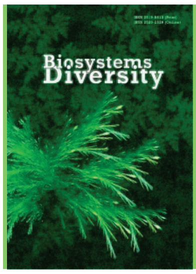

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Recycling and decontamination of organic waste in Ukraine: Current state, technologies and prospects for the biogas industry

O. O. Boyko*, H. V. Hapich*, R. V. Mylostyvyi*, O. O. Izhboldina*,
Y. Chernysh**, ***, V. Chubur**, H. Roubík**, V. V. Brygadyrenko****

*Dnipro State Agrarian and Economic University, Dnipro, Ukraine
**Czech University of Life Sciences Prague, Prague, Czech Republic
***Sumy State University, Sumy, Ukraine
****Oles Honchar Dnipro National University, Dnipro, Ukraine

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Dnipro State Agrarian and Economic University, Serhii Yefremov st., 25, Dnipro, 49000, Ukraine. Tel.: +38-099-405-51-98. E-mail: boikoalexandra1982@gmail.com

Department of Sustainable Technologies, Faculty of Tropical AgriSciences, Czech University of Life Sciences Prague, 16500 Prague, Czech Republic. E-mail: roubik@ftz.czu.cz

Sumy State University, Kharkivska st., 116, Sumy, 40000, Ukraine. E-mail: a.chernysh@ftz.czu.cz

Oles Honchar Dnipro National University, Haharin av., 72, Dnipro, 49010, Ukraine. Tel.: +38-050-93-90-788. E-mail: brigad@ua.fm

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Global and regional competition for natural resources, particularly for land and water, food and fodder, takes place in the context of a dire necessity to limit greenhouse gas emissions and is becoming more and more pressing every year. Environmental soundness, sustainability and security are becoming more relevant and are considered as key elements of modern agricultural enterprises' operation. The concept of the coming years in animal husbandry is non-waste production, which consists in the complete recycling of waste, and if it is impossible – in their safe disposal. If the waste cannot be reused or upcycled, such waste should be transformed into energy. The production of biogas and biomethane contributes to solving two global problems: the growing amount of organic waste produced by modern economies and the negative impact of CO_2 emissions on climate change and the environment. We considered the social and economic prerequisites developed in the main sectors of contemporary Ukrainian livestock breeding in terms of potential sources of raw materials for biogas production. The main focus of the study is on the elements of greening of national agriculture, production and on the prospects for the development of the biogas industry in Ukraine. Favourable conditions for the development of biogas technologies have been identified among large producers of livestock products (dairy cattle breeding, swine breeding and poultry farming). In other sectors, opportunities are still limited due to economic, social and legislative difficulties. The paper also analyses the prospects for the use of various means of combating pathogens for the processing and disposal of organic waste. The main role of anaerobic digestion as an alternative method for the inactivation of dangerous pathogens responsible for infectious and parasitic diseases of animals and humans has been determined.

Keywords: biogas; organic waste processing; animal husbandry; pathogen inactivation.

Introduction

In recent decades, there has been a rapid development of intensive livestock farming concentrated around large urban agglomerations, posing a great social and environmental threat. Many of these farms are located near lakes, rivers, or the sea. The high concentration of animals and animal waste near densely populated areas and far from crop production (where there is a need for animal breeding by-products – manure as organic fertilizers) resulted in significant environmental problems. The scope of antibiotics application in agriculture is rapidly increasing and exceeds the use in medicine, which raises concerns about the possible impact of antimicrobial agents used in agriculture on human and animal health (Kasimanickam et al., 2021). However, the agriculture of the future will be based on the rejection of their application. Since Ukraine has everything necessary for the cultivation of organic products, unlike other countries, it will be advisable to add this competitive advantage to the national strategy for agricultural development. Programs to expand biodiversity through the breeding of rare unconventional animals will provide biologically adequate food products, animal feed, the demand for which is unlimited today, and the development of "green tourism" could additionally serve as a source of income (Zamlynskyi, 2019).

At a time when the whole world is trying to increase the share of organic agriculture, we are intentionally losing the valuable knowledge and practices related to crop rotation and use of organic fertilizers, which are crucial for preserving and rational use of soil cover and agroecosystems. Chemigation allows us to obtain a short-term economic effect, but has no prospects in the future, because the world is gradually abandoning such measures in favour of environmentally friendly and resource-saving projects (Zamlynskyi, 2019).

The livestock farming leads to emissions of 44% of anthropogenic methane (mainly as a result of intestinal fermentation of ruminants), 53% of anthropogenic nitrogen oxide (mainly from manure) and 5% of anthropogenic carbon dioxide. This contributes to global warming and provokes eutrophication of water bodies. Annually, billions of cubic meters of water vapour, carbon dioxide, ammonia, hundreds of thousands of cubic meters of hydrogen sulphide, tens of thousands of tons of dust and pathogenic microflora are released from livestock farms (Mykhalko, 2021).

Improper management and disposal of livestock waste poses a serious threat to the environment. Waste serves as a medium for the accumulation of pathogens that can spread and contaminate soils and the aquatic environment. Unprotected manure contributes to global warming by releasing large amounts of biomethane. Livestock manure can be valuable raw materials for biogas production, preventing the uncontrolled decomposition of such animal waste products, and, at the same time, can be a source for renewable energy production (Mignogna et al., 2023). Emissions of ammonia and nitrous oxide, as well as phosphates, heavy metals and pathogens found in livestock wastewater, can contribute to ecosystem dysfunction, resulting in adverse health effects for animals and agricultural workers (Mironiuk et al., 2023). Large agricultural enterprises in Ukraine are traditionally the main producers of manure and industrial wastewater (Mykhalko, 2021). Controlled anaerobic digestion is one of the most appropriate technologies for manure processing. Digested manure, rich in nutrients, becomes an effective material for the production of environmentally friendly energy sources reducing the use of conventional fossil fuels and emissions of harmful gases (Khan et al., 2021).

Taking into account the above and the prospects for the development of biogas technologies, the publication activity was analysed (Fig. 1) in terms of the selected research topic (according to the Scopus database). Thus, since the beginning of the 21st century, after a series of global economic crises, upon declaring and signing the international agreements to reduce greenhouse gas emissions and promote decarbonization, there has been a surge and an ongoing trend towards the development of alternative energy sources obtained from non-fossil mineral resources.

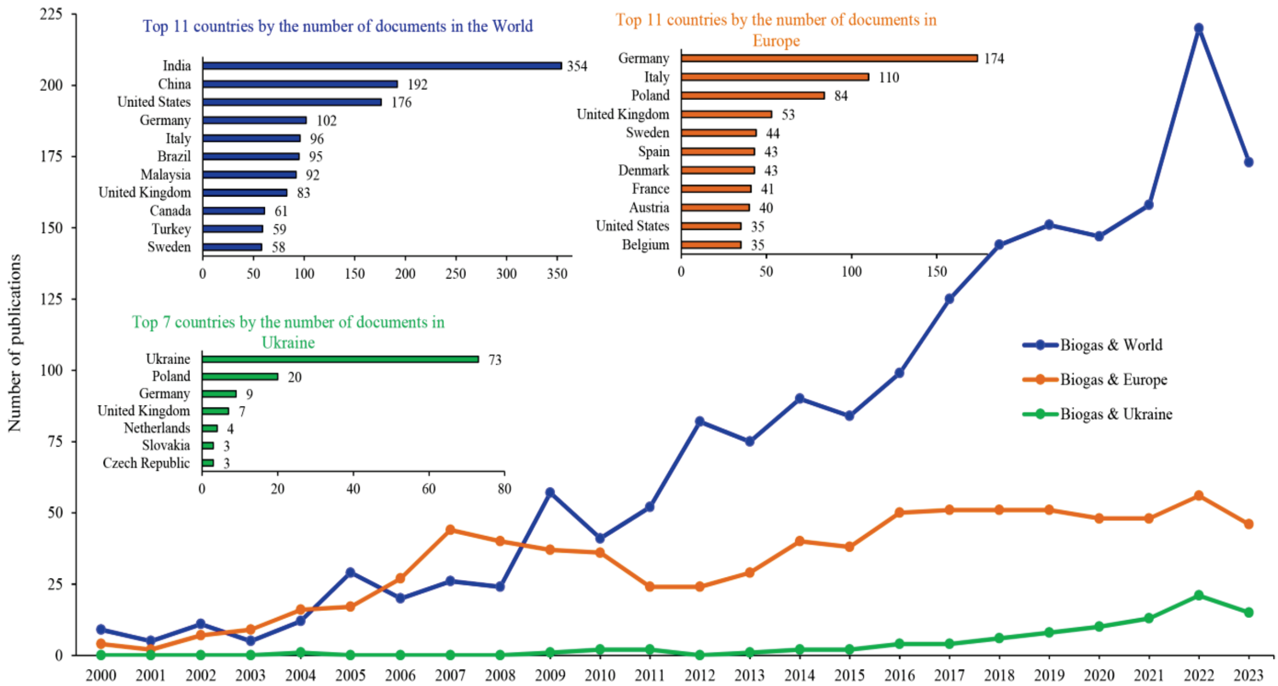

Fig. 1. Dynamics of publication activity related to research topics (according to Scopus data)

Search results for queries based on the keywords "Biogas & World", "Biogas & Europe" and "Biogas & Ukraine" indicate the following. It can be stated that the vast majority of publications in the world and in Europe are written by the authors from the countries that are significantly developed in terms of technologies and are directly involved in the development and supply of modern biogas plants to the global market (Germany, USA, Great Britain, Italy, etc.). Another example is the intensification of bioenergy research in rapidly developing countries (China, India, Malaysia, etc.). The reason for this is several factors: a significant amount of accumulated organic waste, limited natural fuel resources, underdeveloped energy infrastructure and the growing energy needs of the population and various sectors of the economy – such countries are forced to seek alternative options in bioenergy industry. Unfortunately, Ukraine today has a rather "modest" contribution of scientific publications despite having one of the greatest potentials in the world for the development of bioenergy through the livestock and crop industries. Therefore, the objective of this paper is to analyse the actual state, technologies for processing and disinfection of organic waste, as well as the prospects for the biogas industry in Ukraine.

Social and economic prerequisites for the introduction of biogas technologies in livestock breeding

In recent years, there has been a trend towards the development of highly profitable large agro-industrial associations with a closed-loop production cycle (from creating feed bases to processing meat and milk). They are gradually taking over and merging with their direct competitors in small and medium-sized businesses, entire villages are becoming deserted, the workforce is aging rapidly and young people are migrating from rural areas to large cities. Since the beginning of the twentieth century, about 75% of plant genetic diversity has been lost due to farmers worldwide abandoning a range of local crop varieties and breeds in favour of genetically uniform, high-yielding varieties (Zamlynskyi, 2019). Modern genetically modified animals cannot independently survive and reproduce in the wild. By constant selection, the variety of animals is constantly reduced, and only the farm animals that show the greatest increase in live weight in the shortest possible time are retained.

In Ukraine, an imbalance in favour of powerful agricultural producers of livestock products (cattle, swine and poultry breeding) persists. These producers are considered in this paper as the main potential producers of organic raw materials for biogas. Every year, the share of milk produced by households decreases, although it remains quite high (69%). At the same time, the volume of milk produced by agricultural enterprises does not change significantly. According to analysts, the proportion of milk sourced from the households will continue to decrease, due to raising of standards for the quality and safety of milk sent for industrial processing (Milostiviy et al., 2017).

In the total consumption of meat products in Ukraine, pork ranks second (after the consumption of poultry meat) making up approximately 32%. The primary focus of swine breeding intensification involves moving towards industrial practices, driven by innovations and investment. The essence of such a restructuring should lie in the re-equipment of pig farming complexes to an industrial standard, focusing on qualitative changes in the technology and organization of production lines, in the specialization and concentration of swine breeding, which will contribute to improving the quality of pork produced in Ukraine (Mykhalko, 2021). At the same time, the problem of reducing the environmental impact of pork production, compliance with high animal welfare standards and the ability to ensure the profitability of the sector is becoming more acute. There is no doubt that consumer interest in animal welfare around the world will grow (Mylostyvyi, 2023).

Over the past decade, the rate of decline in the number of cattle and pigs in households has increased significantly (by 11% and 45%, respectively) compared to agricultural enterprises (http://sdplatform.org.ua/blogs/farm). However, among the economic factors restraining the development of swine breeding, the increase in the cost of energy carriers and the rise of cheap pork imports and reduction in its exports will also remain. An equally important reason for the stagnation of the industry was African swine fever, which forced commodity producers, especially medium-sized and small enterprises, to reduce their livestock either as a result of the detection of pathogens, or to slaughter early in order to prevent asset loss (Mykhalko, 2021).

According to FAO, in 2019, Ukraine ranked 9th among the countries of the world in terms of exports of shell eggs (3.7% of the global figure) and 11th for the volume of chicken meat exports (2.0% of the global volume). This is primarily due to the high concentration of poultry production, since more than 80% of poultry is kept on farms where its number exceeds 500 thousand birds. The high level of poultry concentration provides producers with a number of advantages due to the effect of scale of production. At the same time, it also has significant negative consequences. First of all, we are talking about environmental problems associated with pollution of the environment with waste related to poultry farming and slaughter products, and small businesses can succeed only by offering consumers products of less common types of poultry (turkeys, geese, ducks, quails, etc.). Organic poultry farming is a potentially attractive niche for small businesses (Yatsiv, 2021).

The potential of other livestock breeding sectors as a stable supply of raw materials for biogas production is quite low. In particular, sheep breeding, which can be considered as an important source of meat production (the share of lamb in the meat balance of the country is about 6.5%, and in some regions of the country it reaches 30%, where it is a necessary product for national dishes), is also characterized as being in a state of steady decline. The decrease in the production of mutton and goat meat is due to a decrease in the number of sheep, as well as a decrease in the production of sheep milk in recent years, in particular due to the higher competitiveness of dairy cattle farming compared to dairy sheep breeding (Susharnyk, 2021). Regarding goat breeding, its development is significantly slowed down due to the lack of documentary separation of this industry from sheep breeding and its recognition as a separate branch of livestock breeding. However, it is quite promising, as evidenced by an increase in the number of goats in agricultural businesses and a rise in consumer demand for goat milk, cheeses and other products. For example, the share of goat milk in the gross milk production of all types of farm animals has increased by 0.37% in recent years. However, to effectively manage the industry and increase the milk productivity of goats, it is necessary to create high-yield breeding herds and replenish the breeding base with valuable imported livestock of promising breeds (Fedorovych et al., 2022).

The current state of rabbit meat production does not meet the minimum needs of the population of Ukraine: while the consumption rate for rabbit meat is 2 kg per capita, the actual average consumption is only 284 grams. The majority of rabbits (97.1%) is on private farms and only about three percent is on agricultural enterprises (Gonchar et al., 2020), which makes it impossible to consider this industry as a reserve for biogas production.

Despite the fact that the total potential of biomethane production in Ukraine is estimated at no less than 7.8 billion m^3 (25% of the current natural gas consumption), biomethane production is not competitive in terms of the market price of natural gas and requires support. The payback period of most biogas projects in Ukraine, at best, is estimated at 5–6 years, and taking into account the efficiency – at least 7–8 years. At the same time, the main components of investment in biogas projects are the costs of the power generation unit (30–40%), the construction of reactors and other technological structures (35–45%), as well as technological equipment (15–25%). That is, only large enterprises can afford such technologies. In addition, a limiting factor for the development of biogas technologies is the fact that Ukraine still does not have legally adopted standards for the construction and operation of individual biogas plants. In addition to an obvious environmental and economic effect achieved by the households through the use of individual biogas plants, it is necessary to take into account the social effect involving the improvement in health and well-being of the population (Pryshliak, 2021).

Biogas plants process the waste from the rural population, thereby improving the hygienic situation for individual users and society as a whole. It is also worth mentioning the improvement of the quality of food products grown using biofertilizers without the use of chemicals (Pryshliak, 2021). Potentially, thermal energy from cogeneration unit (up to 60% of the generated thermal energy) and digestate (fermented mass) as a fertilizer or soil improver can also be the sources of additional income from the operation of a biogas plant. However, the crisis in the national economy, the complex geopolitical situation, internal political tension, and military actions have significant negative consequences for the investment climate in Ukraine, dramatically reducing the ability of agricultural enterprises to attract investment resources for active development, whether from internal or external sources (Ishchenko et al., 2021).

Under wartime conditions, when electricity is cut off, roads are closed, and supplies of feed are unattainable, it is almost impossible to organize the process and save the herd. Farmers are unable to carry out the standard feeding routines and provide the usual care for the animals. There is nowhere to deliver the products, since the chains of supply of raw materials for processing to enterprises are destroyed (Yatsiv, 2021). In addition, Ukraine was importing some feed types and veterinary drugs. Due to the war and logistical problems, it is currently impossible to carry out some of these purchases. Disruption of logistics chains has also affected Ukrainian producers of meat, dairy products and eggs, which were focused solely on the domestic market, because supply to the regions where hostilities are taking place is limited, or entirely impossible (https://agronews.ua/news/tvarynnycztvo-pid-chas-vijny-hto-postrazhdav-najbilshe).

Despite the difficult situation, further development of the national agrarian sector should be considered in the context of the global strategy of efficient and sustainable agro-industrial production, where the first priority is not the profit of the owners, but ensuring the global food and environmental safety, protection of the rural population, the nutritional value and unconditional safety of food products, the resource-saving model of business engaged in the production and processing of agricultural products, and the preservation and improvement of the existing ecosystem, including through the rational utilization of livestock waste using biogas technologies.

Production and prospects of the biogas industry in Ukraine

Hostilities with constant shelling and destruction of hydropower facilities and energy infrastructure that operates on traditional (fossil) resources have caused an acute energy shortage. In this regard, food (Hapich & Onopriienko, 2024), water (Hapich et al., 2024) and energy security (Shahini et al., 2024) will be one of the key areas of development of the Ukrainian economy in the conditions of post-war recovery. This situation encourages wider adoption and actualizes the need for the development of alternative energy sources, primarily the biogas industry (Dudin et al., 2024). Particular attention to this problem was required due to the energy dependence of Ukraine and European states on Russian natural gas and other mineral resources.

In the pre-war period, Ukraine had significant energy generating capacties (nuclear power plants, thermal power plants, hydropower plants) and a developed energy infrastructure, which, first of all, ensured the functioning of industries and household consumption. As the economic and industrial potential has been lost, renewable energy sources are a promising area of energy sector development in Ukraine, which will meet the local needs of individual households or businesses (Pryshliak et al., 2024). The constant increase in energy prices and the need to develop environmental protection technologies stimulates energy generation through the use of different types of organic waste as biofuels (Chubur et al., 2022).

Biogas production is one of the solutions to the problem of the increasing accumulation of organic waste of agricultural enterprises. Also, this partially addresses the urgent need to reduce global greenhouse gas emissions in line with Ukraine's implementation of the Paris Climate Agreement. Following global trends and turning organic waste into a renewable energy resource, biogas production in Ukraine provides promising opportunities for the chain as follows: continuous use of resources → meeting the growing demand for power supply services → ensuring environmental benefits (safety).

As for Ukraine, according to the data provided (UABIO Analytics, https://uabio.org/en/materials/uabio-analytics), as of 2023, 68 biogas plants with a total capacity of 135 MW operate in Ukraine. The production of biogas is mainly provided by five types of raw materials (Fig. 2).

At the same time, the waste from the livestock sector in the general structure is about 22%. In general, the total potential of biomethane production (enriched biogas) in Ukraine (Fig. 3) through the use of livestock waste is estimated to be about 1 billion m^3 of CH_4 (Geletukha et al., 2022). Given the structure of operation, more than a half of biomethane can be produced by poultry breeding and almost a third – by swine breeding. Other species (cattle breeding, goat breeding, sheep breeding) make up about 20% of the total structure.

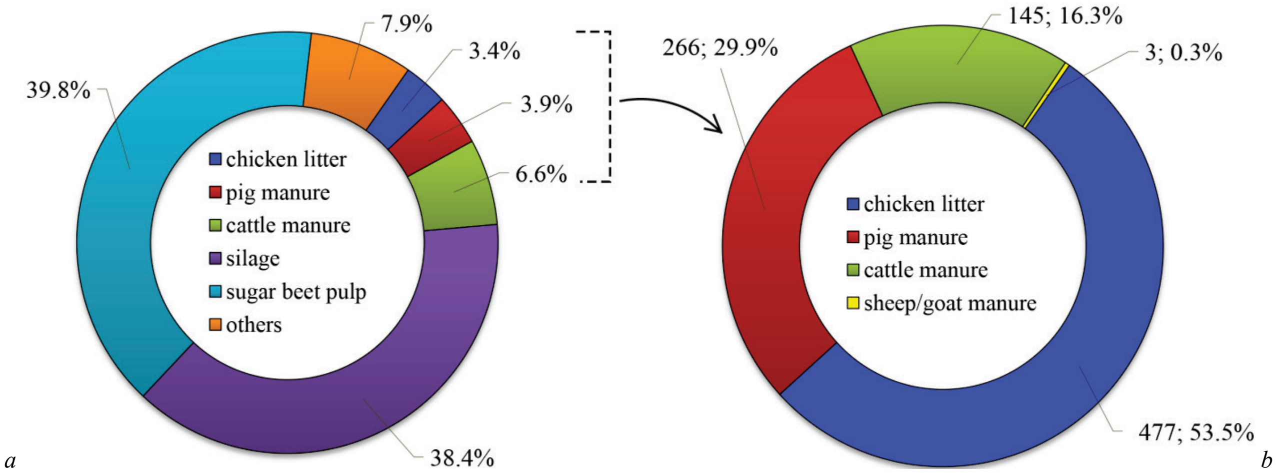

Fig. 2. Structure of raw materials (*a*) used for biogas production in Ukraine and potential biomethane production (*b*) from livestock waste (million m^3 CH_4; %) (Dudin et al., 2024)

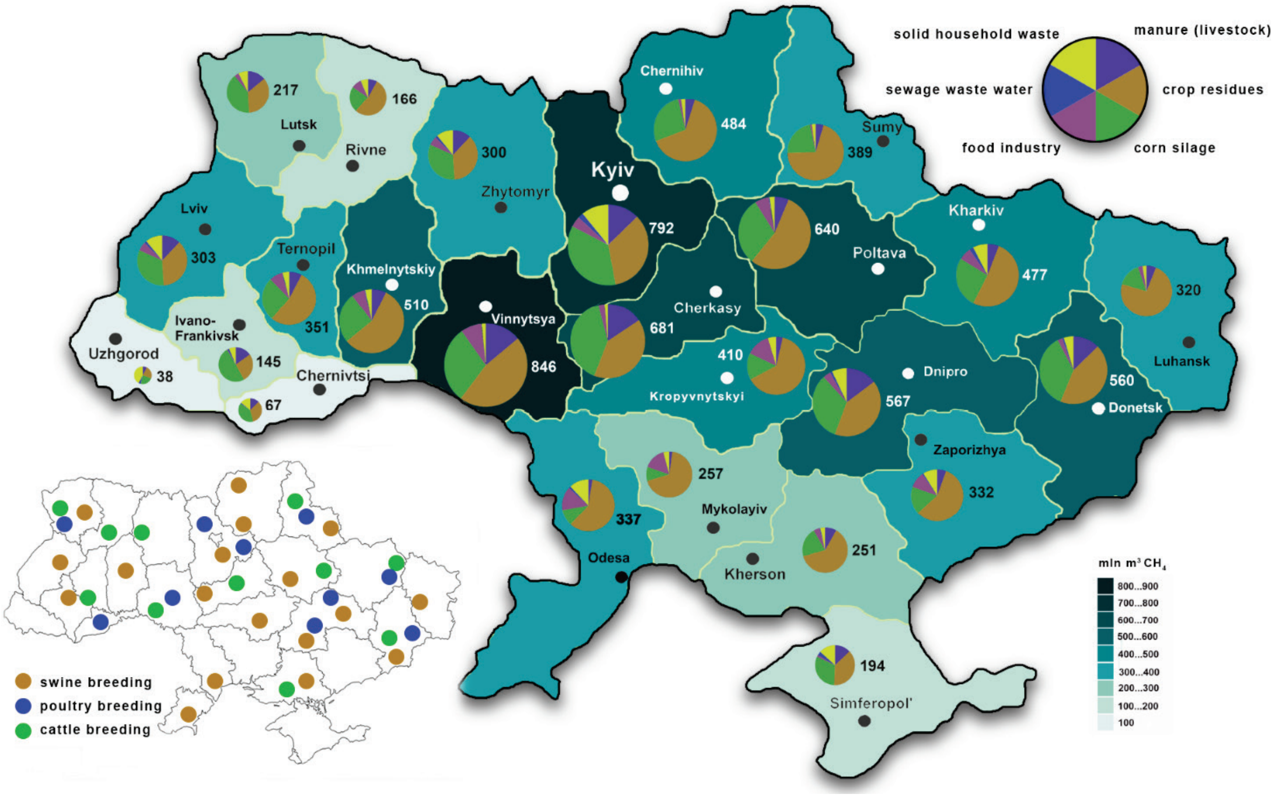

Fig. 3. Regional distribution of biomethane production potential (according to Geletukha et al. (2022))

The peculiarity of the livestock industry in Ukraine is that about 75% of cattle and 52% of pigs are concentrated in the private sector, where the average size of microfarms is up to 20 cows and up to 200 pigs. This highlights the prospects and relevance of developing small biogas plants to meet the own needs of households or small communities (settlements).

Currently, for the conditions of Ukraine, there are several insufficiently resolved and regulated issues related to tariffs and greening of biogas production process. With regard to environmental protection, for example, the EU has a significant number of directives and regulations of the European Parliament (Document 32008L0098: Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives; Document 32009R1069: Regulation (EC) No1069/2009 of the European Parliament and of the Council of 21 October 2009 laying down health rules as regards animal by-products and derived products not intended for human consumption and repealing Regulation (EC) No1774/2002 (Animal by-products regulation); Document 32011R0142: Commission Regulation (EU) No142/2011 of 25 February 2011 implementing Regulation (EC) No1069/2009 of the European Parliament and of the Council laying down health rules as regards animal by-products and derived products not intended for human consumption and implementing Council Directive 97/78/EC as regards certain samples and items exempt from veterinary checks at the border under that Directive Text with EEA relevance) along with national regulations. They are aimed at reducing greenhouse gas emissions and preventing the negative impact of livestock waste on environmental components. The main requirements related to technological operations with manure are to ensure (1) the safety of key components of the environment (water, air, soil) (2) total decontamination, (3) conversion of chemical elements present in manure into a form suitable for absorption by plants. In order to achieve these requirements, the processing of manure by methane digestion is the most fully compliant.

The economic component of the efficiency of modern and promising biogas plants operating in Ukraine depends on the size of investments, operating costs, the amount of biogas and electricity that can be obtained with it. The main income from the operation of the biogas plant is formed through the sale of electricity at the "green" tariff, thermal energy and liquid organic fertilizers. According to studies by Dudin et al. (2024), the average investment cost of a biogas plant with an electrical capacity of up to 75 kW is 9,000€/kW, in contrast to large plants with a capacity of 1,000 kW and implementation costs of 3,750 €/kW. In Ukraine, the estimated payback period of projects in small households is about 10–12 years. At the same time, the general structure of the revenue is as follows: (1) the cost of electric power sold is ~50%, (2) thermal energy is ~20%, (3) liquid organic fertilizers are ~30%.

The sale of organic fertilizers is a generally accepted European practice, which is contradictory in the conditions in Ukraine, since there is practically no legal regulation on the livestock waste. If consistency with EU regulations is ensured, the cost of electric power supply might be increased in accordance with the so-called "green" tariff. Improving the legal framework and state regulation of bioenergy tariffs can reduce the payback period of the plants to 5–7 years, which makes them attractive for further implementation. An additional incentive may be the grant projects for financing or supply of individual structural elements of equipment for the biogas production technological processes.

Methane fermentation – an alternative way to control pathogens

Manure is a potentially dangerous source of environmental pollution, as it contains heavy metals, weed seeds, helminth eggs and pathogenic microflora. Through emission, greenhouse gases – nitrous oxide and methane – are released into the air. Manure is the most dangerous factor in the transmission of infectious agents, particularly of invasive diseases. In solid manure, pathogens of tuberculosis, brucellosis, listeriosis, paratyphoid, erysipelas can remain viable for a period ranging from 70 to 260 days, and dermatomycosis pathogens – for more than eight months. In this organic environment, the eggs and larvae of helminths remain viable for up to 12 months or more. Thus, non-disinfected manure poses a great threat of contamination of bodies of water, soil, groundwater, feed and pastures with pathogens dangerous to humans and animals (Korchan et al., 2019; Borodai et al., 2020).

Given the epizootic, sanitary and epidemiological and environmental risks that manure and manure effluents might cause, the high value of manure in terms of enhancing soil fertility cannot be overlooked. Therefore, the development of new and improvement of existing decontamination technologies, including disinfection, remains a crucial environmental and veterinary task. The method of disinfection shall be chosen considering the severity of the current epizootic situation, the type of pathogen, the availability and type of chemical reagents and technical facilities (Dovhii et al., 2013; Kryvokhyzha et al., 2022).

Today, there are numerous methods for disinfecting organic waste in order to eliminate faecal pathogens. Some of the most common include anaerobic digestion, chemical disinfection, biological additives, solar pasteurization and vermicomposting (Saxena & Den, 2021). To disinfect manure by chemical methods, a large number of disinfectants potentially dangerous to the environment are used, which is associated with the content of xenobiotics, in particular aldehydes, chlorine, phenols, etc. (Cliver et al., 2009; Shkromada et al., 2013). It is recommended to disinfect manure using homogenization. In homogenized manure, the particles are finely ground and pathogens are more accessible to the action of disinfectants. Disinfection of such manure requires 10–15 times less disinfectants (Dubinin et al., 2009; Kryvokhyzha et al., 2022). There is also a steam jet method, which is based on heating manure to 130 °C. Thus, even anthrax spores are neutralized, but naturally, this method is applied under special conditions (Dubinin et al., 2009).

On livestock farms, a method of manure processing by prolonged aging is used, followed by the incorporation of the resulting organic fertilizer into the soil. It involves a number of operations: transportation and loading of liquid manure, bioconversion by long-term aging (in storage), unloading of organic fertilizer and its transportation, incorporation of organic fertilizer to fields (Borodai et al., 2020). On agricultural complexes liquid manure undergoes complex processing. First of all, it is separated into solid and liquid fractions. The simplest method of manure separation is to use settling systems. The solid fraction of manure is stacked, where conditions for biothermal processes are created. After biothermal decontamination, manure is taken to the fields or used to make composts. The liquid fraction is drained into aeration tanks for biological purification through the decomposition of substances by aerobic microflora. In this case, when the sludge settles, it is then removed, dried and used as fertilizer. The clarified liquid is disinfected with chlorine. The chlorine dose depends on the degree of liquid purification and the quantity of particles in the suspension. As a rule, chlorine is administered in an amount not exceeding 15 mg/L. Such a liquid is also used to wash off manure (Dubinin et al., 2009). It is safer to use manure as a fertilizer after composting. The technological process of manure composting is carried out using passive and active methods. With passive (traditional) composting, biological disinfection of manure occurs under natural conditions in heaps. Composting is a biothermal process of mineralisation and humification of organic substances that occurs in aerobic conditions under the influence of microorganisms, mainly thermophilic ones. During composting, organic waste is heated to a temperature of 60 °C, which adversely affects the larvae and pupae of flies, helminth eggs and pathogens (Wu et al., 2017; Wang et al., 2018; Izhboldina et al., 2019; Borodai et al., 2020). The composting process is exothermic; it does not depend on the type of substrate and its volume. The temperature regime is maintained by means of forced ventilation and regulation of the substrate humidity. Machines and compost mixers and aerators are used for this purpose (Izhboldina et al., 2019; Kobets et al., 2019). The advantages of passive composting include a wide range of humidity (60–92%) of the initial manure (using moisture-absorbing materials), low qualification requirements for workers, simplicity of composting site construction, relatively modest capital investments, the absence of unpleasant odours in the compost and a decrease in the number of harmful microorganisms and fungi. The disadvantages are the uneven maturation of the compost, the dependence of the composting process on weather conditions and the increased risk of leakage (Cáceres et al., 2016; Borodai et al., 2020; Skliar et al., 2021).

One of the methods of processing and disinfecting organic waste is also the use of synanthropic fly larvae. Through the assimilation process, these organisms are able to convert organic waste into their biomass. Among scientists, the domestic fly (*Musca domestica* L.) and the black soldier fly (*Hermetia illucens* L.) are of particular interest. Together with valuable organic fertilizers, when cultivating these larvae, secondary products are obtained, in particular biodiesel, biologically active substances, as well as protein for animal feed. Using this waste treatment method, the microbial load of some pathogens is reduced (Čičková et al., 2015; Raksasat et al., 2020; Parry et al., 2021). However, scientists believe that more research is needed on fly species to ensure processing of different types of organic waste (meat processing waste or a mixture of manure waste and meat processing waste, slaughterhouse waste, etc.). Parry et al. (2021) also point to a distinct area of research on fly species associated with pathogen inactivation. Thus, Lucilia sericata is able to produce antimicrobial compounds that promote wound healing. At the same time, it responds well to laboratory conditions of cultivation.

Another method of disinfecting organic waste is vermiculture (growing earthworms), since earthworms are able to break down organic waste (Ganguly & Chakraborty, 2020). Edwards & Arancon (2022) provide a list of the most common species used in waste processing: *Eisenia fetida*, *E. andrei*, *E. eugeniae*, *Lumbricus rubellus*, *Dendrobaena veneta*, *Perionyx excavatus*, *P. hawayana* and *Lampito mauritius*. Such processing produces biohumus, as well as valuable protein that can be used as feed for livestock and fish (Edwards & Arancon, 2022; Hajam et al., 2023). During the process of vermicomposting, plant pathogens are inactivated, as well as pests and nematodes, which are plant parasites. At the same time, Edwards & Arancon (2022) are referencing the studies on the destruction of human pathogens by vermicomposting. Manikanta et al. (2023), note that the processing of organic fertilizers using worms is odourless because they have a capability to create coelomic fluids that are antibacterial. At the same time, vermicomposting products act as biological pesticides.

Mycocultivation is also one of the processes of recycling and disinfection of organic waste. Fungi destroy lignocellulosic substrates by producing lignocellulosic enzymes (Kumla et al., 2020). The processed substrate from fungi can improve the health of plants by inhibiting the plant pathogenic microorganisms in the soil and the sugar beet nematodes *Heterodera schatii* (Grimm et al., 2020).

Therefore, the analysis of previous scientific research shows that the most common biological methods of organic waste disinfection is the use of living organisms in their processing. For this purpose, anaerobic microorganisms, aerobic microorganisms, annelid worms, fungi, fly larvae, and microalgae are most often used (Fig. 4).

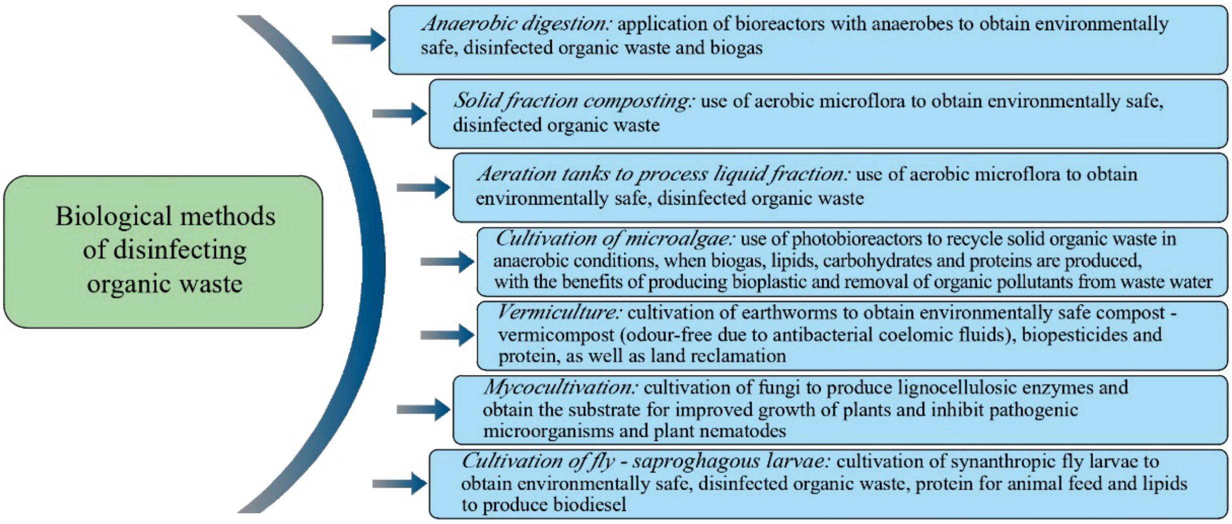

Fig. 4. The most common biological methods of organic waste disinfection

Every year, scientists around the world observe an increase in population and a simultaneous increase in the amount of waste. As the demand for renewable resources for energy production has increased worldwide, anaerobic digestion is an alternative waste treatment method, providing a simultaneous production of valuable biofuels and is considered quite promising (Samoraj et al., 2022; Vyas et al., 2022). The importance and availability of anaerobic digestion is also discussed on a micro scale. This method of waste treatment can be achieved by cheap decentralized waste management. Anaerobic digestion provides energy and valuable organic fertilizers as by-products of fermentation for the majority of the world's population and even for those who have no access to basic public sanitation, energy and fertilizers. But quite often, the digestate obtained does not meet international safety standards for use in agricultural fields. According to McCord et al. (2019), digestate may be an appropriate source of fertilizer, but if improperly managed, it can become a water quality concern. This method of waste recycling plays a significant role in creating a circular economy in the agricultural sector. At the same time, manure of farm animals is the main source of bioenergy production during such processing. More than 20,000 biogas plants around the world operate on such a substrate. On the other hand, manure can pose a great risk to the health of animals, humans, and environment due to contamination by pathogens. Therefore, anaerobic digestion and pathogen inactivation during this process is of great interest due to its safe use after processing (Lin et al., 2022b).

The importance of solid and liquid manure and the risk of their use after anaerobic digestion are also discussed by Nag et al. (2021). They may contain high concentrations of pathogens: after introducing digestate into the soil, pathogens can contaminate various environmental objects and pose a threat to human health, since their complete inactivation is unlikely. The frequent use of anaerobic digestate as agricultural fertilizer creates a sanitary risk for environmental objects. Therefore, the European Union requires that livestock waste undergo thermal pasteurization (hygienisation). The quantity of *Enterococcus faecalis* and *Escherichia coli* decreases 100,000 times in less than 1 minute during thermal pasteurization at 70 °C (Liu et al., 2021).

There are numerous previous studies that suggest a positive result for pathogen inactivation through anaerobic digestion. However there is contradictory data on the effectiveness of this process. Ma et al. (2022) showed that anaerobic digestion can reduce impact of pathogens on humans.

The possibility of contamination of digestate with spore-forming bacteria *Clostridium* spp. is evidenced by studies by Lüdecke et al. (2020). These organisms are capable of forming heat-resistant spores. The authors conducted an experiment on the effect of temperature and sanitation treatment duration on the destruction of *Clostridium* spp. spores. The spores of these pathogens survived at 70 °C for at least ten hours. And only temperatures above 121 °C and prolonged exposure at atmospheric pressure slowed the growth of *C. perfringens* and *C. sporogenes* spores (Lüdecke et al., 2020). The threat to the environment and humans of untreated digestate as a byproduct of biogas production is discussed by Chojnacka & Moustakas (2024). Therefore, safe use of the digestate for various purposes is only possible after further study of technologies and processes (Lamolinara et al., 2022).

Almansa et al. (2023) note the advantages of pathogen inactivation by the anaerobic digestion method with subsequent processing. There is also evidence of benefits of improving anaerobic digestion technologies (to inactivate pathogens) through pre-treatment of organic waste with inorganic or organic substances, as well as the use of various physical methods.

The reduction of pathogens in anaerobic digestion is also influenced by pH, ammonia concentration and biological processes (Pigoli et al., 2021). The high pH, total degradation of solids, and methane yield in the assessment of pathogen inactivation during anaerobic digestion are reported by Yang et al. (2023). According to Subirats et al. (2022), the main factors influencing the inactivation of spore-forming bacteria in anaerobic digestion are also temperature and pH. These microorganisms are commonly present in livestock and human waste that is used as fertilizer for plants. Therefore, pre-treatment of such organic waste through anaerobic digestion before its use in crop production will reduce the number of pathogens in the environment.

Manyi-Loh & Lues (2022) studied the effect of anaerobic digestion of sawdust (25%) and pork manure (75%) at psychrophilic temperature (13.2–24.7 °C) on the reduction of pathogens in waste (*E. coli*, *Salmonella* spp., *Yersinia* spp., *Campylobacter* spp., *Listeria* spp.). This species decreased depending on the number of days of reactor operation. The least resistant to anaerobic conditions of bioreactor is *E. coli* (77 days of viability), and the most resistant is *Listeria monocytogenes* (175 days).

Quite often, mesophilic temperature conditions are used during anaerobic digestion in processing the manure of farm animals. At the same time, the main problem is the inactivation of pathogens in such wastes. The experiment with the preliminary thermophilic and hypertemophilic hydrolysis showed a decrease in the number of cultured *E. coli* bacteria to 6.9 $\log_{10}$, as well as a decrease in the number of *Enterococcus* spp., *Streptococcus* spp. and *Acinetobacter* spp. Despite this, *Clostridium* spp. (*sensu stricto*) showed high relative abundance (Lin et al., 2022a).

The effect of high temperatures on the inactivation of pathogens is also confirmed by the experiments of Seruga et al. (2020). They studied the survival time and inactivation rate of *Salmonella* Senftenberg W775, *Enterococcus* spp. pathogens and *Ascaris suum* eggs under thermophilic anaerobic conditions. On a laboratory scale, elimination of pathogens was recorded for 6.1 hours for *Salmonella* Senftenberg W775, 5.5 hours for *Enterococcus* spp. and about 10 hours for the eggs of *A. suum*.

The effect of temperature on the efficiency of pathogen inactivation during anaerobic digestion is noted by Liu et al. (2021): thermophilic digestion removes pathogens more effectively than mesophilic. According to Cai et al. (2022), who studied the specific methane yield, process parameters and microbial characteristics in anaerobic digestion of conventional agricultural waste (human faeces, food waste and lawn grass), co-digestion reduces the absolute concentration of *Salmonella* spp.

Based on the analysis of previous sources, the limiting factors affecting the viability of pathogens in waste processing are temperature, pH and oxygen concentration in the environment (Fig. 5, Table 1).

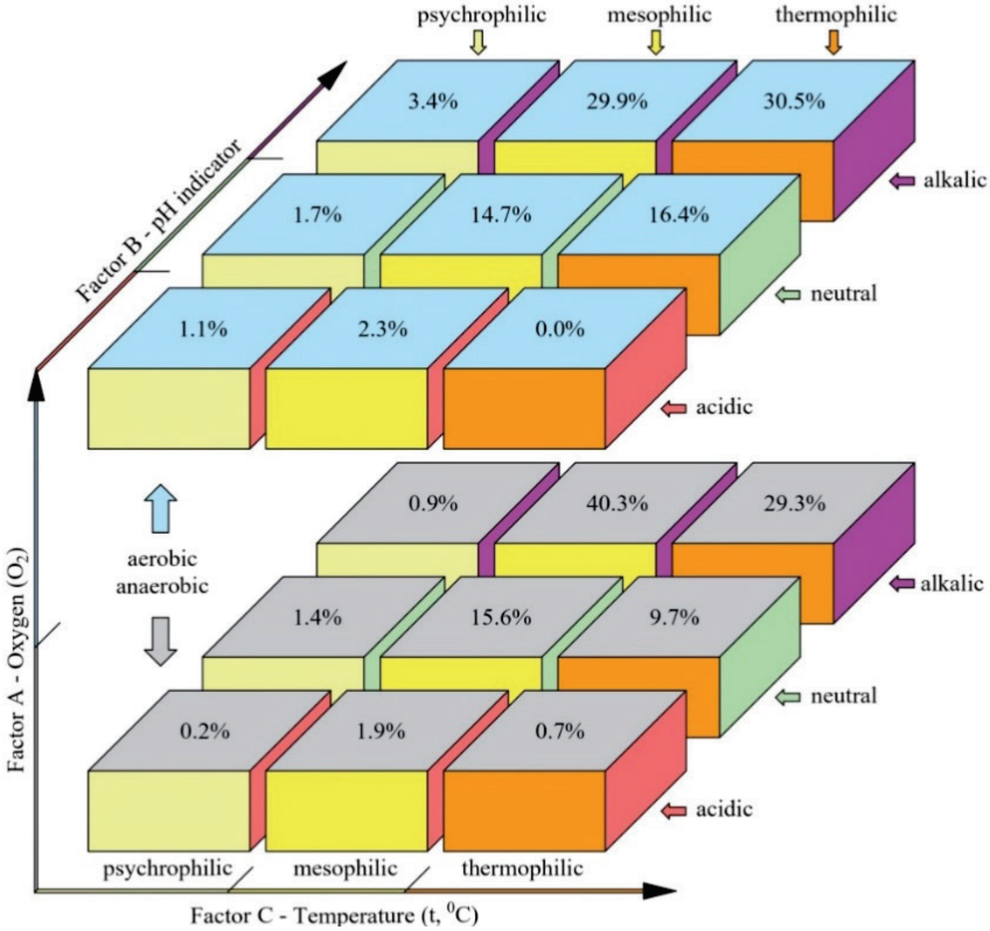

Fig. 5. The main factors affecting the destruction of pathogens during waste processing and the dynamics of publication activity (%)

Table 1
The main factors affecting the destruction of pathogens during waste processing and publication activity in the field of research (according to the Scopus database)

Presence of oxygen	Environment: alkali	Environment: neutral	Environment: acid	Total
Anaerobic conditions	psychrophilic conditions: 6 mesophilic conditions: 53 thermophilic conditions: 54	psychrophilic conditions: 3 mesophilic conditions: 26 thermophilic conditions: 29	psychrophilic conditions: 2 mesophilic conditions: 4 thermophilic conditions: 0	11 83 83
	113	58	6	177
Anaerobic conditions	psychrophilic conditions: 4 mesophilic conditions: 171 thermophilic conditions: 124	psychrophilic conditions: 6 mesophilic conditions: 66 thermophilic conditions: 41	psychrophilic conditions: 1 mesophilic conditions: 8 thermophilic conditions: 3	11 245 168
	299	113	12	424
The total number of articles searched based on keywords in the Scopus database for the period 2000–2023	412	171	18	601

Najdenski et al. (2021) investigated the anaerobic digestion of wheat straw in a bioreactor with an organic load of 2, 5, 7, 10 and 20 g/L, as well as with an exposure time of 18–80 days. Microorganisms of *Bacillus*, *Pseudomonas*, *Enterococcus* and *Aeromonas* genera, as well as the species *Terribacillus halophilus*, have been identified.

Anaerobic digestion is widely used for wastewater treatment. The problem of disinfection quality also exists. An inevitable byproduct of wastewater is sludge, which contains human and animal faeces, so controlling pathogens in public sanitation facilities is of great importance. *Arcobacter* spp. (up to 86.0%) is recorded in bacterial groups of untreated wastewater, according to Cuetero-Martínez et al. (2023). This genus of bacteria contains potentially pathogenic species. According to the same researchers, the DNA of some species can persist after treatment (*Acinetobacter johnsonii*, *A. junii*, *Aeromonas caviae*, *A. hydrophila*, *A. veronii*, *Arcobacter butzleri*, *A. cryaerophilus*, *Chryseobacterium indologenes*, *Hafnia parlvei*, *Moraxella* spp. and *Vibrio cholerae*). This is important to know when reusing water. According to studies by Zuo et al. (2021), the main pathogen of *Pseudomonas aeruginosa* continues to reproduce for the first 8 days, and then its population stabilizes at a higher level than at the beginning. Enteroviruses, *Salmonella* and *Escherichia coli* are also present in the sludge. Therefore, wastewater is the main source of high-risk biological pollutants: pathogenic bacteria, viruses, parasitic protozoa, antibiotic-resistant bacteria, and antibiotic resistance genes. The sludge is treated using various technologies. Composting, anaerobic digestion, aerobic digestion, microwave irradiation, membrane bioreactor, membrane filter, oxidation, constructed wetland, wastewater stabilization pond, nanomaterials, biochar and bacteriophage are often used (Yin et al., 2020; Li et al., 2021). However, most of these treatments do not destroy pathogens and they move from one phase to another. This contributes to secondary pollution. Low pathogen inactivation in anaerobic digestion of sludge is reported by Ruiz Espinoza et al. (2022). Therefore, there is a need to improve the fermentation process. Recently, despite the popularity of anaerobic digestion in wastewater treatment, their pre-treatment has attracted great interest. These include electrochemical, ultrasonic, alkaline purification, coagulation, nanofiltration, air desorption, adsorption, and photocatalysis prior to anaerobic digestion (Anjum et al., 2023).

López et al. (2020) analysed the operation of three plants: an anaerobic digestion plant with mesophilic (35–37 °C) conditions, anaerobic digestion plant with thermophilic (55–57 °C) conditions and thermophilic aerobic plant (55–57 °C). The best indicators for reducing the quantity of *Enterococcus* sp. were obtained during the operation of an anaerobic plant with thermophilic conditions, *E. coli* – during the operation of aerobic thermophilic plant. The studies above indicate a high temperature value during wastewater sludge treatment.

Comparing these two purification methods (under anaerobic and aerobic conditions), Carraturo et al. (2022) investigated the recovery of the growth of *Salmonella typhimurium* and *E. coli* artificially inoculated on mature digestate to assess its effectiveness as a growth medium for microorganisms. For 24–48 hours under anaerobic conditions, these microorganisms were not detected, unlike in aerobic conditions. High concentrations of *S. typhimurium* and *E. coli* bacteria in the second case were observed for 10 days. Negative results were also obtained in the study of mature digestate for the presence of *Salmonella* spp., which is found in wastewater sludge fed to a full-scale plant.

Thermophilic anaerobic digestion combined with pretreatment may be useful for further optimization of animal waste disposal (Tang et al., 2020). A positive result of anaerobic digestion in combination with pretreatment for most pathogenic bacteria is described by Yang et al. (2022). The exception was *Clostridium perfringens*. Slompo et al. (2020) observed $\log_{10}$ removal/inactivation levels: 0.51 $\log_{10}$ for total coliforms and 2.73 $\log_{10}$ for *E. coli* in their study of anaerobically treated black water processed in photobioreactors inoculated with *Chlorella sorokiniana*.

Today, thermal hydrolysis after anaerobic digestion is of great interest. Despite the sterile biological substances obtained from this treatment, recontamination with pathogens is possible (Svennevik et al., 2020). Good results can be obtained by storing solid biological substances obtained by anaerobic digestion and in the process of thermal hydrolysis before anaerobic digestion for 3 days after re-contamination. If it concerns solid biological substances obtained after anaerobic digestion followed by thermal hydrolysis – more than 13 days.

Large volumes of wastewater are produced by aquaculture processing enterprises. The use of a segmented anaerobic reactor followed by an anaerobic filter in the treatment of wastewater generated during fish processing shows a high degree of coliform removal (Sousa et al., 2022).

Conclusion

Focus on green energy, decarbonization and greening of production in the context of global warming were a priority for the national economy until recently. The full-scale invasion has made adjustments to Ukraine's energy security strategies. The difficult situation in the fossil resources market and the worsening environmental circumstances require a comprehensive approach to solving the problem. It is quite clear that the growing epidemiological and epizootic threat from agricultural enterprises, in the conditions of infrastructure disrupted by hostilities, cannot be addressed solely through biogas energy. Methods of preliminary treatment of organic waste as substrates for biogas plants need to be developed and improved, as well as the temperature conditions of the plants themselves, taking into account the peculiarities of the life activities of pathogens. Methods for monitoring the effectiveness of disinfection of organic waste in terms of individual pathogens of infectious and invasive diseases with the further development of biogas technologies also require further study.

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