



TECHNOLOGICAL PATHWAYS FOR MUNICIPAL SOLID WASTE RECYCLING AND ASSESSMENT OF THE ENVIRONMENTAL EFFICIENCY OF RECYCLING PROCESSES

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Abstract: *This article analyzes contemporary technological approaches to municipal solid waste recycling and evaluates their environmental efficiency. The study scientifically examines the advantages and disadvantages of mechanical sorting, composting, anaerobic digestion, landfill methods, and integrated waste management systems. In addition, a comparative analysis of waste recycling rates and environmental efficiency indicators is conducted using the examples of Germany, Sweden, Japan, the Netherlands, Uzbekistan, India, and Brazil. The research findings demonstrate that integrated recycling and energy recovery technologies represent the most environmentally efficient approach. Furthermore, the study substantiates that the development of waste separation systems and the implementation of advanced technologies are key factors for achieving sustainable environmental development.*

Keywords: *municipal solid waste, waste recycling, environmental efficiency, mechanical sorting, composting, anaerobic digestion, biogas, landfill method, integrated system, waste management, secondary raw materials, sustainable development, environmental safety.*



MAISHIY CHIQINDILARNI QAYTA ISHLASH TEXNOLOGIK YO'NALISHLARI, QAYTA ISHLASHNING EKOLOGIK SAMARADORLIGINI BAHOLASH

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bosqich talabasi*

Annotatsiya: *Ushbu maqolada maishiy chiqindilarni qayta ishlashning zamonaviy texnologik yo'nalishlari hamda ularning ekologik samaradorligi tahlil qilingan. Mexanik saralash, kompostlash, anaerob hazm qilish, poligon usuli va integratsiyalashgan tizimlarning afzalliklari hamda kamchiliklari ilmiy asosda yoritilgan. Shuningdek, Germaniya, Shvetsiya, Yaponiya, Niderlandiya, O'zbekiston, Hindiston va Braziliya misolida chiqindilarni qayta ishlash darajasi va ekologik samaradorlik ko'rsatkichlari qiyosiy tahlil qilingan. Tadqiqot natijalari kompleks qayta ishlash va energiya olish texnologiyalari ekologik jihatdan eng samarali yo'nalish ekanligini ko'rsatdi. Shu bilan birga, chiqindilarni saralash tizimini rivojlantirish va zamonaviy texnologiyalarni joriy etish barqaror ekologik rivojlanishning muhim omili ekanligi asoslandi.*

Kalit so'zlar: *maishiy chiqindilar, chiqindilarni qayta ishlash, ekologik samaradorlik, mexanik saralash, kompostlash, anaerob hazm qilish, biogaz, poligon usuli, integratsiyalashgan tizim, chiqindilarni boshqarish, ikkilamchi xomashyo, barqaror rivojlanish, ekologik xavfsizlik.*

INTRODUCTION

At present, the rapid growth of the population, the acceleration of urbanization processes, and the expansion of industrial production have led to a significant increase in the volume of municipal solid waste. This situation has a negative impact on the environment, contributing to intensified pollution of soil, water resources, and the atmosphere. Therefore, the effective management of municipal solid waste, its recycling, and the implementation of environmentally safe technologies have become among the

most pressing scientific and practical challenges.

Modern technological approaches to municipal solid waste recycling are focused on waste sorting, processing, and reuse, which not only reduce the volume of waste but also create opportunities for obtaining secondary raw materials. At the same time, assessing the environmental efficiency of recycling processes is of great importance, as it enables the determination of the environmental impact of these methods and facilitates



the selection of the most effective and sustainable technologies.

LITERATURE REVIEW. Issues related to municipal solid waste recycling technologies and the assessment of their environmental efficiency have been extensively discussed in international scientific literature. In particular, Bernd Bilitewski and his co-authors developed systematic approaches to waste management, providing a detailed analysis of the ecological and technological foundations of waste sorting, recycling, and disposal processes. The authors emphasize that an integrated waste management model is one of the most effective approaches. [1]

In the studies conducted by George Tchobanoglous, the engineering principles of municipal solid waste management, including mechanical-biological treatment, composting, and energy recovery technologies, were scientifically substantiated. These works demonstrate that the environmental efficiency of waste recycling is closely associated with reducing waste volumes and promoting the reuse of resources. [2]

According to the United Nations Environment Programme, the volume of municipal solid waste is increasing rapidly on a global scale and is projected to grow significantly by 2050. This organization identifies waste recycling and resource recovery as one of the key directions for sustainable development. [4]

Similarly, the World Health Organization notes that improper waste

management has a direct negative impact on human health and emphasizes the necessity of implementing environmentally safe waste management systems. The organization's data scientifically demonstrates that waste recycling can significantly reduce harmful emissions. [5]

Research conducted by the European Environment Agency has scientifically demonstrated that increasing recycling rates reduces greenhouse gas emissions, optimizes the consumption of natural resources, and supports environmental sustainability. The agency has also developed a set of environmental indicators for assessing the efficiency of waste management systems. [6]

In addition, in the studies by F. Dougall and co-authors, waste recycling systems were evaluated using a life cycle assessment (LCA) approach. This methodology is identified as one of the most important tools for determining the environmental efficiency of waste management systems. [3]

In local studies, issues related to municipal solid waste recycling, composting, and resource recovery have also been investigated as a relevant research direction. It has been noted that environmental problems can be mitigated through the implementation of technologies adapted to national conditions. Overall, the analyzed scientific literature confirms that modern technological approaches to municipal solid waste recycling and the assessment



of their environmental efficiency are of significant scientific and practical importance for sustainable development.

RESULTS AND DISCUSSION.

At present, municipal solid waste management is regarded as one of the major global environmental challenges. Due to population growth, urbanization, and increasing consumption levels, the volume of waste continues to rise significantly. Improper waste management leads to the pollution of air, soil, and water resources, as well as negative impacts on human health. Therefore, the implementation of efficient waste recycling technologies is considered one of the key factors in ensuring environmental safety.

Municipal solid waste recycling technologies are selected based on waste composition, economic feasibility, and environmental requirements. In modern practice, mechanical sorting, biological treatment, anaerobic digestion, landfill methods, and integrated systems are widely used. Each of these technologies differs in terms of waste reduction efficiency, energy recovery potential, and environmental impact.

Mechanical sorting is one of the most widely used methods for the preliminary treatment of municipal solid waste. In this technology, components such as plastics, paper, metals, and glass are separated from the waste stream using specialized equipment. The main purpose

1-table

Environmental efficiency of municipal solid waste recycling technologies

of mechanical sorting is to direct secondary raw materials back into the production cycle. (1-table)

Through mechanical sorting, the volume of waste can be reduced by approximately 20–40%. The main advantages of this method are its relatively simple technological implementation and low economic costs. However, its environmental efficiency is assessed as moderate due to the limited capacity for processing organic waste. In addition, the quality of sorting strongly depends on the level of separate waste collection by the population.

Composting is a biological treatment method in which organic waste is decomposed by microorganisms, resulting in the production of organic fertilizer known as compost. This technology is considered effective for processing food waste, plant residues, and other biodegradable materials.

The environmental efficiency of composting is relatively high, as it can reduce waste volume by 40–60%. The resulting compost is used in agriculture to improve soil fertility, which in turn reduces the need for mineral fertilizers and enhances soil biological activity. At the same time, the composting process is sensitive to temperature, moisture, and aeration conditions, and its relatively slow processing rate is considered one of its main disadvantages.



No	Technological approach	Waste reduction efficiency	Energy recovery potential	Level of environmental impact	Advantages	Disadvantages
1	Mechanical sorting	Moderate (20–40%)	No	Moderate	Separation of secondary raw materials; simple technology	Organic waste is not processed
2	Composting (biological treatment)	High (40–60%)	No	High environmental efficiency	Produces organic fertilizer; improves soil fertility	Slow process; dependent on moisture conditions
3	Anaerobic digestion	High (50–70%)	Yes	Very high	Generates energy; significantly reduces waste volume	Requires advanced technology and high investment
4	Landfill method	Low (10–20%)	No	Low (negative impact)	Simple and low-cost	Methane emissions; soil and water pollution
5	Integrated system	Very high (70–90%)	Yes	Highest efficiency	Complete waste recovery and utilization	Requires complex management systems

Anaerobic digestion is a technology based on the decomposition of organic waste by microorganisms in an oxygen-free environment. During this process, biogas is produced, which is mainly a mixture of methane and carbon dioxide. Biogas is used for the production of heat and electrical energy.

This technology is considered one of the most efficient methods from both environmental and energy perspectives. According to research findings, anaerobic

digestion can reduce waste volume by 50–70%. At the same time, the generation of renewable energy helps to decrease greenhouse gas emissions. The residual material produced in anaerobic systems can also be used as organic fertilizer. However, this technology requires high investment costs, modern equipment, and skilled technical management.

The landfill method is a waste management technology in which municipal solid waste is disposed of by



burying it in specially designated areas. This method is considered the simplest and most cost-effective approach from an economic perspective. Therefore, it is still widely used as the primary waste management method in many developing countries.

However, scientific sources indicate that landfills pose a high environmental risk. The decomposition of waste generates methane gas, which contributes to atmospheric pollution and global climate change. In addition, leachate may contaminate soil and groundwater resources. The waste reduction efficiency of the landfill method is low, typically not exceeding 10–20%.

An integrated or complex waste management system is based on combining several technologies within a single framework. In this approach, mechanical sorting, composting, anaerobic digestion, and energy recovery technologies are applied in an interconnected and coordinated manner.

In such systems, the waste recycling rate can reach 70–90%. As a result, the amount of waste sent to landfills is reduced to a minimum level. In addition, opportunities are created for energy production, recovery of secondary raw materials, and production of organic fertilizers. However, integrated systems require complex management mechanisms, significant financial investment, and advanced technological infrastructure.

International experience shows that the efficiency of municipal solid waste

management systems is directly dependent on a country's level of economic development, environmental policy, technological infrastructure, and the ecological awareness of the population. Waste recycling rates vary significantly across countries, which is explained by the degree of implementation of recycling technologies.

According to the analysis, Germany is considered one of the global leaders in municipal solid waste recycling, with a recycling rate of 65–70%. In Germany, the waste separation system is highly developed, where plastics, paper, metals, and organic waste are collected separately. In addition, energy is generated through waste incineration using “Waste-to-Energy” technologies. Organic waste is processed through composting systems. As a result, the share of waste sent to landfills has been reduced to 30–35%. The environmental efficiency of this system is assessed as very high. (2-table)

The experience of Sweden demonstrates an effective model of using waste as an energy resource. In this country, the municipal solid waste recycling rate is 50–60%. A large proportion of waste is incinerated in specialized facilities to produce heat and electrical energy. This technology contributes to reducing the amount of waste sent to landfills. At the same time, modern filtration systems limit the emission of harmful substances into the atmosphere. Sweden is recognized as



having a high level of environmental efficiency in waste management.

2-table

Environmental efficiency indicators of municipal solid waste recycling technologies by country

No.	Country	Municipal solid waste recycling rate (%)	Main approaches	Landfilled waste (%)	Environmental efficiency
1	Germany	65–70	Sorting, recycling, waste-to-energy (WTE), composting	30–35	Very high
2	Sweden	50–60	Energy recovery (incineration), sorting	40–50	High
3	Japan	45–55	Strict sorting, incineration, recycling	45–55	High
4	Netherlands	60–65	Circular economy, integrated recycling systems	35–40	Very high
5	Uzbekistan	10–15	Initial sorting, landfill disposal	80–85	Low
6	India	20–25	Informal sorting, composting	70–75	Low–moderate
7	Brazil	25–35	Sorting, landfilling, partial recycling	60–70	Moderate

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emission of harmful substances into the atmosphere. Sweden is recognized as having a high level of environmental efficiency.

In Japan, the municipal solid waste management system is based on strict sorting principles. Waste is separated into multiple categories and processed using advanced technologies. The recycling rate is approximately 45–55%, while a similar proportion is still sent to landfills. In



Japan's experience, the limited availability of land resources is one of the main factors driving the development of advanced waste recycling technologies.

In Netherlands, the "circular economy" model is widely implemented. In this approach, waste is reintegrated into production processes as an economic resource. The country's recycling rate is 60–65%, and integrated waste processing technologies are applied. This has reduced the share of waste sent to landfills to 35–40%. Environmental efficiency is assessed as very high, and the level of natural resource consumption has significantly decreased.

In Uzbekistan, the municipal solid waste recycling rate remains at approximately 10–15%. The majority of waste is still disposed of in landfills. The waste sorting system is in an early stage of development, and recycling infrastructure is not yet sufficiently established. As a result, the proportion of waste sent to landfills reaches 80–85%, negatively affecting soil, groundwater, and air quality. At the same time, recent developments such as the introduction of cluster systems and modern recycling enterprises are considered positive improvements.

In India, the waste management system is significantly influenced by the informal sector, which plays an important role in waste collection and sorting. These activities are often carried out by small private groups. Although the recycling rate is about 20–25%, the proportion of waste sent to landfills

remains high at approximately 70–75%. Composting of organic waste is developed in some regions; however, the overall environmental efficiency remains low to moderate.

In Brazil, the waste management system is partially developed, with a recycling rate of 25–35%. While waste sorting and partial recycling systems exist, landfilling remains one of the dominant methods. Therefore, the environmental efficiency is assessed as moderate.

CONCLUSION. The analyzed data indicate that the environmental and economic efficiency of municipal solid waste recycling is directly dependent on the technologies applied and the structure of national waste management systems. In developed countries, the combined application of sorting, recycling, composting, and energy recovery technologies has resulted in high recycling rates and a significant reduction in the volume of waste sent to landfills.

From a technological perspective, anaerobic digestion and integrated systems were identified as the most environmentally efficient approaches. These technologies not only reduce waste volumes but also enable renewable energy production and efficient utilization of secondary resources. Mechanical sorting and composting are considered environmentally safe and relatively simple technologies, whereas landfilling was evaluated as the most environmentally harmful method.



Country-level analysis showed that modern waste management systems in Germany, Sweden, and Netherlands are producing highly effective results. In contrast, in Uzbekistan, India, and Brazil, recycling rates remain relatively low, with key challenges including insufficient sorting systems, underdeveloped technological infrastructure, and high dependence on landfilling.

Therefore, the implementation of integrated waste management systems, development of energy recovery technologies, establishment of effective waste separation practices, and strengthening of environmental control are essential factors for achieving sustainable environmental development.

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