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ANAEROBIC DIGESTION AND COMPOSTING AS METHODS OF BIO-WASTE MANAGEMENT

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ABSTRACT

The management of biodegradable waste from various sectors of economy is an essential element in terms of environmental protection. The paper discusses issues related to the possibility of bio-waste treatment using anaerobic digestion technologies and composting processes, highlighting the conditions for the processes and their advantages and disadvantages. The challenges of overproduction of bio-waste faced by highly developed countries around the world are also presented. Research showed that the anaerobic digestion of this waste combines both biofuel production and a circular economy. The popularity of this method is linked, among others to a low cost of raw materials and wide range of possible uses for biogas (i.e. electricity, heat, or biomethane). In addition, an alternative bio-waste management option, compost production, was discussed. The study aimed to compare anaerobic and aerobic bio-waste management processes.

Introduction

The management of municipal waste is an extremely important aspect of environmental protection. Bio-waste is aparticular group in the waste stream. In many countries, this waste represents the dominant part of all municipal waste fractions. This is due to the fact that fruit and vegetables are the main sources of food for many people (Czekała et al., 2022). Consequently, bio-waste is also generated every day, virtually by everywhere in the world. In this group, kitchen waste and green waste can be mentioned. Kitchen waste includes unconsumed food of plant origin and inedible plant parts. Green waste includes grass, leaves and branches.

There are several main directions for the management of bio-waste. The simplest of these is landfilling. However, this process is not environmentally beneficial and should be kept to a minimum. Thermal waste treatment processes, especially incineration, are another option. In this case, however, a high content of dry matter and organic matter in the waste should be ensured (Obidziński et al., 2022). Due to their properties, mainly organic matter abundance and water content, the waste in question should be treated by biological processes (Czekała, 2022). Anaerobic digestion and composting are mentioned in this group.

Anaerobic digestion is a process in which biodegradable waste are decomposed under anaerobic conditions (Waliszewska et al., 2019). The products of the process will be biogas and digestate (Koryś et al., 2019). This process requires specific conditions, the most important of which is the absence of oxygen. With this parameter, the two processes in question differ, as the presence of oxygen is essential for composting (Sołowiej et al., 2021). In the presence of oxygen, the decomposition of organic matter takes place. The final product will be compost, a fertiliser rich in organic matter. Its properties allow it to be used successfully in agriculture. Both anaerobic digestion and composting are suitable technologies for bio-waste treatment. The study aimed to compare anaerobic and aerobic bio-waste management processes.

Anaerobic digestion as a bio-waste management method

Characteristics of the anaerobic digestion process

Interest in the bio-waste management using anaerobic digestion is growing steadily and is an important part of the waste management system, especially in highly developed countries. The main reason for using the anaerobic digestion technology is production of renewable energy in the form of biogas (Balanda, et. al., 2022; Kucher et al., 2022). In addition, the use of feedstock in the form of bio-waste fits into the thoughts of a circular economy and reduces greenhouse gas emissions. The use of waste saves resources, reduces landfill space as well as the environmental impact of landfilling. Adapting the technology and choosing the right conditions for the digestion process is necessary, as individual process types and reactors are not always effective in treating all organic waste (Uddin et al., 2021).

In order to manage biodegradable waste, the use of anaerobic digestion is justified both economically and environmentally. There are currently several biogas installations in Europe that process municipal and industrial bio-waste. In addition to industrial installations, the digestion process takes place in the natural environment, e.g., in peat bogs and marshes or in the digestive tracts of ruminant animals. As a result of the decomposition of organic matter by anaerobic microorganisms, a mixture of gases is produced, consisting mainly of methane and carbon dioxide, as well as a by-product, the digestate (Borek and Romaniuk 2020b; Dach et al., 2020; Kukharets, et. al. 2021; Czekała, 2022). The process involves four main steps: hydrolysis, acidogenesis, acetogenesis, and methanogenesis (Bharathiraja et al., 2018; Borek and Romaniuk 2020a). The choice of the appropriate type of technology is determined by several factors, including the availability and type of feedstock, as well as parameters related to its quality, such as biogas efficiency or hydration. The course of the anaerobic digestion process is similar for each process type. The feedstock is placed in a heated and sealed reactor. The tank is usually made of concrete or metal and its volume is adapted to the power of the plant. The key task of the digester is to keep specific temperature conditions to keep the optimal environment for microbial growth, resulting in high biogas production, equivalent to higher electricity production (Meegoda et al., 2018).

Appropriate adaptation of the technology for a given type of waste requires the introduction of a classification system depending on the conditions under which the anaerobic digestion process is carried out. Wet technology is one of the fermentation methods. The dry matter content of the fermenter is between 6% and 15% (Weiland, 2010). By using suitable pretreatment methods and adding liquid substrates or process water, it is also possible to use solid feedstock in this technology. In addition, conditioning allows better homogenisation of the feedstock, and the liquid form facilitates mixing for better distribution of the feedstock and adequate contact with the microorganisms. Another method used for bio-waste management is dry fermentation technology in reciprocating (screw) flow reactors. In this method, it is possible to use various types of solid organic raw materials and the dry matter content of the digester can vary between 20% and even 40% (Shapovalov et al., 2020). A limitation in the application of dry fermentation technology is the volume of the reactor, which results from the presence of large radial forces acting on the walls of the digester. In addition to continuous dry and wet technology, garage reactor systems are also used to process bio-waste (Czekała et al., 2023). The feedstock is delivered in batches and stays in the digester for a period of approximately one month. The chambers are then emptied, and the digester residue is often used as feedstock for the composting process. Inoculation of the feedstock with bacteria takes place using leachate (percolation liquid) with which the substrates are sprinkled. Fermenters of this type are characterised by discontinuous flow and the absence of moving parts such as agitators, which increases durability and reduces operating costs (Bharathiraja et al., 2018; Abdelsalam et al., 2021).

Attention should also be paid to the aspect related to the formation of a by-product in the digestion process, i.e., the digestate. It consists of, among other water, microorganisms, as well as mineral substances and undecomposed organic compounds. The simplest way of utilising it is as fertiliser. It is possible to compare the digestate with other fertilisers used in agriculture, e.g., slurry. In the case of digestate, potential benefits have been demonstrated in terms of for example the availability of nitrogen, which has a definite effect on yield. In addition, digestate is characterised by higher NH_4 levels, a higher pH value, reduced organic matter content, and a lower C:N ratio compared to animal manure. This aspect is an additional benefit of bio-waste management using anaerobic digestion technology (Czekała, 2022; Kovačić et al., 2022).

Collection of bio-waste and process control

Adapting the conditions of the digestion process while maintaining a high-quality by-product requires treating the substrates with undesirable materials contained in the input. Biodegradable waste from households often contains fractions of plastic, glass, metal, or even stones in its composition. Contaminants can cause, among others, failures of mixing systems or grinding equipment. The quality of the technology used to separate contaminants from the substrate translates into the quality of the resulting product after the digestion process and its potential for use (Alessi et al., 2020).

It is possible to use a variety of feedstock for biogas production (Borek et al., 2021). Depending on the type and properties of the feedstock in question, it is necessary to adapt the storage technology. Within the category of bio-waste, a distinction is made between biodegradable substrates, classified as waste from parks and gardens, or food waste from households or production facilities. Each waste has different parameters. The choice of substrate storage method for biogas plants is determined by the level of dry matter of the individual raw material. Liquid substrates are most often stored in underground closed tanks, while solid raw materials are stored in special facilities or warehouses. In addition, it is advisable to install biofilters in the storage halls to prevent odour emissions (Ghosh, 2016).

An example of a substrate that requires proper storage, as well as separation, are expired products that are packaged in cardboard or plastic boxes. Their unpacking and separation requires expensive technologies. Removal of contaminants, in addition to being highly energy-intensive, creates a new fraction that must be managed. In addition, municipal waste from the separate collection is particularly troublesome as its quality depends, among other things, on the public's application of the principles of separate collection. Figure 1 showed the bio-waste from a separate collection of one municipality in Poland. Such bio-waste varies considerably due to factors such as location (urban or rural), level of education or population density. The simplest method that can contribute to improving the quality of the input is educational campaigns on bio-waste management, as well as the inspection of containers by collection companies (Alessi et al., 2020).

Figure 1. Bio-waste from separate collection directed to anaerobic digestion (own study)

Advantages and disadvantages of using digestion for bio-waste management

The anaerobic digestion of green waste and by-products from households or food production facilities offers many advantages. In this context, special mention should be made of the conservation of fossil resources, avoidance of greenhouse gas (GHG) emissions, and associated climate protection. The advantage of biogas technology as a method for waste management stems from the ability to store energy in products such as biogas or biomethane and generate electricity when required (Czekała, 2021). Furthermore, biogas is an excellent solution for decentralised off-grid electricity, especially in rural areas that are not connected to the electricity grid but have significant amounts of biomass. In developing countries, biogas is often directly used as the only fuel for heating or gas lighting (Cecchi and Cavinato, 2015).

In addition to renewable energy, biogas plants produce valuable fertiliser in the form of digestate pulp, which is rich in nutrients and organic matter. All plant-essential nutrients contained in the feedstock remain in the digestate, which can be used as a fertiliser or soil improver in agriculture or horticulture. This is an example of acting according to a closed-loop economy, closing the carbon and nutrient cycle. Digested waste and the alternative of compost from bio-waste are beneficial sources of humus that improve soil fertility as well as soil structure. Applied artificial fertilisers can have a short-lived effect and lead to soil sterilisation (Czekała, 2022).

Despite the many advantages regarding this type of technology, it should be noted that it also has disadvantages. When analysing other bio-waste management options, anaerobic digestion technology is associated with high initial costs. Complex technology, concrete or steel digesters, or process automation are a few of the costs affecting this type of investment. In addition, running the digestion process requires adequate knowledge of how to supervise it. The final biogas product is often contaminated with e.g., H_2S, which causes complications during its energetic use. Another disadvantage associated with anaerobic digestion technology is often negative public perception associated with the construction of new biogas facilities. However, the most common reason is the lack of adequate knowledge related to the technological solutions, as well as the problem related to the odour nuisance of the installations (Uddin et al., 2021).

Development of technology

Anaerobic digestion is an effective process to solve the problem of bio-waste management. The expected further growth of organic waste treatment is an excellent answer to meeting local demand for electricity or heat while reducing landfill. The resulting biogas is a renewable energy source that, with upgrading methods, can be supplied through the same pipeline as natural gas. Biogas has many advantages over other alternative renewable energy sources. It is possible to produce it, and at the same time store and use it when it is most needed. With the continued efforts of scientists to develop technologies to process organic waste, biogas will be an excellent solution for reducing greenhouse gas emissions. The energy demand is constantly increasing, and most of this energy is produced using fossil fuels. Research indicates that anaerobic digestion is a technology that combines biofuel production with sustainable waste management, and there are many trends in the biogas industry that improve the production and quality of the resulting biogas. Further investments in biogas plants are expected to be even more successful due to the low cost of available feedstock and the wide range of applications of the gaseous fuel for processes such as heating or electricity generation (Demichelis et al., 2019; Glivin et al., 2021).

Composting as a bio-waste management method

Characteristics of the composting process

Another method of bio-waste management is composting. This process is the most common method of treating biodegradable waste worldwide (Hemidat et al., 2018). According to the literature, composting is a biological process involving the controlled stabilisation of biodegradable organic matter (including bio-waste). This process occurs with the involvement of many different strains of microorganisms such as fungi, protozoa, and bacteria. Their involvement in biomass processing occurs at different intensities that depend on the process parameters (Azim et al., 2018; Ayilara et al., 2020). As a result of the composting process, the organic matter is decomposed and the produced compost is a stable product (Qi et al., 2020; Zhao et al., 2020). Organic fertiliser is a high-quality product that will provide plants with the nutrients they need to grow (Shi et al., 2020). Composts are often referred to as soil improvers, due to the improvement in soil structure and fertility. The composting process can partially remove toxic substances and pathogenic bacteria from the treated feedstock. In addition, it can contribute to the elimination of the noxious odour of the composted substrate (Ajmal et al., 2021).

Phases and parameters of the composting process

The composting process is based on the natural processes of mineralisation and humification that occur in the environment, e.g., after the introduction of organic matter into soils. However, by carrying out composting, the mineralisation and humification processes occur more quickly. During its implementation, two main phases can be distinguished. The first is characterised by intensive microbial activity, which allows a large part of the organic matter to be biodegraded and stabilised. The second phase is related to the generation of humus from organic matter. This is a material that is seen as a factor responsible for improving the quality of compost (Azim et al., 2018). Indeed, humus is important in ecology, fertilization, and improving soil structure (Vikram et al., 2022).

In addition to dividing the composting process into two main phases, it can also be divided into four successive phases (Zhong et al., 2020). The first of these is the mesophilic. During it, the temperature inside the compost pile slowly increases to the value of about 40°C. The pH of the compost mixture decreases due to the release of organic acids from carbohydrates and lipids, which are degraded by microorganisms (Chang et al., 2021). Once the temperature reaches 40°C, thermophilic microorganisms are activated. This process starts the next stage of composting – the thermophilic phase (Zhang et al., 2022a). It is characterised by a temperature of about 50°C to about 60°C. The reaction of the compost mixture increases due to the decomposition of proteins and the formation of ammonia. When the temperature in the compost heap exceeds 60°C the decomposition of organic matter starts to slow down. On the other hand, once the temperature exceeds 70°C, organic matter degradation occurs only as a result of the activity of enzymes that were released in the previous process step (Azim et al., 2018). The penultimate stage of the composting process is the cooling process (Ge et al., 2022). During it, the compost stabilisation process begins. Thermophilic microorganisms are replaced by mesophilic ones. The last phase of the composting process is the maturation stage of the compost (Zhang et al., 2022b). It is performed at ambient temperature as a result of the activity of mesophilic microorganisms. In addition, antagonism and predation relationships are established between organisms. The reduction of the mass of the compost mixture and the release of heat slows down and remains at a low level. It is during this stage that secondary polymerisation and condensation reactions occur, leading to the formation of humus. Once this stage is complete, stable compost is produced (Azim et al., 2018; Neugebauer, 2018).

Composting is a complex process. To achieve efficient composting, the right conditions must be provided for the bacteria. One of these is the correct ratio of carbon to nitrogen (C:N). In addition to this parameter, the bacteria must be provided with, among other things, the right moisture content, aeration, or the right bulk density (Jakubowski and Sołowiej 2016; Barthod et al., 2018).

Composting technologies

The complexity of the composting process has resulted in the evolution of a variety of technologies to ensure that the process is carried out efficiently. As a result, a composting technology can be selected for a given group of bio-waste to enable it to be managed more efficiently. Figure 2 showed the compost that is subjected to the processes of maturation, storage, and packaging under a shed in the subsequent production stages.

Figure 2. Compost in the storage hall during the maturation process (own study)

Composting in heaps

Composting in heaps is the oldest and most well-known composting technology (Jędrczak, 2018). Substrates that have been stabilised using this technology may require grinding (Barrón-Santos et al., 2021). They are formed into heaps with a triangular or trapezoidal cross-section. A heap formed in this way is characterised by a large surface area, which can result in a rapid loss of temperature values. To prevent this, the volume of the moulded piles should be appropriately adapted to their surface area (Luangwilai et al., 2021). This type of composting can be divided by the way the pile is aerated. Composting in static heaps, static heaps with aeration, flipped heaps, and flipped heaps with aeration can be mentioned (Pergola et al., 2018; Valverde-Orozco et al., 2023). The specificities of this composting technology allow the process to be carried out in the open air and under a canopy. It is more advantageous to run the process under a canopy due to the nullification of the influence of weather conditions on the process. In addition, roofing is conducive to reducing odour emissions from the composting process (Baron et al., 2019; Dalahmeh et al., 2022). Composting is related to significant gaseous emissions (CO_2, CH_4, N_2O). This is due to the flipping of the piles, which results in emissions of gases trapped inside the formed pile (Jędrczak, 2018; Pergola et al, 2018; Keng et al, 2020).

Container composting

Another composting technology is container composting. It is carried out in sealed reactors with a capacity of approximately 20 m^3. Air is pumped into the containers for the correct process. By composting in a closed space, it is possible to carry out complete control of the extracted gases (Graça et al., 2021; Bojarski et al., 2023). The most commercially available container composting technologies provide biofilters which allow almost complete deodorisation of the resulting odours. The closed space also allows a closed leachate water cycle. The composting process in this type of a plant lasts between 7 and 14 days (intensive composting). After this time, the compost mixture is transported to the yard. There, a pile is formed from it, which enables the final stage of composting, i.e., maturation of the compost, to take place. This stage lasts from one to four months, depending on what the requirements are for the quality of the product (Szala and Paluszak, 2008; Jędrczak, 2018; Sikorska et al., 2019).

Vermicomposting

A specific composting technology is vermicomposting. This is a biotechnological process during which earthworms and microorganisms interact. The result of this interaction is vermicompost, which is an organic fertiliser of very high quality. The composting process in this technology takes place at 45-65°C (Thirunavukkarasu et al., 2022; Enebe and Erasmus, 2023). Organic matter in this process undergoes continuous decomposition, bioconversion, and bio-oxidation resulting in stabilised humic material. In vermicomposting, the stabilisation of organic matter occurs faster than in traditional composting. The resulting product contains nutrients essential for plants. The structure of the produced vermicompost resembles peat due to which the material is characterised by its ability to store water (Vuković et al, 2021; Yatoo et al, 2021; Thirunavukkarasu et al, 2022).

Advantages and disadvantages of composting

Commercially available technologies for the composting process ensure that bio-waste is converted to a high-quality organic fertiliser. This fertiliser is clear of weed seeds and most pathogens. As a stabilised product of the composting process, compost can be used for soil remediation. Thanks to its properties, it can restore fertility to soils, which in turn can reduce the need for artificial fertilisers or pesticides in agriculture. The above-mentioned advantages of this organic fertiliser result in a reduction in the cost of crop production, while limiting its negative impact on the environment. Compost produced from bio-waste can be used in other production activities, not only in agriculture. This product can equally well be used in forestry for nursery production or for fertilising green spaces or reclaiming landfills (Cáceres et al, 2018; Cerda et al, 2018; Pergola et al, 2018).

Comparing composting to other bio-waste management methods, the process can be considered as a solution that maximises the material cycle (Cáceres et al., 2018; Shan et al., 2021). Composting is a process that undoubtedly fits into the ideologies of the circular economy. It is a relatively uncomplicated process and cheap to perform. The wide range of available composting technologies makes it possible to adapt the technology to the requirements to be met by the fertiliser produced. In addition, composting makes it possible to manage wood-based waste, which is impossible with anaerobic digestion. Due to the technological requirements, anaerobic digestion is a much more expensive process. Despite the unquestionable advantages of the composting process, its major drawback is that it is not possible to generate electricity. In contrast, this aspect is possible with anaerobic digestion (Jędrczak, 2018; Awais et al., 2021; Haouas et al., 2021; Mengqi et al., 2023).

The future of bio-waste composting

Table 1 presents the amount of municipal waste that has been managed by composting or anaerobic digestion. As can be seen, the amount of waste managed this way is increasing every year. The percentage of such managed waste is also growing, which actually reflects the increased use of these waste management methods. Therefore, it can be assumed that the use of composting and digestion as waste stabilisation methods will become increasingly popular in the near future. The move towards zero-emission means that all waste management methods that have a positive impact on the environment will continue to be developed.

Table 1.
Mass and percentage of collected municipal waste for composting or digestion over five years (GUS, 2018-2022)

Year	Mass of municipal waste for composting or digestion, (Mg)	Percentage of municipal waste to be composted or digested, (%)
2017	848 000	7
2018	1 012 000	8
2019	1 153 000	9
2020	1 578 000	12
2021	1 824 000	13

Research are being conducted into the use of heat generated during the composting process. The main issue in this subject concerns the elimination of the risk of the composting process slowing down or stopping altogether during heat extraction. Given this, the development of technology in which it will be possible to extract energy from the composted mixture represents the future of this bio-waste management method (Smith and Aber, 2018).

Conclusion

Bio-waste is a group of waste that requires special attention. This is due to its quantity and availability everywhere in the world. The waste in question can be recycled, but this requires the quality of the raw material to be adequate, especially in terms of freedom from contamination. Anaerobic digestion and composting are among the predominant management options. As both processes are influenced by micro-organisms, care must be taken to ensure both the purity of the raw material and that the process is carried out under appropriate conditions, including dry matter content, pH, presence of oxygen (composting), or absence of oxygen (anaerobic digestion). Each of the two processes has its advantages and disadvantages. Due to rising electricity prices, an increase in the number of installations for anaerobic digestion processes is to be expected, despite their higher construction cost. Regardless of the technology used, the treatment of bio-waste can prove to be a key aspect of achieving the required recycling levels.

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PORÓWNANIE PROCESÓW BEZTLENOWEGO I TLENOWEGO ZAGOSPODAROWANIA BIOODPADÓW

Streszczenie. Zagospodarowanie odpadów biodegradowalnych pochodzących z różnych gałęzi gospodarki jest niezbędnym elementem w aspekcie ochrony środowiska. W artykule omówione zostały zagadnienia związane z możliwością przetwarzania bioodpadów wykorzystując technologie fermentacji metanowej i procesu kompostowania, z podkreśleniem warunków prowadzenia procesów oraz ich wad i zalet. Przedstawione zostały także wyzwania związane z nadmierną produkcją bioodpadów, przed którymi stoją państwa wysokorozwinięte na całym świecie. Prowadzone badania pokazują, że fermentacja beztlenowa omawianych odpadów łączy zarówno produkcję biopaliw oraz gospodarkę obiegu zamkniętego. Popularność omawianej metody jest związana m.in. z niskim kosztem surowców oraz szeroką możliwością wykorzystania produktu jakim jest biogaz (tj. elektryczność, ciepło lub biometan). Ponadto omówiona została tematyka związana z alternatywną możliwością zagospodarowania bioodpadów jaką jest produkcja kompostu. Celem pracy było porównanie procesów beztlenowego i tlenowego zagospodarowania bioodpadów.

Słowa kluczowe: biomasa, fermentacja beztlenowa, kompostowanie, gospodarka cyrkularna, zarządzanie odpadami.