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The Bioreactor – an Innovative Method of Disposal of Solid Waste

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Abstract: The paper presents a novel method of rational management of solid waste, namely an example of a modern landfill with enhanced leachate recirculation – a bioreactor landfill. The aim of the paper was to compare modern solutions concerning waste storage with traditional methods in terms of sustainability. The comparison was drawn as a result of conducting literature research and an independent analysis of the data obtained. A number of advantages was presented resulting from using technologies with enhanced leachate recirculation in environmental, social, and economic terms. The superiority of modern technologies of waste management over conventional technologies was clearly stated as a result of the analyses performed.

Keywords: solid waste, landfill, bioreactor

JEL codes: Q01, Q24

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1. Introduction

Currently in the global waste management, waste storage is considered the last action taken, which follows the use of any rational methods of its utilisation, processing and treatment (Fig. 1). This is specified in the waste management act "Waste that could not be recovered should be treated to such an extent that only the waste which could not be treated in any way due to technological limitations or being unjustified for ecological or economic reasons should be stored (Journal of Laws [Dz. U.], 2013, item 2)".

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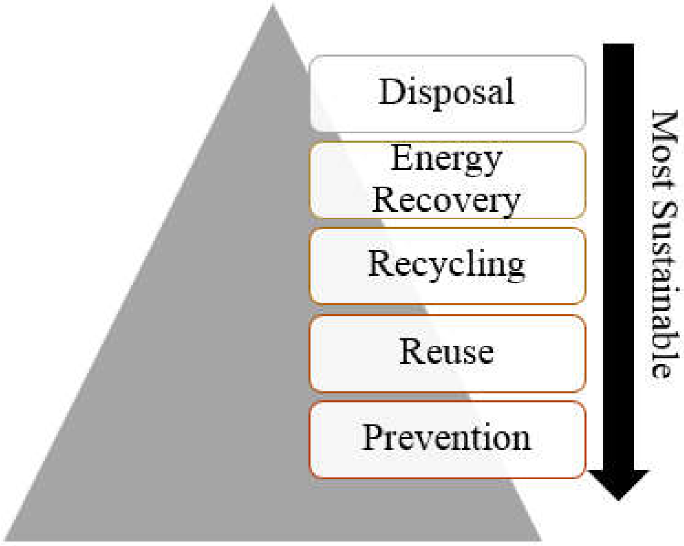
Figure 1. Diagram showing the waste hierarchy according to Directive 2008/98/WE concerning waste



Source: Author's own elaboration based on: Biegańska et al., 2011: 57.

All current guidelines and regulations concerning waste management in Poland result from the necessity of managing waste in compliance with sustainability principles. Their aims are to integrate the most important waste management goals, i.e. environmental, economic, and social aspects.

Nowadays waste is one of the most important environmental issues and, as a result, also social. The amount of waste is constantly increasing due to an increasing number of people, increasing consumption and technological advances. It is estimated that in 2014 over 10.3 million tons of municipal waste was collected in Poland, which is an 8.3% rise in comparison with 2013 (Central Statistical Office [GUS], 2015: 24). The leading producers of municipal waste are households. It is assumed that 270 kg of waste is generated per capita (Central Statistical Office [GUS], 2015: 24). 47% of the municipal waste collected in 2014 was recycled and thermally and biologically treated, whereas the rest, i.e. 5.3 million tons of waste, was stored in landfills. A significant part of the waste stored in landfills is biodegraded. Despite the introduction of sustainability principles in the system of waste management, waste storage in landfills cannot be avoided, however. It is still one of the most universal and common methods of waste management. Therefore, in the frame of rational waste management principles, it is worth reinventing the current waste storage methods in a way that takes into account general environmental rules concerning caution and a sustainable approach, technical feasibility, economic viability, resource conservation, as well as the total impact on the environment, human health, economy and social aspects. Constant improvement of waste storage methods, or treating landfills as bioreactors will allow for the minimalisation of risks and environmental pollution. Moreover, the process of landfill gas production will be intensified as a result of the optimalisation of the processes that take place in landfills. The quality of landfill gas will be increased which may allow for its use in energy generation. It is worth mentioning that landfill gas is considered a renewable source of energy. Therefore, the dependence on non-renewable energy sources, such as bituminous coal or lignite, may be reduced. Another advantage of landfill gas is the reduction of costs related to the treatment and storage of leachates generated in landfills, because the processes of leachate treatment and volume reduction take place as a result of their return flow to the system. Naturally the prerequisite for these advantages is the proper design and construction of the landfill, as well as the constant control and optimalisation of its conditions of use (Kwiatkowski and Żygadło, 2011: 103 – 116; Kaczorek and Ledakowicz, 2005: *69 – 87).* Modern landfills should also be suitably located, i.e. hydrological and geotechnical criteria should be taken into account. The conditions of the counteraction and minimalisation of odour production and the uncontrolled emission of landfill gas should be fulfilled, and the protection from noise pollution should be ensured (Rosik – Dulewska, 2006: 93 – 102).

2. Solid waste landfill

Landfills are very complicated facilities because their "lives" do not end once the last kilogram of waste is stored there. Due to biochemical changes taking place in landfills, they become to live only after some time. According to Kaczorek and Ledakowicz (205: *69 – 87*), landfills can be divided into the following groups on the basis of their use concept:

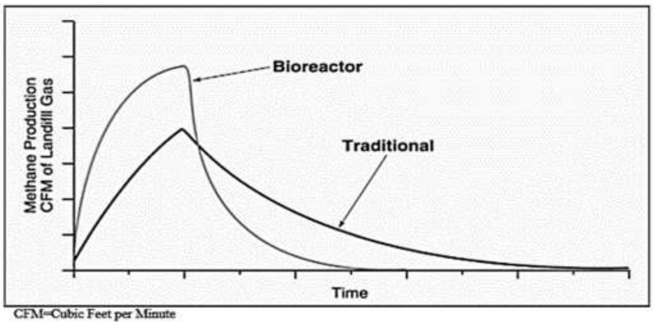
- dry landfills, modern landfills with a limited access to water. They are characterised by a small volume of leachates and landfill gas, which are produced very slowly due to a low level of moisture content of waste. From a negative point of view, it takes a long time for waste to degrade and, in some cases, the degradation processes cannot end at all. Dry landfills are also expensive, have to be monitored for a long time due to the environmental hazard in case the system has leaked.

- landfills as bioreactors, that is landfills with enhanced leachate recirculation (ELR), according to the Environmental Protection Agency (EPA) they are defined as "Bioreactors are landfills where non-hazardous liquid waste or water is added in a controlled way, thus enhancing the acceleration of waste degradation and landfill gas generation."
- landfills as the last storage facilities – only waste that has been sorted before is stored in these landfills. Waste is organised so as to contain as little organic material as possible and to minimise possible leaching of inorganic matter. They are characterised by the minimal production of landfill gas and leachates.

Conventional or classical (dry) landfills are engineer facilities where only non-hazardous solid waste is stored. Solid waste is stored in the so-called landfill sites, then it is rolled and compacted using a compactor or bulldozer, and is covered daily with a thin layer of inert material at the end of the day.

On the other hand, bioreactor landfills are also conventional landfills where microbial processes are intensified, leading to the degradation and stabilisation of biodegradable components of waste within 5 to 10 years. Landfill stabilisation means that the landfill gas composition, its volume and the number of leachates produced should remain at the same level for the whole duration of processes taking place in landfills. Shortly after the landfill is closed, the landfill gas production will be most efficient, but it will eventually drop and stabilise. The same goes for the contaminant concentration in leachates and their volume (Wartih, 2003: 61 – 70; Thampan and Chandel, 2013: 256 – 260). Figure 2 shows landfill gas production curves in classical landfills and bioreactor landfills. It may be concluded that the process of landfill gas production begins significantly earlier and is more intense, i.e. the volume of landfill gas produced is higher and takes shorter time, in the bioreactor landfill.

Figure 2. Landfill gas production curves for classical landfills and bioreactor landfills



Source: Thampan and Chandel 2013: 256 – 260.

The degradation process in dry landfills will not be completed after roughly 10 years – it may take decades, even 30 to 200 years – whereas the process will be completed in bioreactor landfills after 10 years (Wartih, 2003: 61 – 70; Thampan and Chandel, 2013: 256 – 260).

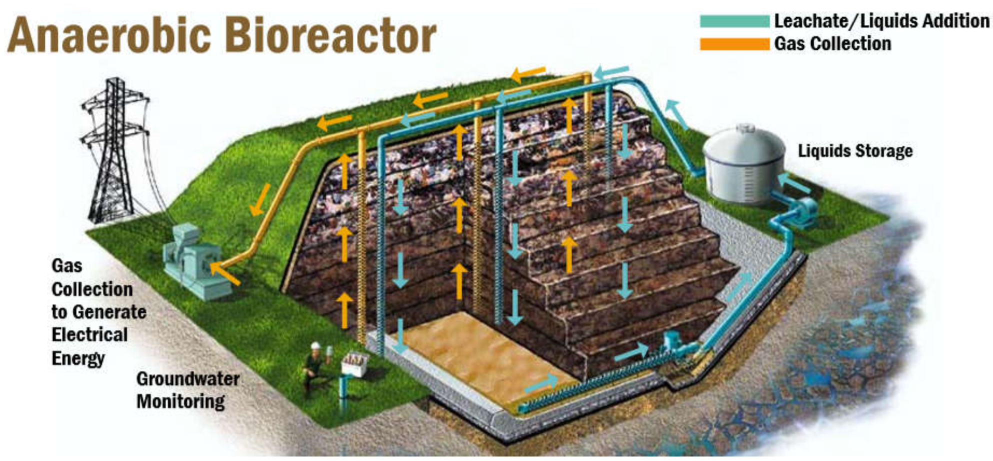
The intensification of biological processes in bioreactor landfills is achieved by ensuring the moisture content of waste is optimal, the leachate recirculation is appropriately managed and other non-toxic liquids are added (e.g. from food industry). The treatment and volume reduction of waste are the advantages of using the leachate recirculation back to the waste mass. Other very important elements are to ensure waste is shredded properly, its pH and temperature are adjusted, and that waste is conditioned. These elements may also have a significant effect on the optimalisation of biochemical processes. When choosing the right recirculation solution, not only the optimal amount of liquid has to be taken into account but also the minimalisation of the environmental impact (e.g. aerosol formation when the landfill surface is sprinkled) along with the compliance with regulations (Kwiatkowski and Żygadło, 2011: 103 – 116; Thampan and Chandel, 2013: 256 – 260).

3. Types of bioreactor landfills

Bioreactor landfills may be classified according to the primary process taking place in a given system, i.e.:

a) Anaerobic – in this type of landfill (Fig. 2) the optimalisation of habitats of anaerobic bacteria is implemented, which results in the acceleration of waste degradation. These microorganisms are responsible for the conversion of organic matter into organic acids, then into methane and carbon dioxide. It is very important to ensure the proper moisture content of the landfill as the processes take place in the absence of oxygen. The average moisture content level in the landfill is 10 to 20%, whereas the level required is 35 to 40%. The increase in moisture content is carried out by adding recirculated leachates, water or other not harmful liquids to the waste mass. The advantages of this type of landfill are the greenhouse effect reduction by minimising the emissions of gas and it can also be used for energy generation (Wartih, 2003: 61 – 70; WM Waste Management, 2004; Thampan and Chandel, 2013: 256 – 260; ITRC Interstate Technology & Regulatory Council, 2005: 1 – 73). Such bioreactor landfills are among the most popular in the modern solid waste management in the United States.

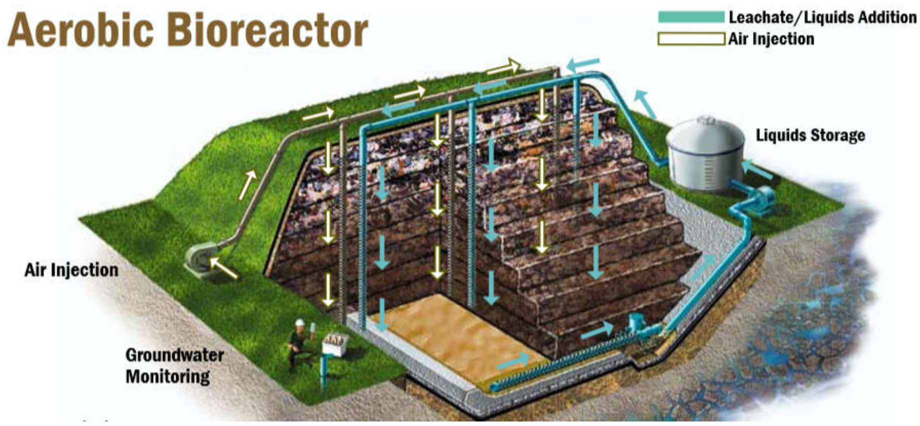
Figure 3. Anaerobic solid waste bioreactor landfill



Source: WM Waste Management 2004.

b) Aerobic – analogous to anaerobic bioreactor landfills, leachates are stored and then recirculated into the system along with other liquids in order to retain the appropriate level of moisture content (Fig. 4). Air is injected into the waste mass in order to ensure the optimal conditions for aerobic bacteria to grow. Air is injected using vertical or horizontal wells. This results in the acceleration of aerobic degradation of organic solid waste by these microorganisms. Aerobic bioreactor landfills do not produce landfill gas; therefore, there is no hazard that the gas is emitted into the atmosphere in an uncontrolled manner (Wartih, 2003: 61 – 70; WM Waste Management, 2004; Thampan and Chandel, 2013: 256 – 260; ITRC Interstate Technology & Regulatory Council, 2005: 1 – 73).

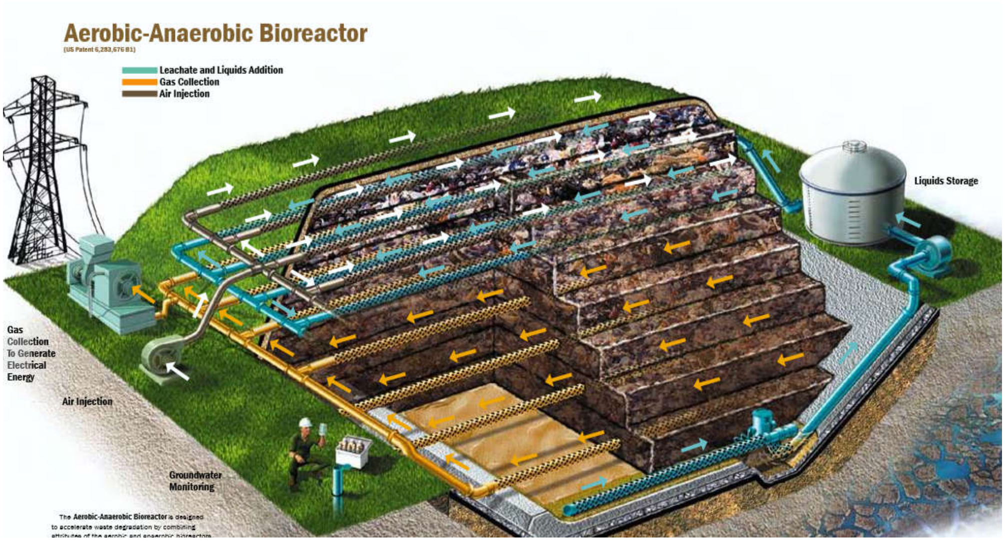
Figure 4. Aerobic solid waste bioreactor landfill



Source: WM Waste Management 2004.

c) Hybrid, also known as aerobic-anaerobic – are designed to accelerate waste degradation by combining both aerobic and anaerobic bioreactor features that use aerobic and anaerobic processes at the same time. The aim is to accelerate the degradation of organics by employing a sequential aerobic-anaerobic treatment (Fig. 5). Biodegradable compounds are degraded in the upper sections of the landfill and these sections are aerated, whereas landfill gas and leachates are stored and collected in the lower sections. Horizontal wells are installed in every section. They transport landfill gas, leachates, liquids and air (Wartih, 2003: 61 – 70; WM Waste Management, 2004; Thampan and Chandel, 2013: 256 – 260; ITRC Interstate Technology & Regulatory Council, 2005: 1 – 73).

Figure 5. Aerobic-anaerobic solid waste bioreactor landfill



Source: WM Waste Management 2004.

4. Sustainability principles – classical landfills vs. bioreactor landfills

In order to analyse landfill functionality in terms of sustainability principles, dry landfills and modern bioreactor landfills with enhanced leachate recirculation were compared. The analysis was carried out by the intensity assessment of the most important ecological impacts on the environment and by the functionality assessment of landfills in social terms. As far as the assessment of economic aspects is concerned, the focus was put on capital and operating costs of both technologies and the analysis of revenues was made. The costs and revenues were estimated by means of a three-point scale.

a) Environmental aspect analysis

In order to make the analysis of the environmental impacts, the assessment of both solutions has been carried out using an independent estimation method of their impact intensity. The impact intensity was measured on a scale of 0 to 3. Points corresponding to the intensity are as follows:

- 0 – no impact
- 1 – small impact
- 2 – medium impact

- 3 – high impact

Uncontrolled emissions of solid and liquid contaminants and odours were classified as the main environmental issues resulting from the use of such landfills.

Table 1 shows the list of classical landfill and bioreactor landfill impacts on the environment.

Table 1. The list of classical landfill and bioreactor landfill impacts on the environment

Type of impact	Dry landfill		Bioreactor landfill	
	Occurrence	Intensity	Occurrence	Intensity
Water consumption	Yes	1	Yes	2
Gas emission	Yes	1	No	0
Odour emission	Yes	2	Yes	1
Dust emission	Yes	1	No	0
Energy emission (noise)	Yes	1	Yes	1
Substance emission (leachates)	Yes	2	No	0
Total	-	8	-	4

Source: Author's own elaboration.

The maximum number of impact points is 18. The total number of impact points received by dry landfills is more than 44.4% of the maximum value, whereas for bioreactor landfills it is only a little bit more than 22.2% of the maximum value. On the basis of the results obtained, it is concluded that dry landfills will have twice as high impact on the environment as bioreactor landfills. Therefore, it is considered that bioreactor landfills will not have a significant impact on the environment. Moreover, monitoring and control systems and proper layers that seal the landfill site will contribute to further environmental protection against contamination.

Environmental aspects concerning the use of bioreactor landfills can also be considered positive. Bioreactor landfills, as opposed to dry landfills, offer a number of environmental benefits, such as:

- Quicker recovery of the area used – it is caused by the fact that waste is degraded and stabilised more quickly – 5 – 10 years. It may take hundreds of years for dry landfills to finish these processes, or they may not even finish.
- Less area is needed – in dry landfills leachates have to be collected and treated using proper facilities and, therefore, more area is needed, whereas in bioreactor landfills leachates are recirculated back to the system where they are treated.
- Intensification of biological processes – due to the fact that a high level of moisture content is maintained, the intensification, stabilisation, and reduction of landfill gas production process

take place.

- Reduction of volume and toxicity of leachates, which could contaminate water and soil.
- Reduction of the negative impact on the greenhouse effect due to landfill gas collection.

b) Social aspect analysis

Social aspects are closely connected to environmental aspects. Environmental impacts caused by both the investment and use of landfills may, to a considerable extent, affect the lives of local people. This subsection focuses on aspects connected with the use of such landfills. Table 2 shows the list of social aspects concerning dry landfills and bioreactor landfills.

Many of the social aspects presented below can be mitigated by placing landfills appropriately, e.g. far from residential areas, cultural facilities, or bodies of water.

The total number of impacts points for dry landfills is 14 points, which is more than 77.7% of the maximum value, whereas for bioreactor landfills the value is more than 22.2%. This means dry landfills may be viewed more unfavourably by the society.

Table 2. The list of social aspects concerning dry landfills and bioreactor landfills

Social aspect	**Dry landfill**		**Bioreactor landfill**	
	Occurrence	Intensity	Occurrence	Intensity
Reduction of landscape and esthetic values of an area	Yes	2	Yes	1
Use of a large area of land	Yes	2	Yes	1
No energy recovery	Yes	3	No	0
No possibility to recover an area quickly	Yes	3	No	0
Negative impact on the environment (contamination)	Yes	2	Yes	1
Negative impact on the society (odours)	Yes	2	Yes	1
Total	-	14	-	4

Source: Author's own elaboration.

Landfills with enhanced leachate recirculation will allow for the improvement of the waste management system and the development towards sustainability in all aspects; therefore, the society should view bioreactor landfills much more favourably.

c) Economic aspect analysis

It is very difficult to make an economic analysis in both cases, because it depends on many factors, i.e. the surface area of the landfill, its infrastructure, collection and transport systems implemented, waste segregation systems, location, volume and quality of waste received, and the waste management system in use. The problem with accessing bioreactor landfills in economic terms is caused by modern technology, which is used in a small number of places, mainly in the United States, on a large scale.

In order to make the analysis of capital and operating costs and revenues, the assessment of their amount has been carried out using an independent method. The costs and revenues were estimated by means of a three-point scale. Points corresponding to the amount of costs are as follows:

- 0 – zero
- 1 – small
- 2 – large

Table 3 shows the capital costs of dry landfills and bioreactor landfills.

Table 3. The list of capital costs of dry landfills and bioreactor landfills

Capital costs:	**Dry landfill**		**Bioreactor landfill**	
	Occurrence	Points	Occurrence	Points
Leachate collection tank	Yes	1	Yes	1
Leachate treatment system	Yes	1	No	0
Sealing of the landfill basin	Yes	2	Yes	2
Surface water drainage systems	Yes	1	Yes	1
Leachate, liquid distribution system	No	0	Yes	1
Leachate collection systems	Yes	1	Yes	1
Landfill gas collection systems	No	0	Yes	1
Monitoring systems	Yes	2	Yes	1
Biogas plant	No	0	Yes	2
Mechanical equipment	Yes	2	Yes	2
Total:	-	10	-	12

Source: Author's own elaboration.

The maximum number of points is 20. The total number of points received by dry landfills is more than 50% of the maximum value, whereas for bioreactor landfills it is more than 60% of the maximum value. The capital costs are high in both cases. Modern technologies require more money to build facilities and their equipment. Leachate and landfill gas collection systems are the most expensive, but the biogas plant and equipment costs are also high. However, all these capital costs will contribute to generating profit in the future.

Table 4 shows the operating costs of dry landfills and bioreactor landfills.

Table 4. The list of operating costs of dry landfills and bioreactor landfills

Operating costs:	**Dry landfills**		**Bioreactor landfills**	
	Occurrence	Points	Occurrence	Points
Location costs (taxes)	Yes	2	Yes	1
Employment costs	Yes	1	Yes	1
Fuel costs	Yes	2	Yes	2
Electricity costs	Yes	2	No	0
Heat costs	Yes	1	No	0
Depreciation of the equipment used	Yes	2	Yes	2
Water consumption costs	Yes	1	Yes	1
Total	-	11	-	7

Source: Author's own elaboration.

The total number of points received by dry landfills is 11, which is 78.5% of the maximum value. For bioreactor landfills, however, the total number of points received is lower, i.e. 5% of the maximum value. The defect-free operation of modern bioreactor landfills requires much less money than the operation of dry landfills. The major advantage of landfills with enhanced leachate recirculation is the possibility of meeting their electricity and heat demands on their own due to the production and collection of landfill gas, which can be processed into the given energy carriers in cogeneration units.

Table 5 shows the revenues of dry landfills and bioreactor landfills. In this test, the highest result will be the most beneficial. The total number of points received by bioreactor landfills is 7, which is 90% of the maximum value, whereas for dry landfills the total number is significantly smaller, i.e. only 12.5% of the maximum value. On the basis of the results obtained, it is confirmed that despite initially higher capital costs the use of the newer technology can generate significantly higher revenues.

Table 5. The list of revenues of dry landfills and bioreactor landfills

Revenues:	**Dry landfill**		**Bioreactor landfill**	
	Occurrence	Points	Occurrence	Points
Landfill gas production	No	0	Yes	2
Electricity sales	No	0	Yes	2
Green certificate sales	No	0	Yes	2
Secondary material sales	Yes	1	Yes	1
Total	-	1	-	7

Source: Author's own elaboration.

In conclusion, the most important advantages proving the superiority of landfills with enhanced leachate recirculation over other landfills in connection with sustainability can be specified as follows:

Ecological aspects:

- Acceleration of waste degradation, which will allow for the storage of more portions of waste.
- Quicker area recovery with the possibility to use the same area again.
- Reduction of the greenhouse effect by the use of landfill gas for energy generation – renewable energy development.
- Storage and treatment of leachates on site.
- Environmentally friendly technology, the use of modern monitoring systems.

Social aspects:

- Reduction of the demand for landfill site areas, the possibility to use a few landfill sites cyclically in which the waste degradation process is in different degradation phases. The degradation process of the oldest landfill site finishes after 10 years; therefore, the stabilised waste can be dug out and sold as compost. Afterwards another portion of waste can be stored in the landfill site. This process should be repeated for different landfill sites.
- Significant reduction of the negative impact on the environment by the self-treatment of leachates and the use of landfill gas.
- Generation of heat and electricity from renewable sources – landfill gas.

Economic aspects:

- Production of higher-quality landfill gas.
- Sales of electricity and green certificates.

- Reduction of costs related to the demand for electricity and heat.
- Elimination of costs of leachate treatment off site.
- Stabilised waste can be used as compost and then sold.

5. Conclusions

Nowadays the waste management system has to comply with sustainability principles not only in terms of the use and processing of waste but also in terms of its storage. Sustainable waste management relies on the integration of and balance between its primary environmental, economic, and social aspects.

The concept of bioreactor landfills, i.e. landfills with enhanced leachate recirculation, is currently used in the United States only, but the technology, due to its numerous advantages, stands a chance to become applied widely. The implementation of this solution will be beneficial not only in environmental and social terms but also in financial terms. Due to the comparison and analysis performed, a number of advantages was presented that prove the superiority of modern waste management technologies over classical ones. The development of landfills with enhanced leachate recirculation shows a major concern for the environment, which has a positive impact on public opinion. Additional advantages, very important in ensuring balanced development, are economic aspects resulting from the production of electricity from landfill gas and the possibility to obtain green certificates by generating energy from a renewable source. Despite higher capital costs of bioreactor landfills in comparison to dry landfills, the former will generate revenues over time.

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Bioreaktor – innowacyjne składowisko odpadów stałych

Streszczenie

Artykuł przedstawia innowacyjną metodę racjonalnego gospodarowania odpadami stałymi, a mianowicie przykład nowoczesnego składowiska odpadów z ulepszoną recyrkulacją odcieków - bioreaktora. Celem pracy jest porównanie nowoczesnych rozwiązań dotyczących składowania odpadów z metodami klasycznymi w aspektach zrównoważonego rozwoju. Porównania dokonano w wyniku przeprowadzenia przeglądu literaturowego oraz autorskiej analizy zebranych danych. Nakreślono szereg zalet wynikających z stosowania technologii z ulepszoną recyrkulacją odcieków w aspektach środowiskowych, społecznych oraz ekonomicznych. W wyniku przeprowadzonych analiz stwierdzono jednoznacznie wyższość nowoczesnych technologii gospodarowania odpadami nad technologiami klasycznymi.

***Słowa kluczowe**:* odpady stałe, składowiska odpadów, bioreaktor.