Machinery & Energetics
Vol. 15, No. 1. 2024

Journal homepage:
https://technicalscience.com.ua/en

UDC 628.477.6
DOI: 10.31548/machinery/1.2024.86

Lyudmyla Mikhailova*
PhD in Technical Sciences, Professor
Higher Educational Institution "Podillia State University"
32316, 12 Shevchenko Str., Kamianets-Podilskyi, Ukraine
https://orcid.org/0000-0002-3419-5446

Viktor Dubik
PhD in Technical Sciences, Associate Professor
Higher Educational Institution "Podillia State University"
32316, 12 Shevchenko Str., Kamianets-Podilskyi, Ukraine
https://orcid.org/0000-0002-9743-1565

Oleksandr Dumanskyi
PhD in Technical Sciences, Associate Professor
Higher Educational Institution "Podillia State University"
32316, 12 Shevchenko Str., Kamianets-Podilskyi, Ukraine
https://orcid.org/0000-0002-1750-5844

Oleksandr Kozak
PhD in Technical Sciences, Associate Professor
Higher Educational Institution "Podillia State University"
32316, 12 Shevchenko Str., Kamianets-Podilskyi, Ukraine
https://orcid.org/0000-0002-0919-0344

Possibilities of landfills and solid waste sites for energy production in Ukraine

Abstract. Dynamic changes in the energy sector towards the priority of renewable energy are stimulated by the political decisions in the European integrated environment aimed at achieving climate neutrality within the framework of the European Green Deal. The study aims to provide an in-depth investigation of the potential of landfills and solid waste sites for energy production in Ukraine. The study was conducted using general scientific methods, in particular, analysis and synthesis, abstraction, and comparison. The study examined the issues of developing the bioenergy potential of solid waste sites in Ukraine, including organisational, regulatory, technological, financial and investment aspects. The position of various operations for bioenergy waste processing in the solid waste management system, in particular, anaerobic digestion and solid fuel production, was identified, and an analysis of several thermal waste processing technologies was carried out. Among the features and characteristic requirements for the biogas production process using anaerobic methodology, the aspects of technological availability and economic feasibility are highlighted. The study examines the experience of production and use of organic Refuse Derived Fuel and Solid Recovered Fuel produced from solid waste sites, proving the need to optimise the regulatory support for biogas production at solid waste sites storage sites in the national legislative field. The article emphasises the possibility of practical use of Refuse Derived Fuel and Solid Recovered Fuel, in a partial format, to offset the shortage of fossil fuels in Ukraine and actively implement the concept of a sustainable green course for rational waste management. The results obtained can be used to improve the optimisation of strategic programmes for solid waste management in terms of their bioenergy potential

Keywords: renewable fuel resources; calorific value; biogas; morphological composition; biomass; sustainable development

Article's History: Received: 03.10.2023; Revised: 15.01.2024; Accepted: 28.02.2024.

Suggested Citation:
Mikhailova, L., Dubik, V., Dumanskyi, O., & Kozak, O. (2024). Possibilities of landfills and solid waste sites for energy production in Ukraine. *Machinery & Energetics,* 15(1), 86-94. doi: 10.31548/machinery/1.2024.86.

*Corresponding author

INTRODUCTION

The priority of developing the biogas and biomass potential is intensified by the introduction of the principles of circular production processes and climate neutrality against the background of general European integration processes. Solid waste sites (SWS) have a significant bioenergy potential due to their specific morphological composition. The overall morphological composition of municipal waste in Ukraine is made up of food waste (30-45%), paper and cardboard (5-15%), secondary polymers (8-17%), glass (9-14%), and other waste (Davydov and Chebanenko, 2023). Among the key priorities of biofuels derived from SWS, particular emphasis should be placed on the potential for a significant contribution to electricity production and reduction of energy dependence, and the possibility of replacing traditional fuels in heat and power generation and transport.

The relevance and urgency of the need to study the bioenergy potential of SWS is determined by the irrationality of the traditional approach to municipal waste processing in Ukraine, which involves the joint disposal of components dumped in landfills, landfills and unauthorised locations. A particular danger is posed by the prevalence of biogenic fractions in the morphological composition of household waste, which is a source of potential pollution of the water and soil environment, as well as the air, and an increased level of fire hazard due to the presence of biogas (Chupa & Adamenko, 2023). If the optimal management and technological concept of waste management based on recycling is implemented, opportunities for the effective transformation of biogenic waste into a sustainable source of energy needs are opened.

The interdisciplinary concept of the problem under study has created the need for a preliminary study of a significant volume of scientific sources from various fields of knowledge. Modern studies highlight the basic concepts of the potential of using landfills and landfills for energy production and consider the risks and challenges related to their practical implementation. L. Haponych *et al.* (2022) study the algorithm of technology for the production and use of organic fuels such as Solid Recovered Fuel (SRF) and Derived Fuel (RDF) produced from SWS. Scientists see the advantage of the method of producing RDF/SRF from SWS fractions as the conversion of waste into renewable fuel that can be accumulated, stored, transported and used in the energy sector. The researchers believe that this concept can partially meet the shortage of organic fuels while complying with EU waste management requirements.

Yu. Holik *et al.* (2023) study the environmental aspects of using the potential of solid waste as a source of biogas, in particular, in terms of the complication of the situation due to martial law. The researchers note that Ukraine is experiencing a shortage of primary energy resources and is highly dependent on external supplies. They also note that significant volumes of waste pose a real danger to the environment, which is a complex problem that needs to be addressed urgently. At the same time, V.M. Marchenko *et al.* (2022) study the peculiarities of fuel characteristics in approximation with the emission of pollutants in the process of thermal utilisation of biomass. The scientists note that the volume and efficiency of thermal waste treatment are determined by the state environmental policy, the availability of sufficient natural energy sources, and the ability of the facilities to ensure that the technological process meets environmental standards. In continuation, O.A. Trehub (2022) thoroughly investigates the economic feasibility of introducing modern recycling and biofuel production technologies. The author emphasises that the definition of "landfill" biogas as a pollutant rather than a potentially efficient fuel dominates in the Ukrainian waste legislation. According to O.A. Trehub (2022), such a significant inconsistency requires immediate elimination as part of the adaptation to Directive 1999/31/EU on landfill.

Modern studies addressed the criteria for developing and assessing the possibilities of effective SWS processing to maximise their potential as a source of alternative energy, which is positioned as a current trend in the global integrated environment. In particular, S. Kobzar *et al.* (2021) substantiate the priority vectors of transformation of the use of biogas potential, considering the global concept of growing interest in biofuel production at waste storage sites. O.O. Romaniuk & V.S. Yarovenko (2020) focus on the complexities of implementing biogas production and use systems. The researchers argue that the efficiency of thermal waste treatment plants depends on the structure of SWS, with the fractions with the highest bioenergy potential characterised by the least controllability of combustion product indicators. According to the authors, the maximum efficiency can be achieved under conditions of continuous receipt of large volumes of waste.

Despite the relevance of the issue of using landfills and landfills for energy production by scientists, the issues of developing the bioenergy potential of solid waste in the national space remain poorly understood. The study aims to provide an extended investigation of the potential of landfills and landfill sites for energy production in Ukraine through innovative technological approaches.

MATERIALS AND METHODS

The study was carried out using several general scientific methods. The systemic approach, as well as the accepted concepts of complexity and dialectic, were chosen as the basis of the methodological and theoretical framework. The systemic concept created the prerequisites for an effective analysis of the phenomenon under study as a systemic phenomenon in the entirety of interconnections. The analytical method was used to identify opportunities and trends in the development of the subject of research. Using the analytical and synthetic methods, the essence and strategic directions of unlocking the potential of using landfills and landfills for energy production in Ukraine were identified. The article also identifies the characteristic features of the functionality of the influencing elements on the dynamics of the development of biofuel production opportunities in places of solid waste storage within the current socio-economic realities.

The identification of basic categorical concepts was carried out employing abstraction. It was used to form the

concept of integrity and the structural and consequential nature of the processes of the solid waste recycling system. Using this method, the characteristic properties and relations of the research object were separated, focusing on the most valuable ones. As a logical continuation of abstraction, the method of generalisation was applied, which involves approximating the characteristic range of potential opportunities for solid waste recycling, summarising the dynamics of scientific thought from a general judgement to a specific vision of the possibilities of using the identified potential. The method of specification was used to identify the effectiveness and feasibility of implementing SWS energy transformation technologies, select the best solutions to maintain optimal environmental conditions and mitigate environmental risks in the case of using waste storage sites for biogas production.

Induction was used to study the facts that characterise the properties of SWS, which led to the generalised characteristics of biofuels produced from SWS. Along with induction, the deductive method was used to identify the specifics of biofuel production in the process of waste recycling for Ukrainian realities. A comparison method was used to compare the performance indicators of individual methods of obtaining renewable energy from waste, as well as their environmental impact. The formalisation method was used to identify the priority aspects of optimising the waste management system to tap the potential of using landfills and landfill sites for energy production in Ukraine. To track and analyse the actual state of solid waste management, we used statistics from official sources, namely the State Statistics Service of Ukraine (2024) on the morphological composition of waste and the state of implementation of productive waste processing operations. Data on the energy use of SWS were obtained through the Bioenergy Association of Ukraine.

RESULTS

The production of biogas from solid waste is one of the most promising areas, as Ukraine generates approximately 10 million tonnes of waste annually (State Statistics Service of Ukraine, 2024). The intensification of the involvement of the bioenergy potential of SWS use is driven by the national strategy for climate change prevention and environmental security stabilisation, which positions the vector development of energy towards the involvement of renewable sources as promising (Order of the..., 2021). The waste management hierarchy operating in Ukraine provides for the main strategic vectors of waste prevention, reuse and recycling, as well as regeneration through energy production. For bioenergy, the object of research, development and practical use is the bioorganic component of SWS. Energy operations, by their very nature, do not fall within the definition of recycling, as they are a one-time use of raw materials without variability in their prospective recovery. Anaerobic decomposition of the bio-organic component of SWS is considered an exception. This approach allows to produce biogas to meet energy needs, as well as organic fertiliser for agronomy.

In general, two modes of anaerobic digestion are basic, with a temperature range 28-40°C (mesophilic) and 41-55°C (thermophilic). In the case of the mesophilic mode, the processes are slower and with lower biogas production, but despite these disadvantages, mesophilic reactors are used more often due to low energy costs (Kolienko *et al.*, 2023). The anaerobic digestion process algorithm includes a certain order of processes, which include acid genesis, hydrolysis, methanogenesis and acetogenesis, with the specifics of the process depending on the nature of the interaction of microorganisms that can participate in each stage of digestion (Atelge *et al.*, 2020). In the case of single-stage batch reactors, the entire volume of waste is loaded at the same time, so all stages of the process algorithm can be carried out sequentially in one location.

Figure 1 shows that the basic functional component of the proposed plant is a methane digester, which directly implements the process of biomass decomposition using methanogenic bacteria, provided that the required temperature for anaerobic digestion is met.

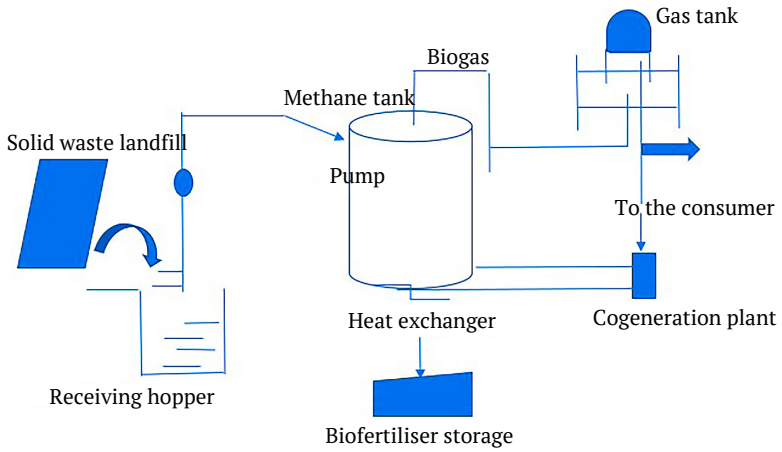

Figure 1. Anaerobic SWS treatment process in a single-stage reactor
Source: compiled by the authors based on M.R. Atelge *et al*. (2020), V.M. Marchenko *et al*. (2022)

It is worth characterising each stage of the anaerobic digestion process to identify potential productivity and, therefore, to search for promising optimisation. Hydrolysis is the process of transformation of biogenic fractions into individual components involved in the functional activity of acidogenic bacteria (Ghosh *et al.*, 2020; Zupančič *et al.*, 2022). The acetogenesis stage involves the conversion of the resulting substances into acetate compounds, which is accompanied by the release of hydrogen. The resulting hydrogen forms a synthetic functional bond – an interspecies hydrogen delegation. At the same time, excessive partial pressure is considered extremely harmful to acetogenic microorganisms (Atelge *et al.*, 2020).

Methanogenesis is the final stage of the anaerobic digestion algorithm, where methanogenic microorganisms consume available variations of intermediates to produce methane. It is worth noting that methanogens require more time for regeneration than other microorganisms in the overall anaerobic digestion process. The difference is, on average, 5-16 days (Ghosh *et al.*, 2020). The completion of the methanogenesis process in batch reactors is identified by the stop of biogas production. At the same time, the degree of sludge digestion is determined based on information on the content of volatile solids and their ability to completely dewater (Zupančič *et al.*, 2022).

In the case of the multi-stage method, the fermentation process is differentiated into several reactors or chambers in one fermenter. Considering the need for different environmental conditions for microorganisms at different stages of the process, this method allows for greater process efficiency, although it requires more significant financial costs. Multistage methods are more appropriate in case of mandatory substrate hygiene, the need to increase the degree of hydrolysis with a small volume of the fermentation chamber, in case of difficulty in implementing the mixing process at maximum fermenter loading. Thus, the recommended optimal approach to ensuring the process of digestion of the organic fraction of SWS is the mesophilic digestion mode, single-stage digestion and wet fermentation, with continuous operation of the digester.

The energy generated from the thermal treatment of SWS has a significant potential for transformation into electricity and heat. The concept of Waste-to-Energy (WtoE) includes the production of biogas, as well as SRF and RDF fuels (Nwokolo *et al.*, 2020; Arias *et al.*, 2021). The approach proposed by WtoE technology is currently positioned as the main effective vector for saving fossil energy resources and minimising greenhouse gas emissions. Today, the most popular basic technological solutions for the extraction of a high-calorie specific SWS fraction that is appropriate for RDF are mechanical and biological treatment (MBT) of waste and dry stabilisation (Maroušek *et al.*, 2020). MBT is based on the convergence of mechanical and biological methods, with the separated recyclable materials being processed. The fractions of waste that are biodegradable are sent to composting and anaerobic digestion processes, while the rest is used to produce solid fuels RDF or SRF.

In the case of the dry stabilisation process, the selected SWS is subject to biological treatment, during which it is dried and stabilised by composting. As a result, a fuel with a high calorific value is produced. Thus, RDF is identified as an organic fuel obtained by separating recyclable materials from waste. Equipment based on pyrolysis processes for SWS processing consists of certain elements (detectors, separators, crushers, dryers, vibrating screens). The process of processing SWS directly into RDF fuel follows a certain universal algorithm (Fig. 2).

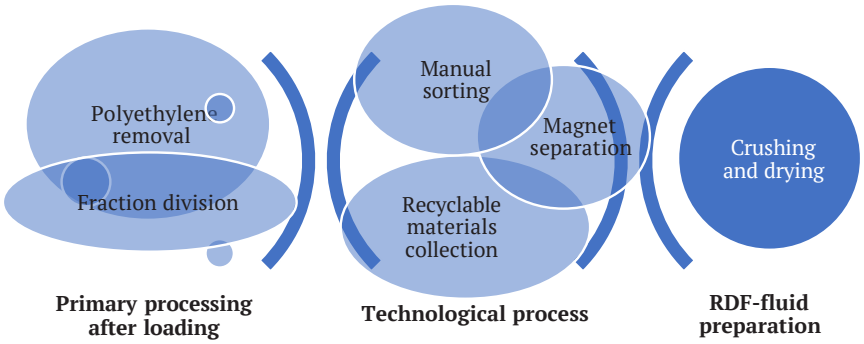

Figure 2. A general algorithm for processing solid waste into RDF fuel
Source: compiled by the authors based on S. Kobzar *et al*. (2021), N. Nwokolo *et al*. (2020)

Analysing the algorithm shown in Figure 2, an important point is the fact that this type of equipment is advantageous due to the variability of parameter adjustment for a specific type of raw material, maximum process automation and remote control, and high productivity. The RDF production process begins with the loading of household waste into a conveyor hopper, which is stripped of its plastic packaging through an automated process, followed by its separation into fractions and transport to the manual sorting and magnetic separation stage. At this stage, metal components, stones and glass are removed. Subsequently, crushers are used to crush the waste in stages, followed by drying it in a special drum. The hammer crusher crushes the raw material to a fraction of no more than 5-10 mm (Arias *et al.*, 2021).

Pyrolysis equipment for SWS processing has an attractive payback period. RDF fuel is positioned in the

energy market as an inexpensive source of thermal energy. Additional benefits of the RDF production process include reduced funding for solid waste disposal and the possibility of extracting glass and metal fractions. An incinerator is a modern facility with the functionality of processing various wastes based on thermal treatment, with mandatory subsequent maximum purification of combustion products. For incineration, certain types of thermal treatment of SWS are used, including incineration, pyrolysis and gasification (Nwokolo *et al.*, 2020). Technologies for the production and practical use of RDF/SRF fuels are most popular in developed European countries – the UK, Germany, Italy, and Austria. The annual demand for RDF/SRF in these countries reaches 55-67 million tonnes (Maroušek *et al.*, 2020). According to experts, Ukraine has a significant potential for RDF/SRF production, so the latter is considered an affordable and economically viable source of renewable energy (Marchenko *et al.*, 2022; Davydov & Chebanenko, 2023).

The implementation of the WtoE concept in practical projects is characterised by significant financial costs, so the potential of solid waste to energy in the national field will only be unlocked if the process of waste disposal is costlier than its recycling. There is a need for significant changes in the legal and regulatory framework for Ukraine's obligations in this area. According to the national strategy, the rate of solid waste disposal through thermal recycling should reach 10% by 2030, through the construction of thermal recycling facilities (Romaniuk & Yarovenko, 2020). Ukraine should take advantage of the practical experience of developed countries, where the main advantage of this approach is the transformation of waste into marketable products. Thus, the biogenic component of SWS is seen as an effective feedstock for biogas production and a component of solid fuels such as SRF and RDF. The outlined concept finds active support at the level of the state management paradigm and can be intensified by attracting available international support tools during the post-war recovery period.

The phenomenon of a certain struggle for priority between biogas and multicomponent solid fuels is based on the fact that anaerobic waste processing can be carried out in both wet and dry environments, so that biogas is produced from identical biogenic fractions of SWS through recycling, and solid fuels are produced through recovery operations (Pak & Pak, 2017). The hierarchy of the waste management system prioritises recycling, i.e. biogas production using anaerobic digestion, over waste incineration. However, it is necessary to consider the practical difficulty of maintaining the desired strategic line due to the influence of the commercial component (Order of the..., 2021; Zupančič *et al.*, 2022). In the process of searching for variations in energy transformation towards sustainable energy generation solutions, the possibilities of effective development of the potential of sustainable biomass are seen as relevant. The production of biogas and biomethane through anaerobic digestion is seen as an optimal alternative to the current paradigm of solid waste management. Aerobic and anaerobic ways of using landfills and landfills for energy production are technologically more accessible and cost-effective than thermal utilisation of pre-treated (RDF, SRF) of SWS.

In a globally integrated environment, the resolution to maximise the efficiency of reducing methane emissions from landfills through its controlled collection and utilisation is a priority. In addition, the successful implementation of energy recovery projects minimises greenhouse gas and air pollutant emissions, which positively affects environmental quality and reduces potential risks to public health (Abdibattayeva *et al.*, 2021). Such projects significantly reduce dependence on certain types of energy, contributing to savings, the creation of new jobs and the overall regional development of economic processes. Significant opportunities for expanding the use of landfill bioenergy potential are identified. At the same time, the priority of selecting a particular method of biogas utilisation is formed under the influence of determining factors, such as individual conditions of economic activity at the landfill and the availability of a solvent consumer of energy produced from biogas. In most developed countries, this process is stimulated by the state through regulatory and legislative regulation. The cost-effectiveness of biogas production and use projects demonstrates the feasibility and profitability of the proposed concept of solid waste management, which is intensified by the presence of an industrial gas consumer near the waste storage site.

Currently, about 6,000 landfills and landfills covering an area of more than 9,000 ha have been identified in Ukraine (State Statistics Service of Ukraine, 2024). At the same time, only 19 landfills are equipped with a biogas extraction system. Thus, the biogas resource of solid waste disposal sites is not used on a national scale in today's realities. The absence of developed infrastructure for energy transformation of waste in the Ukrainian national space creates optimal preconditions for the implementation of an effective and viable system of solid waste management. The proposed concept will help to expand the capabilities of recycling technologies, which will allow full use of landfills and landfills for energy production in Ukraine. This approach will maximise the expected positive effects in terms of environmental optimisation, energy imbalance and agricultural-technical intensification.

DISCUSSION

Research on the possibilities of using the potential of organised solid waste storage sites for renewable energy production is reflected in the results of numerous scientific studies by modern researchers, which reveal several characteristic features of the field under study in diametric positions, which stimulate the intensification of improving approaches to studying the potential of bioenergy in the concept of strategic development of Ukraine.

M. Govarthanan *et al.* (2022) focus on the individual qualities of renewable fuels, which are seen as potentially possible based on WtoE solutions. The authors argue that

the directions of development of technological possibilities for the use of landfills and landfills for energy production are formed using optimal design of regional development and economic efficiency for business, which is synergistic with the findings of this study.

Contemporary researchers K.R. Chew *et al.* (2021) consider the large-scale use of RDF and SRF to be one of the positive factors influencing the air protection system against excessive pollution and reducing carbon emissions. The researchers claim that, compared to the environmental burden of traditional solid waste disposal, the introduction of thermal treatment methods for pre-treated waste has environmental benefits. The statement is valid only in terms of the catastrophic consequences of spontaneous waste disposal, as the relative advantages of thermal treatment of pre-treated waste do not offset the destructive impact of these processes on environmental parameters, which becomes apparent against the background of more advanced waste management methods that exclude interference with the system of morphological and functional concepts of the environment (Rausch & Suchanek, 2021).

The conclusions of Q. Haar (2023) identify the management support of the solid waste management paradigm as a basic prerequisite for energy transformation within the framework of a green development course. The scientist shows that the concept of waste management is characterised by the dynamics of functionality against the background of the global trend of greening, being identified as a hub of potential concepts within the general vector of the modern ecosystem approach towards sustainable development. The scientist emphasises that efficient and cost-effective growth in biogas production and utilisation is possible only in the case of successful convergence of regulatory support, management support and investment intensification. Comparing the results of the researcher with the conclusions of the current study, the priority task of the state administrative paradigm in the field of waste management policy implementation, within the framework of the post-war regeneration paradigm, is the active implementation of innovative technologies for thermal utilisation of municipal solid waste components.

F. Aliaghaei *et al.* (2020) emphasise the priority role of sustainable biomass and biogas in the green energy transformation, while, according to scientists, waste incineration is less competitive. The separation of the biogenic flow from the total volume of solid waste for biogas production is important to ensure that the destructive trends of the national energy crisis are levelled. According to scientists, this approach meets global requirements for decarbonising energy generation.

A separate strategic vector for the optimal use of the bioenergy potential of SWS is the production of biogas directly at waste disposal sites (Danylyshyn & Koval, 2023). This is supported by the research by S. Gerassimidou *et al.* (2020). This approach is significantly inferior in the functional aspect to the organised process of anaerobic digestion of waste fractions, but, according to these researchers, it is possible to produce almost three times more methane under artificially created conditions, removing up to 70% of biogas from the landfill body. The scientists insist that their proposed method of biogas production has certain disadvantages, including the financial burden of building a special complex biogas collection system. Nevertheless, the scientists argue that the installation of innovative biogas collection systems at solid waste sites with their subsequent utilisation is not only technically feasible but also a cost-effective and environmentally sound solution. The results of the study by the researchers are synergistic with the conclusions of the current study in terms of the priority of the renewable energy concept using the potential of SWS.

J.S. Chae *et al.* (2020) note that the phenomenon of biogas uncontrollably generated in places of large-scale accumulation and disposal of municipal waste in urban agglomerations should be considered in two concepts of impact: negative – as an environmental hazard of a substance, and positive – as a renewable fuel. The researchers analyse the algorithmic structure of a typical scheme of controlled biogas production, expanding the traditional vision of the technological target potential and justifying the need to intensify investment in this area. The authors strongly believe that renewable nature is the main component of a sustainable approach to the management paradigm in the field under study, which allows ensuring the sustainability of ecosystems that can function effectively without requiring significant investment.

A. Calbry-Muzyka *et al.* (2022) provide a list of the main prerequisites for the priority reorganisation of the municipal solid waste management system in the concept of stimulating biogas production. While assessing the practical effectiveness of waste management system optimisation in several developed countries, scientists have found that local requirements, obstacles and advantages are the priority factors influencing the implementation of optimisation measures. Considering the specifics of the current study, it is necessary to formulate an individual strategy for the development of the waste management system in the context of Ukrainian realities. This approach will allow stabilising and development of the sustainability and competitiveness of national economic processes (Piskun *et al.*, 2024).

A. Sobczak *et al.* (2022) combine the effectiveness of technologically competent waste management with the principles of sustainable development. The scientists argue that the bioenergy approach balances the balance in the socio-economic space and promotes the rational use of resource potential and the overall optimisation of the environment. In addition, scientists draw attention to the need to implement the principles of sustainable development in the waste management sector, highlighting the related issues of financing, investment and availability of qualified personnel. Considering the results of scientific research in the context of the specifics of the current study, it should be noted that promising opportunities to involve international cooperation mechanisms in post-war reconstruction will allow for to resolution of the issue of targeted

investments and subsidies for the introduction of modern technologies for the use of landfills and landfills for energy production in Ukraine.

Active motivation and economic tools to stimulate the use of innovative bioenergy projects at the national and regional levels are currently positioned as the main effective means of optimising the situation in the industry. The proposed strategy of solid waste management allows us to expect optimisation of the socio-economic and environmental microclimate in society, an increase in the financial efficiency of projects, and an overall improvement of the social environment of urban agglomerations. The effectiveness of the practical testing of the outlined concept directly depends on the level of formation of the management paradigm in the industry, the establishment of strict standards and measures of responsibility for their violation, and the motivation of process participants in the effectiveness of measures. The prognostic perspective is to expand the functionality of the urban agglomerations' solid waste management system as a component of a successful management paradigm in the energy sector of post-war Ukraine. This concept involves intensifying the indicators of the economic feasibility of innovations and the successful implementation of green energy development projects.

CONCLUSIONS

The current study provided a detailed analysis of the possibilities of using the potential of landfills and landfills for energy production in the national Ukrainian space. In the process of studying the problems of developing the bioenergy potential of solid waste in Ukraine, the importance of various operations for bioenergy waste processing in the solid waste management system was highlighted. The analysis of several technologies for thermal waste processing has made it possible to identify the characteristic features and requirements for the biogas production process using an anaerobic methodology, in particular, technological prerequisites, organisational and economic aspects, and the specifics of the innovative concept.

In the course of the research, based on the study of practical experience in the production and use of organic fuels RDF and SRF produced from SWS, the priority of the potential for biogas and biomethane production through anaerobic digestion was argued, which is considered to be the best alternative to the existing waste management paradigm. The results of the study show that aerobic and anaerobic ways of using landfills and landfills for energy production are more technologically accessible and cost-effective than thermal utilisation of pre-treated (RDF, SRF) SWS. There is a need to optimise the regulatory framework for biogas production in specialised SWS storage facilities in the national legislative field. The production and practical use of RDF and SRF can partially offset the shortage of fossil fuels in Ukraine. In addition, innovative technological capabilities will satisfy the accepted integrated requirements for sustainable waste management.

Bioorganic components of SWS are positioned as a valuable renewable energy resource, the rational management of which contributes to strengthening energy independence and solving global climate problems. The functional paradigm of SWS management in Ukraine requires a gradual transition towards the introduction of economically and environmentally efficient waste management methods, among which the priority is given to the technology of anaerobic digestion of SWS components. The study established the need to understand the risk of redistributing the functionality of processing bioorganic components of SWS in favour of thermal treatment processes of waste as RDF and SRF, which will slow down the integration of anaerobic biogas production.

The direction of promising research in this area is the establishment of special criteria in the national legal field for the positioning of waste decomposed in the anaerobic environment as such that has undergone the recycling process, which will create preconditions for the integration of innovative opportunities to regulate household waste management. In the process, it is advisable to use the results of practical testing of the successful experience of other countries, involving a range of innovative approaches and methods of waste management based on regeneration and sustainable development.

ACKNOWLEDGEMENTS

None.

CONFLICT OF INTEREST

None.

REFERENCES

[1] Abdibattayeva, M., Bissenov, K., Zhubandykova, Z., Orynbassar, R., Tastanova, L., & Almatova, B. (2021). Purification of oil-containing waste using solar energy. *Environmental and Climate Technologies*, 25(1), 161-175. doi: 10.2478/rtuect-2021-0011.

[2] Aliaghaei, F., Pazoki, M., Farsad, F., & Tajfar, I. (2020). Evaluating of refuse derived fuel (RDF) production from municipal solid waste (case study: Qazvin Province). *Environmental Energy and Economic Research*, 4(2), 97-109. doi: 10.22097/EEER.2020.187286.1088.

[3] Arias, D.E., Veluchamy, C., Habash, M.B., & Gilroyed, B.H. (2021). Biogas production, waste stabilization efficiency, and hygienization potential of a mesophilic anaerobic plug flow reactor processing swine manure and corn stover. *Journal of Environmental Management*, 284, article number 112027. doi: 10.1016/j.jenvman.2021.112027.

[4] Atelge, M.R., Krisa, D., Kumar, G., Eskicioglu, C., Nguyen, D.D., Chang, S.W., Atabani, A.E., Al-Muhtaseb, A.H., & Unalan, S. (2020). Biogas production from organic waste: Recent progress and perspectives. *Waste and Biomass Valorization*, 11, 1019-1040. doi: 10.1007/s12649-018-00546-0.

[5] Calbry-Muzyka, A., Madi, H., Rüsch-Pfund, F., Gandiglio, M., & Biollaz, S. (2022). Biogas composition from agricultural sources and organic fraction of municipal solid waste. *Renewable Energy*, 181, 1000-1007. doi: 10.1016/j.renene.2021.09.100.

[6] Chae, J.S., Kim, S.W., & In Ohm, T. (2020). Combustion characteristics of solid refuse fuels from different waste sources. *Journal of Renewable Materials*, 8(7), 789-799. doi: 10.32604/jrm.2020.010023.

[7] Chew, K.R., Leong, H.Y., Khoo, K.S., Vo, D.V.N., Anjum, H., Chang, C.K., & Show, P.L. (2021). Effects of anaerobic digestion of food waste on biogas production and environmental impacts: A review. *Environmental Chemistry Letters*, 19(4), 2921-2939. doi: 10.1007/s10311-021-01220-z.

[8] Chupa, V., & Adamenko, Ya. (2023). Study of ash level and content of chemical elements in ash of different types of household solid waste and solid fuel pellets. *Ecological Safety and Balanced Use of Resources*, 14(1), 92-98. doi: 10.31471/2415-3184-2023-1(27)-92-98.

[9] Danylyshyn, V., & Koval, M. (2023). Analysis of biogas production and prospects for the development of biogas technologies in Ukraine. *Ukrainian Black Sea Region Agrarian Science*, 27(3), 90-102. doi: 10.56407/bs.agrarian/3.2023.90.

[10] Davydov, V., & Chebanenko, M. (2023). The main problems in the utilisation of municipal solid waste. In *Proceedings of the III International Scientific and Practical Conference "Theoretical and Practical Aspects of Modern Scientific Research"* (pp. 104-109). Seoul: ΛΌΓΟΣ. doi: 10.36074/logos-24.11.2023.31.

[11] Gerassimidou, S., Velis, C.A., Williams, P.T., & Komilis, D. (2020). Characterisation and composition identification of waste-derived fuels obtained from municipal solid waste using thermogravimetry: A review. *Waste Management & Research*, 38(9), 942-965. doi: 10.1177/0734242X20941085.

[12] Ghosh, P., Shah, G., Sahota, S., Singh, L., & Vijay, V.K. (2020). Biogas production from waste: Technical overview, progress, and challenges. In *Bioreactors* (pp. 89-104). London: Elsevier. doi: 10.1016/B978-0-12-821264-6.00007-3.

[13] Govarthanan, M., Manikandan, S., Subbaiya, R., Krishnan, R.Y., Srinivasan, S., Karmegam, N., & Kim, W. (2022). Emerging trends and nanotechnology advances for sustainable biogas production from lignocellulosic waste biomass: A critical review. *Fuel*, 312, article number 122928. doi: 10.1016/j.fuel.2021.122928.

[14] Haar, Q. (2023). *Refuse Derived Fuels (RDF) and Solid Recovered Fuels (SRF) A case study of characteristics and opportunit*ies. Retrieved from https://hdl.handle.net/11250/3092828.

[15] Haponych, L., Topal, O., Golenko, I., & Kobzar, S. (2022). Estimation of potential of RDF production based on found technological and morfological properties of munisipal solid wastes of Ukraine. *Scientific Papers of the National University of Food Technologies*, 28(3), 44-59.

[16] Holik, Yu., Krot, O., & Serha, T. (2023). Household solid waste as a reserve energy potential of the city. In *Ecology. Environment. Energy Saving* (pp. 37-47). Poltava: National University "Yuri Kondratyuk Poltava Polytechnic".

[17] Kobzar, S., Topal, O., Haponych, L., & Golenko, I. (2021). Investigation of the co-firing of natural gas and RDF in a model combustion chamber. *Bulletin of Igor Sikorsky Kyiv Polytechnic Institute. Series "Chemical Engineering, Ecology and Resource Saving"*, 20(4), 67-73. doi: 10.20535/2617-9741.4.2021.248946.

[18] Kolienko, A., Shelimanova, O., & Biletskyi, D. (2023). Factors of using waste as fuel in thermal energy systems of. *Energy and Automation*, 6, 98-107. doi: 10.31548/energiya6(70).2023.098.

[19] Marchenko, V.M., Kavtysh, O.P., & Makalyuk, I.V. (2022). Energy potential of waste in the EU and Ukraine. In *Materials of the XVIII International Scientific and Practical Conference "Modern Problems of Management"* (pp. 54-56). Kyiv: Igor Sikorsky Kyiv Polytechnic Institute.

[20] Maroušek, J., Strunecký, O., Kolář, L., Vochozka, M., Kopecký, M., Marouškova, A., & Cera, E. (2020). Advances in nutrient management make it possible to accelerate biogas production and thus improve the economy of food waste processing. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*. doi: 10.1080/15567036.2020.1776796.

[21] Nwokolo, N., Mukumba, P., Obileke, K., & Enebe, M. (2020). Waste to energy: A focus on the impact of substrate type in biogas production. *Processes*, 8(10), article number 1224. doi: 10.3390/pr8101224.

[22] Order of the Cabinet of Ministers of Ukraine No. 1363-r "On Approval of the Strategy of Environmental Safety and Adaptation to Climate Change for the Period up to 2030". (2021). Retrieved from https://zakon.rada.gov.ua/laws/show/1363-2021-%D1%80#Text.

[23] Pak, Y.N., & Pak, D.Y. (2017). Solid fuel quality control by the pulsed neutron-gamma method. *Solid Fuel Chemistry*, 51(3), 183-187. doi: 10.3103/S0361521917030089.

[24] Piskun, V., Zolotarov, A., Ponomarova, M., Zolotarova, S., & Yevsiiukov, O. (2024). Utilisation of livestock by-products for resource-saving biogas production in industrial pork production. *Scientific Horizons*, 27(1), 117-126. doi: 10.48077/scihor1.2024.117.

[25] Rausch, P., & Suchanek, M. (2021). Socioeconomic factors influencing the prosumer's investment decision on solar power. *Energies*, 14(21), article number 7154. doi: 10.3390/en14217154.

[26] Romaniuk, O.O., & Yarovenko, V.S. (2020). Thermochemical methods of energy production from waste. In *Proceedings of the III International Scientific and Practical Conference "Energy Saving and Industrial Safety: Challenges and Prospects"* (pp. 316-322). Kyiv: Osnova.

[27] Sobczak, A., Chomać-Pierzecka, E., Kokiel, A., Różycka, M., Stasiak, J., & Soboń, D. (2022). Economic conditions of using biodegradable waste for biogas production, using the example of Poland and Germany. *Energies*, 15(14), article number 5239. doi: 10.3390/en15145239.
[28] State Statistics Service of Ukraine. (2024). *Economic statistics/Environment*. Retrieved from https://ukrstat.gov.ua/operativ/menu/menu_u/ns.htm.
[29] Trehub, O.A. (2022). Development of bioenergy potential of household waste in the conditions of post-war recovery: Economic and legal dimension. *Economics and Law*, 3(66), 47-59. doi: 10.15407/econlaw.2022.03.047.
[30] Zupančič, M., Možic, V., Može, M., Cimerman, F., & Golobič, I. (2022). Current status and review of waste-to-biogas conversion for selected European countries and worldwide. *Sustainability*, 14(3), article number 1823. doi: 10.3390/su14031823.

Людмила Миколаївна Михайлова
Кандидат технічних наук, професор
Заклад вищої освіти «Подільський державний університет»
32316, вул. Шевченка, 12, м. Кам'янець-Подільський, Україна
https://orcid.org/0000-0002-3419-5446

Віктор Миколайович Дубік
Кандидат технічних наук, доцент
Заклад вищої освіти «Подільський державний університет»
32316, вул. Шевченка, 12, м. Кам'янець-Подільський, Україна
https://orcid.org/0000-0002-9743-1565

Олександр Васильович Думанський
Кандидат технічних наук, доцент
Заклад вищої освіти «Подільський державний університет»
32316, вул. Шевченка, 12, м. Кам'янець-Подільський, Україна
https://orcid.org/0000-0002-1750-5844

Олександр Володимирович Козак
Кандидат технічних наук, доцент
Заклад вищої освіти «Подільський державний університет»
32316, вул. Шевченка, 12, м. Кам'янець-Подільський, Україна
https://orcid.org/0000-0002-0919-0344

Можливості використання звалищ та полігонів твердих побутових відходів для виробництва енергії в Україні

Анотація. Динамічні зміни у енергетиці в напрямку пріоритетності відновлюваної енергетики інтенсифікується спрямованістю політичних рішень у євроінтегрованому середовищі на досягнення кліматичної нейтральності у межах реалізації Європейського зеленого курсу. Мета статті полягає у поглибленому дослідженні потенціалу звалищ та полігонів твердих побутових відходів для виробництва енергії в Україні. Реалізація дослідження проводилась із залученням загальних наукових методів, зокрема, аналізу та синтезу, абстрагування, порівняння. Вивчено проблематику освоєння біоенергетичного потенціалу твердих побутових відходів в Україні, у тому числі, організаційний, нормативно-правовий, технологічний та фінансово-інвестиційний аспекти. Проведена ідентифікація позиції різнопланових операцій щодо біоенергетичної переробки відходів у системі поводження з твердими побутовими відходами, зокрема, анаеробного знезараження та виробництва твердого палива, реалізована аналітика низки технологій термічної переробки відходів. Серед особливостей та характерних вимог щодо процесу виробництва біогазу з застосуванням анаеробної методики виділені аспекти технологічної доступності та економічної доцільності. У дослідженні розглядається досвід виробництва і використання органічного палива з відходів (RDF) та твердого відновлюваного палива (SRF), що виробляються з твердих побутових відходів, доведена необхідність оптимізації нормативного забезпечення виробництва біогазу у місцях складування твердих побутових відходів у національному законодавчому полі. Акцентовано спроможність практичного використання органічного палива з відходів (RDF) та твердого відновлюваного палива (SRF), у частковому форматі, нівелювати дефіцит викопних видів палива в Україні та активно втілювати концепцію сталого зеленого курсу щодо раціонального поводження з відходами. Отримані результати можуть бути застосовані при вдосконаленні оптимізаційних стратегічних програм управління твердими побутовими відходами у аспектах їх біоенергетичного потенціалу

Ключові слова: відновлювані паливні ресурси; теплота згоряння; біогаз; морфологічний склад; біомаса; стійкий розвиток