain Territories, **10,** 493–499 (2018). DOI: 10.21177/1998-4502-2018-10-4-493-499.

12. B. Zh. Akhmetov, A. Zh. Kasenova, O. E. Merzlyakov, L. M. Tatarintsev. Modeling of sustainable agricultural land use on the basis of agroecological assessment of the territory. Sustainable Development of Mountain Territories, **15,** 17–26 (2023). DOI: 10.21177/1998-4502-2023-15-1-17-26.

13. B. Zh. Akhmetov, A. Zh. Kasenova, O. E. Merzlyakov, L. M. Tatarintsev. Modeling of sustainable agricultural land use on the basis of agroecological assessment of the territory. Sustainable Development of Mountain Territories, **15,** 17–26 (2023). DOI: 10.21177/1998-4502-2023-15-1-17-26.