



Overview of promising research in the field of solid waste recycling for further use as solid fuel materials

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Abstract. The relevance of the stated topic of this research is the global increase in environmental problems, including resource depletion and pollution, which has led to an urgent need to develop solutions for sustainable waste management. This study is concerned with municipal solid waste processing, with a particular focus on the conversion of waste into solid fuel materials. A comparative analysis of the literature for the period up to 2024 was carried out to identify the most efficient waste-to-energy technologies. The findings highlight two key societal issues: environmental degradation due to inadequate waste management practices and resource scarcity caused by urbanisation and industrialisation. Among the notable results is the identification of waste incineration and pyrolysis as promising technologies for energy recovery, landfill reduction and environmental mitigation. In particular, it was shown that pyrolysis produces more energy and emissions than traditional incineration. In addition, the analysis showed the potential of waste-to-energy and microbial fuel cells as innovative approaches to sustainable energy production from waste. These technologies can provide additional sources of energy for domestic and industrial needs, while reducing the environmental impact of waste disposal. The practical value of this research lies in its potential to develop advanced technologies for processing municipal solid waste for energy, which can improve resource efficiency and energy sustainability

Keywords: energetic resources; waste sorting; global warming; industrial processing

Introduction

Any waste is an inevitable product, the amount of which is rapidly increasing due to population growth. This in turn pushes for an increase in demand for waste disposal. There are various kinds of waste in the world, for example, non-hazardous waste that occurs in everyday life – plastic, paper, food, etc., which are generally called municipal solid waste (MSW). The MSW content usually consists of a diverse mixture of materials, but, however, the main share is organic content. Until 2024, the most widely used methods of solid waste recycling were landfill disposal and incineration, which seem to have reached maximum occupancy. Such waste disposal

options have a detrimental effect on the environment, i.e., to environmental and social problems, for example, to soil and sea pollution, and this leads to a deterioration in water quality, the spread of pests and various diseases and viruses, the emergence and spread of unpleasant odours, etc. The reason for this is the release of substances that include polychlorinated dibenzo-p-dioxins and dibenzofurans, including methane. S. Khan *et al.* (2022) noted that all these pests belong to persistent organic pollutants (POPs) – toxins that have a harmful effect on human health and the environment, and can also be sources of greenhouse gases. It should

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also be borne in mind that when burning household waste, incomplete combustion of hydrocarbon fuel occurs, in which soot particles are released. In turn, they negatively affect the environment, because they are carriers of toxic substances. J. He *et al.* (2022) conducted a study of the morphology of soot particles that are formed during the combustion of solid household waste, namely paper, kitchen waste, plastic and textiles. The results of the study showed a significant influence of the composition of waste on the physical properties of soot particles. This kind of work can provide valuable information for modelling carbon black nanostructures and heat transfer in the furnace. In particular, the study did not present a comprehensive account of the long-term stability and degradation behaviour of carbon black nanostructures under varying thermal conditions. Moreover, the interaction mechanisms between soot particles and diverse furnace materials, which may markedly influence heat transfer efficiency, remain insufficiently explored.

There are other traditional methods of municipal solid waste disposal – these include recycling, reuse, incineration without energy generation, gas production as a result of pyrolysis and industrial incineration with the use of released energy. However, the heterogeneity of the composition of waste to some extent may limit the use of traditional approaches. K. Lin *et al.* (2022) noted that incineration, pyrolysis, gasification, anaerobic digestion and landfill disposal are fraught with a potential risk of explosion during operation. The household also has a significant impact, since it is one of the largest sources of solid waste in the world. In the course of the H. Alhassan *et al.* (2020) study, the factors determining the characteristics of households for waste separation and disposal options were studied. It was identified that the most and least separable solid waste are bags and food waste, respectively. In addition, the most significant factor motivating and hindering the activity of households to separate sources is the financial incentive. H. Alhassan *et al.* (2020) also found that the government should develop and implement a waste minimisation policy and it is necessary to provide and make waste separation facilities accessible and convenient, since this can contribute to waste separation behaviour.

The introduction of innovative waste-to-energy conversion technologies can help in the management of solid waste while maintaining a relatively stable level of energy scarcity. The study by S.K. Awasthi *et al.* (2022) proved that the number of patents in the field of solid waste processing continues to grow rapidly, which stimulates the use of methods to combat solid waste pollution. Energy extraction as a result of waste disposal is the most preferable and profitable, because this will reduce the amount of waste, and reduce the production of thermal energy. Much attention of S.K. Awasthi *et al.* (2022) has been devoted to the

issue of a more profitable technology for processing solid waste with the conversion of solid fuel materials, which solves most of the problems associated with the environment. In this regard, the purpose of this work is to analyse the latest and current research with an overview of effective methods of processing municipal solid waste for further use as solid fuel materials.

M. El Alouani *et al.* (2024) investigated the potential of utilizing bulk solid waste in the creation of flame retardant materials. This approach offers an alternative avenue for the utilization of solid waste beyond its conventional use in fuel production. Such materials can be integrated into industrial processes, thereby reducing the necessity for the utilization of primary resources while simultaneously enhancing the sustainability of the process. Similarly, A. Machín *et al.* (2024) demonstrated the potential of solid waste in improving the hydromechanical behaviours of soils, thereby contributing to more stable construction practices and offering another avenue for waste utilisation in infrastructure development. Furthermore, Y. Xiong *et al.* (2024) investigated the recycling of hazardous lithium-ion batteries, demonstrating the potential to transform these materials into catalytic substances with high added value. This work emphasises the necessity for recycling technologies that address both environmental concerns and resource recovery, particularly in the context of hazardous materials.

The objective of this research was to investigate innovative approaches to municipal solid waste management, with a particular focus on the conversion of waste into solid fuel materials. This approach has the potential to address both environmental and energy concerns.

Materials and Methods

The basis of the methodological approach in this scientific study is a combination of the method of comparative analysis of the results of available literary sources in the field of assessing current achievements in the field to processing municipal solid waste, with an analytical study of the best options for their disposal. In addition, when conducting this scientific study, the conditional division of municipal solid waste into four key categories was taken into account, with the addition of two auxiliary categories – production waste, which is formed exclusively as a by-product during the production of the main product, as well as consumer waste, which is unusable for use in everyday life.

The work also considers solid fuel materials obtained by processing solid waste were studied. One of these most common materials is considered to be Resource Description Framework (RDF). In turn, RDF is classified in accordance with the standards established to accelerate the sale of this fuel for energy use and increase its calorific value (Chavando *et al.*, 2022). Among the key standards that were considered in this study are:

▼ ASTM International Standard No. E856-83(2004) (1998): RDF is officially defined by the American Society for Testing and Materials (ASTM) through the ASTM E-38-01 Committee on Resource, Energy Recovery. This standard is used and applied mainly in the incineration industry;

▼ UNI 9903-1:2004 (2004) is a European standard used mainly in Italy for the incineration and cement industries. This standard also establishes the physical and chemical characteristics of solid fuel obtained from waste (conventionally called RDF), including general requirements for its storage, processing and transportation.

The practical application of the method of comparative analysis of the results of the study of modern achievements in the field of solid waste processing made it possible to assess the real need to develop measures to introduce rules and prepare laws on solid waste processing. This subsequently makes it possible to create an integral structure for ensuring the proper level of environmental cleanliness, which has been introduced to 2024 in a number of large cities around the world, as well as to create the proper conditions for the separation and processing of solid household and other waste.

An analytical study of the best available options for the processing and disposal of municipal solid waste made it possible to give a comprehensive assessment of the traditional methods, such as incineration, burial, composting and anaerobic digestion, as well as non-traditional ones, among which pyrolysis, gasification, plasma gasification, hydrothermal carbonization should be noted and torrefaction. This made it possible to evaluate the effectiveness of the currently used technologies for the processing of municipal solid waste and to make a choice of the most preferable of them in various time perspectives.

Results and Discussion

Solid household waste is mainly classified into 4 categories – residual, recyclable, food, and hazardous. However, waste can be divided into two large groups: the first includes production waste, which is formed as a by-product during the development of the final product, and the second – consumer waste, products that are not suitable for use in everyday life and agriculture. Waste also belongs to the hazard classes: extremely dangerous; highly dangerous; moderately dangerous; low-risk; practically harmless. To understand the correctness of the ratio of waste products, a detailed classification is listed below, considering the most common with examples and MSW compositions:

▼ organic products – food and plant residues (leftovers and scraps from fruits, scraps, bones, leaves, manure, grass, etc.);

▼ plastic – plastic materials (wrapping films, plastic bags and bottles, polyethylene, hoses, packaging materials from hygiene products, including cosmetic and decorative, disposable tableware);

▼ glass – glass materials and products (bottles, dishes, light bulbs, mirrors, ceramic and porcelain materials, and products where organic impurities such as sand and clay are present);

▼ cardboard napkins, office paper, all paper products, newspapers, boxed products.

It is also necessary to attach importance to the influence of the time of year, the financial situation of the country on the quantity, composition and nature of solid waste. A proper understanding of the composition, classification and quantity of waste contributes to proper management practices and gives an approximate idea and understanding of how much energy can be extracted from solid household waste.

Solid particles contained in food, beverages and air carry heavy metal pollutants into the human body. These pollutants can enter the body in three ways: by swallowing the product, inhaling the smell or by skin contact. The amount of a contaminant inside the body can be toxic to humans, and the consequences may not appear immediately, but with the accumulation of such substances. It is also worth paying attention to the problem of handling solid waste from the standpoint of mechanical safety, because the risks of skin damage are also high, for example, fragments from glass products can provoke bruises/wounds, etc. The working class, which is engaged in solid waste processing, has the greatest probability of encountering such dangerous cases.

To eliminate and pre-mitigate the increasing environmental pressure, countries need to develop policies and introduce rules and laws on the issue of solid waste recycling. A small method that is already used in almost all developed countries can be cited – waste sorting. With the introduction of a separate garbage sector for waste in cities, the collection, transportation and processing of garbage is reduced, which leads to mitigation of climate change. It should also be borne in mind that the separation of waste should be at the home, household level. It is necessary to educate people about the proper sorting of garbage – to separate paper from glass, and to fold plastic separately. Thus, it is necessary to modernise the waste sorting system. According to D.G. de arros Franco *et al.* (2022), an effective waste management system is proposed that has a beneficial effect on society, while simultaneously attracting economic, environmental and medical benefits. This study has shown the possibility of improving public and private waste disposal systems at the regional level. That is, the elementary separation of waste into inert ones can have the most favourable and beneficial effect on the environment. In combination with waste-to-energy conversion technologies, this provides numerous benefits, such as energy production, recycling of materials for secondary use and reduction of landfills and landfills. After all, it is worth giving the main importance to the fact that a number of materials, turning into solid

household waste, can store energy in chemical bonds, when they break, a huge amount of energy is released.

Given that waste management is a societal issue, it is imperative that the general public is made aware of the issues surrounding waste and that those responsible for implementing recycling programmes are adequately trained. J. Sun *et al.* (2023) demonstrated that the promotion of waste sorting, recycling and the utilisation of innovative technologies, such as microbial fuel cells and refuse-derived fuel, may be impeded in the absence of comprehensive public education and the provision of training for relevant personnel. Moreover, the accessibility and comprehension of waste management practices at all levels of society directly influence the extent of participation and the overall efficacy of recycling initiatives. It is therefore evident that government intervention in the form of educational campaigns and the integration of informal waste collectors into formal waste management systems is necessary. These measures will facilitate the acquisition of knowledge and the allocation of resources, thereby overcoming the current impediments to the development of comprehensive waste recycling systems.

The incineration method is the most economical and reliable. As a result of municipal solid waste incineration, two main products are formed – fly ash and bottom ash. The fly ash is collected after the filtration process and carefully sealed to avoid contamination of the local surroundings, which are then moved to completely closed “hazardous landfills” that do not allow leaching into the environment. Bottom ash is the main by-product, accounting for almost 80% of the total volume of ash produced. It also consists of inert, non-combustible materials and metals. A.M. Matos & J. Sousa-Coutinho (2022) investigated the possibility of using shredded bottom ash from municipal solid waste incineration as an additional cementitious material for concrete mixtures. The results showed a good potential for use in the construction sector, but the adverse effects of the presence of metallic aluminium were also noticed. C. Zhao *et al.* (2022) demonstrated the features of chlorine and metal ions during the heat treatment of fly ash, which demonstrate a significant effect on the harmlessness and resource of fly ash. The results showed that it is possible to remove chlorides and heavy metals at a firing temperature above 750°C. According to C. Li *et al.* (2022), an analysis of previously undetected organic pollutants formed and released during municipal solid waste incineration was carried out. The authors identified their identity, and carried out a toxicity assessment and provided recommendations for a detailed study conditioned upon their highly dangerous toxicity. Pollutants were found in both flue gas and fly ash from various types of incineration activities. Conditioned upon the pandemic caused by COVID-19, clinical waste has increased dramatically. They were disposed of mainly by co-incineration with

solid waste, which causes an increase in the main elements and non-volatile heavy metals in polluted air. D.-Y. Lan *et al.* (2022) showed that with such combustion, the content of alkali metals and HCl in the flue gas increases, which contributes to the potential corrosion of the boiler. Thus, the incineration method is a good choice only by reducing the volume of waste, which can reach up to more than half, but there are also negative sides – air pollution, bottom and fly ash.

The burial method is quite old and cheap; however, it occupies a large area of the land resource and can cause secondary contamination of soil and groundwater. Therefore, this technology has been mostly neglected. Basically, there are 3 main alternatives:

- ▼ direct disposal of unprocessed waste in a landfill;
- ▼ recycling of waste before final disposal;
- ▼ recycling of waste to extract resources (materials and/or energy, followed by the disposal of residues).

Direct transportation (the first option) to a landfill is usually the cheapest disposal option. However, every day the places on landfills are decreasing, which leads to a significant increase in the cost in settlements. The second option serves to reduce the amount of waste. The third option involves processes that recover energy or materials from solid waste, which eventually gives only their residues. All of this energy and/or material extraction systems involve significant capital and operational costs. However, the sale of both energy and materials reduces the net cost of restoration. Such methods allow conserving resources, and waste residues require much less space to be placed on the ground than unprocessed waste (Daskalopoulos *et al.*, 1997). In an open environment, various biochemical reactions naturally occur from waste, which leads to the development of landfill gas. Such gas can be used for energy purposes; however, such a process is time-consuming. P. Sharma & S. Kumar (2021) found various organic compounds that remain stable and unchanged in the medium even after a long stay. The work proves that various organic polymers, metals and other related pollutants pose a danger to the environment. Thus, the main advantage of choosing a method of solid waste disposal is the simplicity and cheapness of the technology itself, but the main disadvantage is that the territory on Earth is limited, and land pollution can reduce it altogether.

There is also a common method of thermal decomposition of waste (pyrolysis), in the complete absence of air and creating products in three states, such as solid carbon residues, bio-oils and non-condensing gases. The output products differ in composition due to the type, shape of the reactor, etc. Basically, the pyrolysis process allows getting more energy compared to the method of solid waste incineration. This is explained by the substances formed in an inert atmosphere – nitrogen oxide (NO_x) and sulphur oxide (SO_x) (Shah *et al.*, 2021). The decomposition temperature is usually

in the range of 300 to 850°C. Basically, this method of processing is used conditioned upon high efficiency in the production of biofuels. There are also varieties of pyrolysis – conventional, fast and flash pyrolysis. Advantageous combinations with pyrolysis are also offered, for example, the use of solar energy. In this case, the reactor receives heat from the sun, but for 2024 there is little research in this area (Mukherjee *et al.*, 2021). Thus, pyrolysis technology is good because it is possible to produce raw materials, but, however, the cost of such a procedure is high.

Solid household waste can be quite suitable sources of energy. Studies show that MSW contains about 20.72% of organic waste, 37.86% of combustible materials, 20.95% of commercial materials and 20.46% of various waste (Gurunathan & Sahadevan, 2022). As a result, it can be concluded that they can be a substitute for coal. A number of studies have been devoted to a new recycling technology – microbial fuel cell (MFC). This method is environmentally friendly for generating electricity from liquid waste due to bacteria and oxygen. Through the process of anaerobic digestion, wastewater is treated, which reduces the number of pathogenic microorganisms and also allows the conversion of biogas into electricity. Thus, the provided MFC technology is known for the production of energy from waste, without the use of any external or additional energy, however, MFC appears as a technology for the production of ethanol, hydrogen, biogas, enzymes and bioremediation of wastewater. Therefore, MFC has the potential to work in various fields and in various applications (Vyas *et al.*, 2022). Thus, this new method is environmentally beneficial, it is expected to contribute zero to greenhouse gas emissions during production from waste, and also an important advantage is that with this technology no unpleasant odours come from, but on the contrary it is eliminated.

Effective waste management will contribute to mitigation with global challenges, affecting even energy recovery. New technologies for processing solid household waste include biological ones, with the help of which it is possible to extract and develop hydrogen (H₂) production. An example is biochemical leaching at extremely high temperatures using concentrated sulfuric acid or NaOH followed by acid treatment or heating CaCO₃ and CaCl₂ and HCl at temperatures above ≥975°C followed by leaching with 3% HCl solution (Sharma & Kumar, 2021). There is also a microbial electrolysis cell (MEC) technology, which uses microorganisms with which it is possible to convert solid household waste into H₂, acetate, formic acid, ethanol, etc. This technology has similarities with the above MFC method, the difference is only in the cathodes. MEC can convert any biodegradable waste into H₂ and biofuels, i.e., into high-value energy carriers and bio-products. The only downside is the high cost of this method.

There are also technologies for producing fuel from waste. To do this, the sorted waste is delivered to factories, where it is deformed using a drum machine. Then the compostable fraction mixed with inert materials is passed through the holes. The remaining waste, which is a fraction suitable for combustion, is processed into solid secondary fuel RDF. However, this will require sorting solid waste – removing food waste, metals, glasses, etc. from the total mass. The result should be an inorganic composition with the lowest possible moisture content. Large-sized fractions and recyclable plastics and metals are sorted manually, and the remaining combustible waste is transferred to a mechanical separation unit. Incombustible and inert materials are separated from light combustible fractions when air is supplied. At the end, the combustible material is crushed, and then crushed manually into a fine fluffy fraction called RDF fluff (Kaur *et al.*, 2021).

C.-H. Liu & C. Hung (2023) investigated the utilisation of thermochemical processes, including gasification and pyrolysis, for the generation of energy from municipal solid waste (MSW). The findings indicate that pyrolysis, in particular, produces a high-quality solid fuel and significantly reduces the environmental footprint in comparison to traditional incineration methods. Furthermore, the study emphasises the potential of co-pyrolysis with other waste materials to optimise energy recovery and minimise harmful emissions. This approach could provide a more sustainable method of waste disposal by integrating with other sectors, such as agriculture, where waste from organic farming could be co-processed for energy recovery.

Another innovative approach is the utilisation of hydrothermal carbonisation, as discussed in a study (Li *et al.*, 2024). Hydrothermal carbonisation has the potential to convert organic waste materials into carbon-rich solids, commonly known as hydrochar, which have a high calorific value and can be used as a renewable energy source. This technology is particularly well-suited to the processing of high-moisture content waste, such as food waste, which presents a significant challenge in terms of incineration. Furthermore, the study underscores the significance of hydrothermal carbonisation in reducing the volume of waste and producing value-added materials, such as activated carbon for industrial applications.

Furthermore, R. Shi *et al.* (2024) conducted an economic analysis of the viability of RDF production in developing countries, with a particular focus on the integration of RDF production within existing municipal waste management systems. The results of the study indicate that RDF has the potential to serve as a substitute for conventional fuels in industries such as cement manufacturing. Nevertheless, the success of such initiatives is contingent upon the implementation of governmental policies that facilitate waste sorting at the source and investments in infrastructure. Furthermore,

it was discovered that the calorific value of RDF could be augmented by combining it with agricultural waste, which is prevalent in numerous regions.

In the study by B. Wei *et al.* (2023) assessed the utilisation of MEC for the processing of organic waste with the objective of hydrogen production. This approach offers two distinct advantages: the recovery of energy in the form of hydrogen and the reduction of greenhouse gas emissions. Although still in its infancy, this technology shows great promise in addressing both waste management and renewable energy needs, particularly in regions where other waste-to-energy technologies may be uneconomical. Further research is required to optimise the cost-effectiveness and scalability of this method for its widespread adoption.

For 2024, the commercial application of RDF for energy production is mainly used in the cement industry for heating cement furnaces, but is also used for combined heat and electricity production in incinerators. It was also found that during incineration, joint operation with biomass, coal and bird droppings is possible at conventional waste-to-energy processing plants. Studies show that active pyrolysis occurs in the temperature range of 300-550°C, and the interaction of various RDF components has a great influence on the kinetic parameters. A comparative assessment of the life cycle of rapid thermochemical processing of solid waste with burial, incineration and anaerobic digestion shows that the pyrolysis process is one of the most environmentally friendly technologies for solid waste valorisation (Bhatt *et al.*, 2021).

A. Veses *et al.* (2020) carried out the pyrolysis process in conjunction with the stage of thermal catalytic cracking of solid waste at the installation, which includes a reactor with a fixed layer and a tubular cracking reactor. The results showed that with the help of this technique, it is eventually possible to obtain synthesis gas, including mainly solid fuel. Such a process tactic can be considered cost-effective and profitable conditioned upon the potential of using the resulting charcoal as a fuel obtained from waste to meet the energy needs of the process. The paper by P. Rajca *et al.* (2020) presents the results of a study showing that RDF consists mainly of 2 types of materials: biomass and thermoplastic polymers. Further, the authors carried out pyrolysis of samples at a temperature of 900°C in a nitrogen atmosphere in the form of a periodic process using a technological furnace. The results of the analyses showed a high calorific value. Thus, the great potentials of the above techniques and processes have been demonstrated, which can be effectively operated with the production of solid fuel materials of good

quality. RDF can become an interesting alternative to traditional fuels, while at the same time contributing to limiting the role of waste storage and increasing the level of environmental protection.

Conclusions

The government needs to introduce programmes and develop a system for the disposal of municipal solid waste, and find innovative ways to integrate informal waste collection contractors into the formal system, as they seek to fill the gaps created by the formal waste collection contractor. It is important for authorities, researchers, formal and informal businesses, global communities and organisations to be interested in conducting a feasibility study in the field of waste management. Waste sorting helps to improve waste volume control. It is necessary to increase the level of knowledge and training at all levels of the population, because there is a lack of awareness of people and the availability of trained specialists in the field of waste recycling. Technological improvements in recycling methods can help reduce environmental protection costs. The waste recycling system in energy is not only a useful way of obtaining energy, but also a comprehensive solution to a number of problems. The latest technologies allow significantly expanding the production of energy from waste. The current, innovative and safest technologies for processing solid household waste into electricity, and into fuel cells are the microbial fuel cell and microbial electrolysis cell technology. Municipal solid waste can be converted into solid fuel materials such as RFD, i.e., it is possible to use it to obtain useful energy vectors, thereby solving problems such as excessive consumption of fossil fuels and the exponential growth of landfills. Prospects for subsequent scientific research in the direction of studying the prospects for the processing of municipal solid waste for the purpose of their use as solid fuel materials lie in the possibility of finding optimal solutions to this problem and creating the appropriate conditions for high-quality energy supply of modern industrial and household enterprises. This will be expressed in the possibility of obtaining additional energy sources for the needs of these areas, which will contribute to the effective solution of energy supply issues in the short and long term.

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Conflict of Interest

None.

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Огляд перспективних досліджень у галузі переробки твердих побутових відходів для подальшого використання як твердопаливних матеріалів

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Анотація. Актуальність заявленої теми даного наукового дослідження полягає в глобальному зростанні екологічних проблем, включаючи виснаження ресурсів і забруднення, що призвело до нагальної потреби у розробці рішень щодо сталого управління відходами. Це дослідження стосується переробки твердих побутових відходів, з особливим акцентом на перетворення відходів у тверді паливні матеріали. Було проведено порівняльний аналіз літературних джерел за період по 2024 рік з метою виявлення найбільш ефективних технологій перетворення відходів на енергію. Отримані результати підкреслюють дві ключові суспільні проблеми: погіршення стану довкілля внаслідок неадекватних практик поводження з відходами та дефіцит ресурсів, спричинений урбанізацією та індустріалізацією. Серед помітних результатів – визначення спалювання та піролізу відходів як перспективних технологій для відновлення енергії, зменшення кількості сміттєзвалищ та пом'якшення впливу на довкілля. Зокрема, було показано, що піроліз дає більше енергії і призводить до менших викидів, ніж традиційне спалювання. Крім того, аналіз показав потенціал палива з відходів та мікробних паливних елементів як інноваційних підходів до сталого виробництва енергії з відходів. Ці технології можуть забезпечити додаткові джерела енергії для побутових і промислових потреб, одночасно зменшуючи вплив на навколишнє середовище, пов'язаний з утилізацією відходів. Практична цінність цього дослідження полягає в його потенціалі для розробки передових технологій переробки твердих побутових відходів з метою отримання енергії, що може підвищити ефективність використання ресурсів та енергетичну стійкість

Ключові слова: енергетичні ресурси; сортування відходів; глобальне потепління; промислова переробка