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Pyrolysis-Based Municipal Solid Waste Management in Poland—SWOT Analysis

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Abstract: Poland's management of municipal waste, which amounts to over 13 million tons/year, is not efficient—about 60% of the waste is subjected to recovery processes, about 20% of all municipal waste is converted into energy, and almost 40% is landfilled. The authors of this article recognize the potential of pyrolysis as a method of the thermal processing of waste allowing the potential of the energy contained in the waste to be utilized. Pyrolysis is an economically attractive alternative to incineration, with a significantly lower environmental impact, allowing efficient waste management and the use of pyrolysis by-products in the energy sector (pyrolysis gas), or in the building materials sector (biochar). Despite so many advantages, this method is not employed in Poland. The aim of the paper is to indicate a recommended strategy for the application of pyrolysis in Poland as a method of the thermal processing of municipal solid waste. SWOT (strengths, weaknesses, opportunities, threats) analysis was used as a research method. In the first step, on the basis of the literature review, the factors which may affect the use of pyrolysis in Poland were identified. In the second step, five experts evaluated the weights of those factors and the interactions between them. The products of the weights and interactions allowed, in accordance with SWOT analysis methodology, the most desirable strategy of pyrolysis application in Poland to be determined, which turned out to be an aggressive one. This means that pyrolysis as a thermal waste processing method should be implemented on a large scale in Poland to improve the indicators of municipal waste management.

Keywords: SWOT; municipal solid waste; management; pyrolysis

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1. Introduction

Recent decades have seen a rapid increase in the amount of human-generated waste. Solid waste management has become a critical issue to the environment [1]. The main reasons for that are the growing rate of technological progress and consumerist lifestyle [2]. According to information published by Eurostat, the amount of generated municipal waste did not increase between 2010 and 2019 in the EU (in 2010 the generated municipal waste was 503 kg per capita and in 2019 it was 502 kg per capita) [3]. However, the composition of the generated municipal solid waste (MSW) has changed, with the amount of plastic waste generated in the EU increasing by 24% (+6.7 kg) per capita over 10 years. Moreover, municipal waste coming from the European Union area constitutes about 12% of the world's municipal waste production.

Data analysis shows that since Poland's accession to the European Union—i.e., since 2004—the amount of waste produced per capita has increased by 31%—i.e., from 256 to 336 kg in 2019. The increase in waste production may be related to an increase in the wealth of the society, which translates into an increase in consumption, and consequently, the amount of generated waste. The general trend in Poland is therefore opposite to the EU one. In this period, the statistical inhabitant of the European Union reduced the production of municipal waste from 506 to 502 kg [3].

Although municipal waste accounts for less than 10% of the 2.5 billion tonnes of waste generated annually in the EU, it is highly visible and complex in nature due to its composition, multiple sources, and its link to consumption patterns in society [4].

The continuously increasing amount of solid waste causes serious global concerns regarding sustainable waste management, hence the growing interest in effective management systems [5,6]. There is increasing awareness among scientists, politicians, and practitioners that, in order for the practices of waste management and disposal to improve, better systems are needed [7]. Waste generation reduction that promotes waste prevention and resource recovery has been treated as a priority [8]. However, local government units in developing countries lack appropriate resources and knowledge needed to control the increasing problems related to solid waste management. Municipal solid waste management (MSWM) still faces significant challenges due to limited resources, outdated equipment and technologies, as well as failure to fully implement relevant regulations [9]. The waste management system presented in Figure 1 includes three methods of waste handling: recycling, biological treatment, and thermal treatment [7].

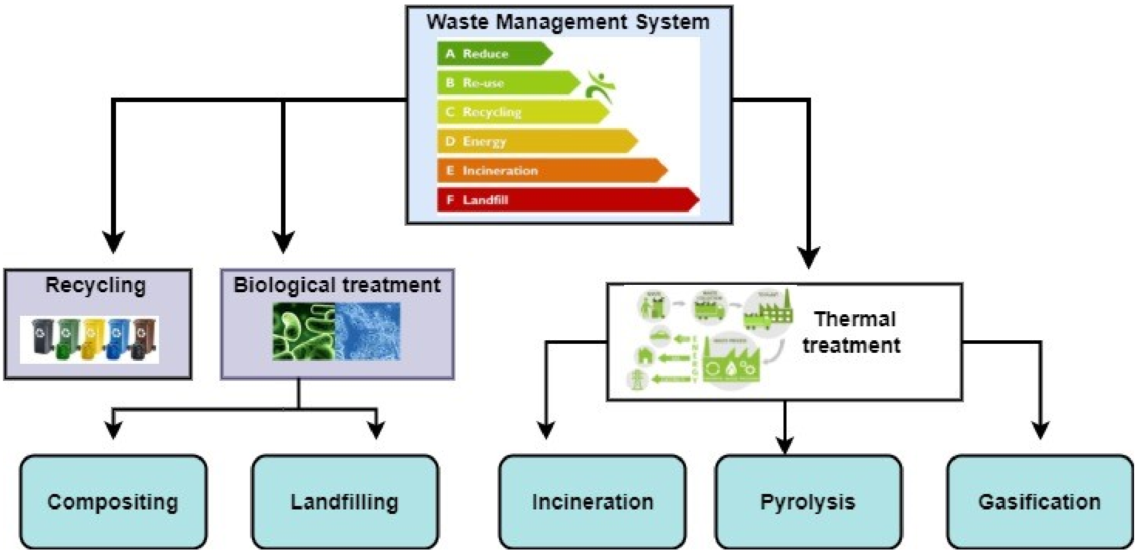

Figure 1. MSW management system [7].

It is important to first select recyclable material from the waste and then recover energy from the residual waste. Energy recovery processes include the biological and thermal treatment of waste. Waste that cannot be recycled or processed to recover energy is landfilled. Biological treatment includes the process of composting (anaerobic digestion) organic waste with the participation of microorganisms, which results in high-methane biogas and biofertilizer (digestate). This process makes economic sense for wet organic waste such as food waste, sewage sludge, or agricultural waste. The thermal treatment of waste includes three main processes, namely incineration, gasification, and pyrolysis, which are discussed later in this article. Waste management systems (Figure 1) should be assessed using comprehensive tools for evaluation of their economic, environmental, and social benefits and effects. The efficiency of waste management systems depends on their capability of using economic efficiency and technological advantages to support social mobilization and environmental integrity [9]. In order to promote sustainable performance, practitioners should consider new technologies for data acquisition and communication, circular economy, technical capacity, as well as organizational and leadership capabilities [10]. Development of sustainable MSWM requires designing appropriate strategic solutions based on the resources and strengths of an individual local government unit [11]. With the traditional landfill method facing numerous problems, such as land scarcity and underground water contamination [12], there is a global interest in waste-to-energy (WTE) methods, including incineration [13,14], pyrolysis [15,16], and gasification [17,18].

Shrinking global resources of chemical energy and a constant, increasing demand for such energy make it necessary to seek new, alternative methods of energy generation from waste or renewable energy. One of its forms is chemical energy contained in the huge amounts of waste deposited on landfill sites [19]. The global energy consumption in 2018 grew almost twice as fast as the average rate recorded since 2010. It is not only economic growth that is responsible for the rapid pace of energy consumption, but also perceptible climate change. Wind and solar energy generation grew at double-digit rates, but it was fossil fuels that met most of the growing demand. This has also translated into higher emissions of climate-harming carbon dioxide. The total global energy demand increased by 2.3% in 2018 and the electricity demand increase was almost double that—increasing by 4% (up 900 TWh) compared to 2017. This is the fastest pace since 2010 [20]. In the case of Poland, energy consumption has decreased. In 2020, electricity consumption in Poland was 171 TWh. At the same time, domestic power generation declined (by 3.8%, or 6.2 TWh compared to 2019) and amounted to 157.7 TWh. Despite the epidemic-induced lockdown of the country, last year's decline in domestic power generation was marginally less than that of 2019 (at that time, Poland's energy generation declined by as much as 3.9%). In contrast, the net energy imports increased in 2020 (by 2.6 TWh compared to 2019) to a record high of 13.3 TWh [21]. Comparing data from 2019 and 2020, there was a decrease in production in power plants and CHP plants fired with hard coal (by 9%, or by 7.2 TWh) and lignite (by 8%, or by 3.4 TWh). As a result, the share of hard coal in power generation in Poland in 2020 was 46%, while the share of lignite was 24%. This means that the most carbon-intensive coal sources accounted for 70% of the total national generation of electricity in 2020. At the same time, in 2018. Poland was ranked first in the EU in terms of hard coal mining and second in terms of lignite mining [22].

The decrease in electricity production from coal in Poland in the described period was accompanied by a very large increase in energy imports. Almost half of the household electricity consumption in Poland in 2020 was covered by energy imported from neighbouring countries [21]. In Poland, municipal waste remains an untapped energy source.

At the same time, the increasingly restrictive European level of municipal waste recovery and recycling forces Poland, among other countries, to not only increase the powers of regional facilities for municipal waste treatment, but also to extend the possibilities for utilizing the waste fractions produced there. One of them is high-calorie oversize fraction, which, following appropriate preparation (removal of non-combustible parts such as metal and glass, multiple grinding for reduction of volume and moisture content, among other things), is converted into refuse-derived fuel (RDF) [10]. At present, cement works are the only receivers of RDF in Poland.

Research into the feasibility of pyrolysis as a method of processing selected types of waste to produce useful products is being conducted in the context of a closed loop economy around the world. The pyrolysis method is an innovative technology for the management of municipal waste, including waste mixed with medical waste generated in the era of the COVID-19 pandemic, allowing the negative impact of waste on the environment to be reduced.

At present, there is no industrial-scale installation for the pyrolysis of municipal solid waste in Poland, only a pilot installation for the pyrolysis of RDF waste. Efficient utilization of this category of waste is therefore a challenge of a technological, material, and economic nature. The development of technological procedures and know-how will not only allow the safe processing of municipal waste in the era of COVID-19, but will also indicate the directions for the effective management of thermal conversion products.

The need for the research conducted in this paper arises primarily from the fact that the proposed pyrolysis technology is an economically attractive alternative to incineration plants, with a much smaller impact on the environment, allowing efficient waste management and the use of pyrolysis by-products in the energy sector (pyrolysis gas) or in the construction materials industry (biochar). The estimated cost of a typical installation with an average throughput of 250 kg/h is PLN 100 million, which makes this solution applicable also to relatively small businesses, thereby increasing its competitiveness and attractiveness [23]. The costs of the construction and operation of incineration plants (including environmental charges) are definitely higher, and what is more, these costs are constantly growing due to increasingly restrictive environmental regulations. For example, the planned capital expenditures of an incineration plant in Szczecin with a capacity of 150 thousand tons of waste/year were PLN 666 million gross, while the final cost was PLN 711 million gross [24]. It should be emphasized that thermal conversion of waste by pyrolysis is a potentially effective technology for the neutralization of municipal solid waste. An important argument in favor of wider application of this technology is also the possibility to use the solid and gaseous products generated as a result of waste pyrolysis, which reduces the total cost of pyrolysis.

As a developing country, Poland still struggles with an increasing amount of municipal and industrial waste. Solutions have not been developed yet to eliminate this problem. The research carried out in this paper has contributed to filling the research gap by providing policy makers in Poland with a strategy for implementing pyrolysis as a method of municipal solid waste management under current management conditions. The authors not only reviewed the current state of knowledge, but also enumerated the key factors of the studied phenomenon. The novelty of the conducted analyses lies in the use of a strategic approach to adapt the pyrolysis process of municipal solid waste on a nationwide scale. The literature review gives reasons to claim that such analyses have not been carried out in Poland to date. The authors of this paper see the process of pyrolysis as a chance for Poland to improve municipal solid waste management. The aim of the paper is to indicate a recommended strategy for the application of pyrolysis in Poland as a method of the thermal processing of municipal solid waste. The research problem was stated by formulating the following research questions:

RQ1. What are the strengths and weaknesses of pyrolysis as a method for thermal treatment of municipal solid waste in Poland?

RQ2. What are the opportunities and threats of using pyrolysis as a method for thermal treatment of municipal solid waste in Poland?

RQ3. What strategy of using pyrolysis of municipal solid waste in Poland is advisable?

2. Literature Review

2.1. Municipal Solid Waste

The amount and morphological composition of municipal waste hugely depends on the place of its generation, the season and, as pointed out by Talalaj and Walery [12], gender and age of those producing the waste. The amount of municipal waste collected per capita is also strongly correlated with the economic condition of the individual regions of a country [13].

Municipal waste and the threats related to it are also becoming an increasing problem in Poland [14]. In 2020, 13.1 million tonnes of municipal waste were collected in Poland. 11.3 million tonnes of waste were collected from households, which accounted for 86.1% of all the municipal waste generated. The municipal waste collected in 2020 was subjected to the following processes: 1. recovery—7732.8 thousand tonnes, including: recycling—3498.6 thousand tonnes, biological treatment processes (composting or fermentation)—1577.9 thousand tonnes, thermal treatment with energy recovery—2656.2 thousand tonnes; 2. disposal—5384.1 thousand tonnes, including: by thermal treatment without energy recovery—166.4 thousand tonnes, by landfilling—5217.7 thousand tonnes [22]. Figure 2 presents ways of handling municipal waste collected in 2020.

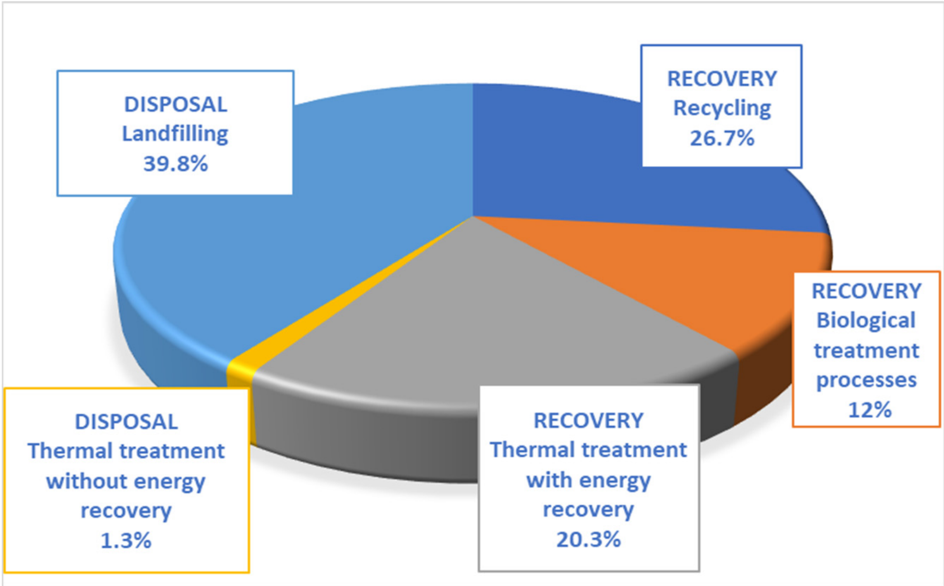

Figure 2. Ways of handling waste in Poland in 2020 (%) [22].

At the end of 2020, there were 271 landfill sites in Poland which accepted municipal waste, with over 94% of them equipped with degassing installations, and incineration of contained gas allowed the recovery of around 97,357 thousand MJ of thermal energy and around 113,116 thousand kWh of electric energy (Figure 2) [22]. For comparison, in 2019, almost 225 million tonnes of municipal waste were generated in the EU, which is 502 kg per capita. Poland was at the bottom of the ranking, producing relatively the least rubbish per capita. In the EU, there is an increase in municipal waste recycling and incineration, accompanied by a decrease in the amount of municipal waste that goes to landfill sites. According to Eurostat data, 107 million tonnes of waste—i.e., 239 kg per capita—were recycled and composted in the EU in 2019. Meanwhile, the amount of incinerated municipal waste in the EU doubled from 30 million tonnes (70 kg per capita) in 1995 to 60 million tonnes (134 kg per capita) in 2019. Although the total amount of waste generated in the EU is slightly larger than in the previous years, the total amount of municipal waste deposited on landfill sites in the EU decreased from 1995 by more than half: from 121 million tonnes (286 kg per capita) in 1995 to 54 million tonnes (120 kg per capita) in 2019 [3].

Due to the lack of a definition, the term RDF is used in everyday practice to refer to a range of caloric wastes [11]. This means that the composition and quality of RDF varies hugely, which poses a threat to both the manufacturers and users. As RDF is not tested or assessed in a standardized manner, customers have no certainty regarding its composition [25]. In order to facilitate the handling of refuse-derived fuel, a definition of SRF (solid recovered fuels) was introduced. SRF is fuel with standardized quality properties (e.g., caloric value, chlorine content, mercury content) generated from non-hazardous wastes and used as a source of energy in the processes of waste incineration or co-incineration [26]. It should be stressed that these standards are not obligatory, and meeting a certain level of quality is not required. Consequently, the required quality of SRF is defined by the customer, which means that it may differ depending on waste fraction [25].

Regional facilities for municipal waste treatment accepting and treating waste from an area inhabited by at least 120 thousand people were meant to be the basis for the efficient functioning of the municipal waste management system in Poland. Among the wastes entering regional facilities for municipal waste treatment are raw material fractions that are sent for material recycling and biological fractions that are composted or constitute feedstock for a biogas plant [15]. It is the non-recyclable part of waste that represents a problem. The residual fraction of municipal solid waste, which is non-recyclable due to its high caloric value (above 6 MJ/kg), poses a problem for most regional facilities for municipal waste treatment. This results from the regulations in force in Poland, under which this fraction cannot be landfilled from 1 January 2016. RDF as a product created from non-recyclable waste can be used in energy recovery processes such as pyrolysis. Studies of RDF feedstock conducted for a dozen or so locations in Poland confirmed high availability of waste raw material of appropriate quality [19].

RDF is treated as an alternative fuel in many countries, in contrast to Poland, where, unfortunately, from a legal point of view it is still considered as waste [16]. Currently, utilising this caloric fraction of waste in an ecological and cost-effective manner represents a huge problem for regional facilities for municipal waste treatment. The main reasons for low usage of RDF in Poland for production of electric energy and heat are as follows [27]:

- lack or low awareness of the huge hazard posed by the lack of a long-term, effective policy allowing for a wider use and proper storage of alternative RDF fuel among policy makers in Poland,
- lack of transparent legislative and fiscal rules guaranteeing the profitability of investments in units dedicated to power engineering in a long-term perspective,
- formal and legal requirements established for combustion and co-combustion of waste,
- low public awareness of the economic benefits associated with the recovery of energy from waste,
- current technical level of boiler installations, in particular including exhaust after-treatment systems, which prevent non-investment and environmentally safe implementation of waste co-incineration technologies with fossil fuels,
- emission of pollutants,
- possible occurrence of adverse changes in ash parameters.

In this context, it seems important to assess the possibilities of modernising the existing regional facilities for municipal waste treatment to allow the implementation of pyrolysis installations. An argument in support of that would be the fact that in 2017 the cost of producing 1 kWh of electric energy was minimum PLN 0.60, whereas the cost of one kWh of energy generated from gas in the process of pyrolysis was only around PLN 0.20 [19].

2.2. Pyrolysis vs. Other Methods for Thermal Treatment of Municipal Waste

Energy recovery from waste refers to the processing of non-recyclable waste materials. Due to their energy characteristics, such as, among other things, caloric value of over 6 MJ/kg, such wastes can be used in the production of heat, electric energy, or fuel through various processes, including incineration, gasification, and pyrolysis.

The methods of thermal treatment of waste have only been present in technological practices since the 1990s. The leader in this area is Japan, which from the beginning relied on gasification as the most appropriate process in technological and environmental terms [13]. At present, the most commonly used thermal treatment technique in Europe is incineration (Figure 3), whereas the least common one is pyrolysis. Other methods, such as gasification, despite their long history, are not widely used, due to—among other things—technical difficulties connected with the inhomogeneity of the chemical composition of the waste intended for gasification as well as the difficulties with ensuring an appropriate distribution of granulation [13]. Pyrolysis, in contrast, is used for thermal treatment of defined wastes, e.g., used tires [17] and plastics [18].

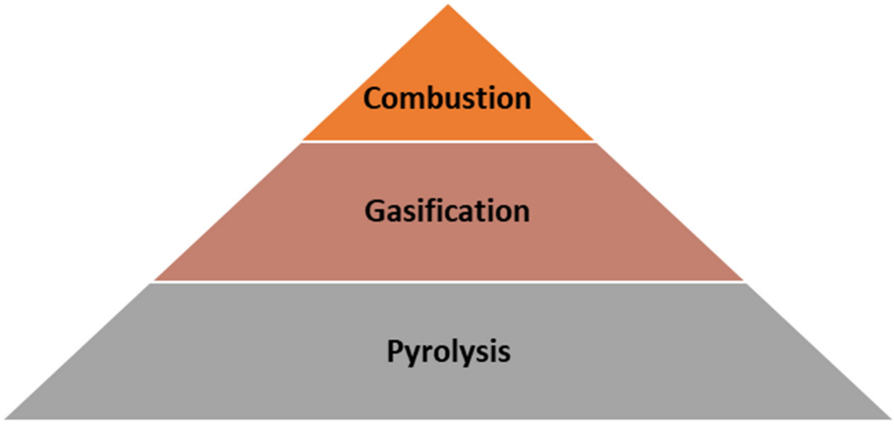

Figure 3. Recommended hierarchy of the methods for thermal treatment of municipal solid waste.

Given the advantages of the process of pyrolysis, as presented in Table 1, it is pyrolysis that should be the dominant method for thermal treatment of waste within the recommended hierarchy of the methods for thermal treatment of municipal solid waste, especially with respect to the waste generated during the pandemic.

Table 1. Comparison of the processes of thermal treatment of municipal waste [7,28].

Process Type	Advantages	Disadvantages
Combustion	• Commonly used MSW conversion technology. • Technology with an established industrial infrastructure. • Converts MSW into combined heat and energy, electricity, and steam. • Significant reduction of waste quantity (70–80%). • Low operating costs.	• Generates huge amounts of greenhouse gases and pollution. • Production of dioxins and other persistent organic pollutants (POP). • High capital and operating costs. • Highly ineffective process for waste with a high moisture content.
Gasification	• Reducing the volume of waste by 50–90%. • High versatility (the possibility of managing various types of waste). • Converts MSW to H_2 rich synthesis gas and carbon products. • High content of H_2, CH_4, and CO in the synthesis gas can increase its calorific value.	• Tar production. • More suitable for large power plants. • Higher operating and capital costs. • Corrosion of metal pipes during reaction. • Higher energy consumption.
Pyrolysis	• High efficiency, up to 80% energy recovery. • Converts MSW into bio-oil, biochar, and pyrolysis gas. • Limited field requirements. • Lower NO_x and SO_2 emissions. • High versatility—the possibility of managing various types of waste, for example plastics. • Pyrolysis technology is suitable for almost all kinds of waste plastic, no matter if it is clean or unwashed and unsorted. • No need to do the shredding work. • All the processes from plastic to fuel oil is carried out inside the pyrolysis reactor together with its accessory system, very convenient and man-power saving.	• Coke formation from liquid products. • Liquid products have a high water content.

Pyrolysis is a process conducted at a lower temperature compared to incineration (and co-incineration) [29]. The major advantages of pyrolysis in comparison with incineration include: (1) reduced production of toxic substances in waste gases and no need for building a complex gas clean-up system; (2) lack of the phenomenon of entrainment of solid particulates in a gaseous phase, which reduces the need to install dust removal equipment for emission control; (3) at a lower temperature, corrosion is reduced, which lowers installation maintenance costs; (4) low temperature allows secondary raw materials, especially non-ferrous metals, to be recovered from post-pyrolysis solid products; (5) due to the endothermic character, pyrolysis is an easier to control process than incineration; (6) high flexibility of the composition of the fuel subjected to pyrolysis; (7) products of pyrolysis can be stored and used at a later date for energy purposes [30,31].

Aparcana stresses in his work [8] that when designing a waste management strategy, it is important to indicate barriers to be eliminated as well as the measures that will increase the chances for a successful long-term implementation of the strategy (Table 2).

Table 2. Classification of the typical barriers to and measures for the implementation of a waste management strategy [7,9].

Categories	Barriers
Policy and legal arrangements	Lack of adequate policies, clear laws, and strict regulations; waste legislation is fragmented, with many important elements missing (technologies, cost-effectiveness aspects, enforcement mechanisms); licensing requirements; policies that support the extractive industries.
Economic/financial instrumen	Budgetary constraints, lack of economic support from the central government, poor fund raising strategies from residents, inadequate economic and financial planning; high investment costs, difficulty in raising external investment capital, long return on investment, low performance due to limited access to materials, uncertain margins, different investment cycles, unstable market (uncertain market).
Institutional/organizational solutions	Lack of organizational capacity and managerial skills (leadership) of local authorities; the perception that environmental protection conflicts with national economic objectives; sharing of similar roles and responsibilities, confusion about their designation and division; limited cooperation between units.
Social acceptance	Lack of education and awareness campaigns on the importance of a proper waste management system and the role of citizens as waste generators; social rejection: working as a recycleris associated with low status and is considered undesirable; there is a general lack of respect for work, resulting in a poor work ethic for employees and poor quality of their work; social isolation between organizations; lack of commitment on the part of the organization; lack of time and resources; other priorities in the company; lack of trust between organizations; an aversion to cooperation and dependence; reluctance to change on the part of the organization; resistance from the residents.
Technical/operational	Unavailability of technology and manpower, lack of skilled personnel with technical knowledge in waste management, lack of country-appropriate technology, faulty equipment and waste structures (waste transfer stations, warehouses, old waste vehicles, etc.), poor roads, unreliable data and lack of information sharing among stakeholders; distance-related barriers; the by-product requires complex processing beforere use; incompatibility between industries; technical solutions not on a commercial scale; the material is not reusable; lack of technical knowledge; requirements concerning quality assurance of materials; quantity requirementsfor materials; requirements for delivery of materials over time; limited knowledge of the market and of cooperation methods; limited information on potential benefits; lack of contact and communication between companies; high logistical requirements; strict administrative requirements.

Table 2. *Cont.*

Categories	Common Recommended Remedies
Policy and legal arrangements	Favorable national policies, regulations, national and local political support, law enforcement; eco-efficiency: reduction of packaging, producer responsibility.
Economic/financial instruments	Micro-credit initiatives, expansion of capitalbase, financial incentives; entering new service roles and niches (service diversification); increase in bargaining power; appropriate payment systems to reduce economic uncertainty.
Institutional/organizational solutions	Organizing the informal sector, creating cooperatives/micro and small businesses, cooperatives and associations; stakeholder engagement, collaboration and partnerships among waste management system stakeholders, good relations with industry and formal MSWM system, national initiative—participatory approach.
Social acceptance	Information and education campaigns, training and empowerment of various stakeholders; recognition and acceptance by the authorities; benefits that informal recycling can bring, integration of informal recycling into waste management, political and legal recognition, public acceptance, changing perceptions of decision makers of informal recycling activities; occupational safety practices, social and environmental health, improvement of working conditions and equipment.
Technical/operational	Evaluation and documentation of the existing MSWM system, accurate data collection on waste and recycling markets, data quality; pilot projects, access to suitable sorting and storage sites, infrastructure, topographical considerations, better quality of recyclables; appropriate technology, economic and technical assistance, improving technical qualifications of waste handling personnel.

Although there are more and more empirical studies on the process of pyrolysis, the number of publications that assess (by means of SWOT method) the possibilities of using pyrolysis for municipal solid waste treatment in Poland is still limited. The authors of the paper notice the need to intensify research in this field, as it is a dynamic area.

3. Methodology of SWOT Analysis

The aim of the paper is to identify the strengths and weaknesses as well as opportunities and threats of pyrolysis as one of the methods for thermal treatment of municipal solid waste and the possibility of using it on a wide scale in Poland. The aim was executed using a strategic planning tool, namely SWOT analysis.

SWOT (Strengths, Weaknesses, Opportunities, Threats) analysis is a popular strategic planning tool used for general assessment of an organization's internal capabilities (strengths and weaknesses) as well as for assessment of the external situation. SWOT provides valuable information about internal and external factors that have a positive and negative impact on the development of the organization and encourages the decision makers to take the best actions [32]. One of the currently most popular divisions of SWOT analysis factors was proposed by Kotler [33] (Table 3).

Table 3. SWOT analysis strengths (S), weaknesses (W), opportunities (O), and threats (T).

	Positive Factors	Negative Factors
Internal factors	**Strengths** Internal capabilities that may help company reach its objectives.	**Weaknesses** Internal limitations that may interfere with a company's ability to achieve its objectives.
External factors	**Opportunities** External factors that the company may be able to exploit to its advantage.	**Threats** Current and emerging external factors that may challenge the company's performance.

Based on the assessment, a strategy is recommended, which, for it to be successful, should be based on a good alignment of the organization's strengths and weaknesses as well as the opportunities and threats existing in its environment [34] (Table 4).

Table 4. SWOT analysis framework.

Combination	Strengths (S)	Weaknesses (W)
Opportunities (O)	SO strategy (aggressive strategy)	WO strategy (competitive strategy)
Threats (T)	ST strategy (conservative strategy)	WT strategy (defensive strategy)

SWOT analysis, apart from its advantages such as simplicity and clarity, has also downsides, which include, among other things, high degree of subjectivity in defining SWOT analysis factors, lack of empirical verification, lack of timely response to the changing environment and lack of implementable steps [35]. With respect to the limitations of SWOT analysis, strategic planning experts can be divided into two groups: experts who resign from using this method in favor of other methods and experts who use it and at the same time strive to increase its usability in the implementation of the organization's goals [34]. In this paper, the latter approach was adopted. The reason for that was the fact that SWOT analysis is widely used in various studies on strategic management and planning, such as sustainable energy development, assessment of energy technologies, and political strategy design. The usefulness of SWOT analysis as a research method to identify the market, verify project assumptions, and study trends in the energy sector is supported by many authors including [36–39].

The authors, based on literature review, identified the factors impacting the use of pyrolysis of MSW in Poland, and then presented them to five experts for assessment: one expert representing enterprises engaged in pyrolysis, three experts representing academia, and one expert representing local authorities. The selection of experts for the study was purposive. The group of potential experts was divided into three subgroups: (1) experts representing enterprises using waste pyrolysis, (2) experts representing scientific and research centers, (3) experts representing local government units. For the first group, the number of experts is limited due to the lack, mentioned in the article, of industrial-scale pyrolysis facilities for municipal solid waste. In the case of the second group, the authors of the article invited representatives of all three scientific and research centers in Poland where experimental pyrolysis research is carried out. Representatives from the three research centers agreed to participate in the study. In the case of the third group, the pilot study carried out in local government units showed low knowledge of the respondents concerning the possibilities of using MSW pyrolysis in Poland, which was the reason for their refusal to participate in the study. As a result, an opinion was obtained from only one expert in this group. The study was conducted in September 2021.

The authors identified the following stages of the research process:

1. Identification of strategic factors. Based on the literature review, the authors have identified factors affecting the application of pyrolysis of municipal solid waste in Poland.
2. The selection of experts.
3. Identify and evaluate the interrelationships that exist between strategic factors. In this step, experts were asked:
    a. Qualifying each of the factors presented to them to one of the four groups of strategic factors: S (strengths): everything that constitutes an asset, an advantage, an advantage; W (weaknesses): everything that constitutes a weakness, barrier, drawback; O (opportunities): anything that presents a chance for beneficial change; T (threats): anything that poses a danger of adverse change. The study adopted the principle that strengths and weaknesses are internal factors (related to the characteristics of pyrolysis), while opportunities and

threats are external factors (related, among others, to the economic, legal, and environmental factors in Poland).

b. Analyze the interrelationships among four seemingly independent groups of strategic factors and assign values to the characteristics. For this purpose, the experts assigned weights in the numerical range (0–1) to particular factors which might affect the application of the pyrolysis process of municipal solid waste in Poland. The sum of the weights in the factor group was 1.0. This allowed the following questions to be answered in the next step: (1) Will the strengths of pyrolysis enable the exploitation of existing opportunities? (2) Will the strengths of pyrolysis overcome the risks? (3) Will weaknesses in pyrolysis get in the way of opportunities? (4) Will weaknesses in pyrolysis compound the impact of existing risks? Then the interactions between the studied factors were identified—the occurrence of interaction was marked with a value equal to 1, while the lack of interaction with a value equal to 0. Experts, at the time of the study, did not know the responses of other participants.

4. Calculations and interpretation of the results obtained.

The authors, in each of the four groups of strategic factors calculated the number of interactions taking place between the links, the value of the weights assigned to them, and then the value of the product of the weights and interactions. The results obtained were assigned to the appropriate boxes of the matrix, which allowed the most desirable strategy to emerge.

4. SWOT Analysis of the Factors Impacting the Use of Pyrolysis of Municipal Solid Waste in Poland

In the first stage of the study, based on a literature review, the authors identified factors affecting the application of the pyrolysis of municipal solid waste in Poland. In the second stage of the study, the experts were asked to qualify each of the factors presented to them to one of the four groups of strategic factors: S—strengths: everything that constitutes an asset, an advantage, a merit; W—weaknesses: everything that constitutes a weakness, barrier, drawback; O—opportunities: anything that presents a chance for beneficial change; T—threats: anything that poses a danger of adverse change. The authors presented the obtained results in the form of a four-category strategy matrix (Figure 4), in which the left half contains categories of positive factors, and the right half contains categories of negative factors impacting the possibility of using pyrolysis of municipal solid waste (MSW) in Poland.

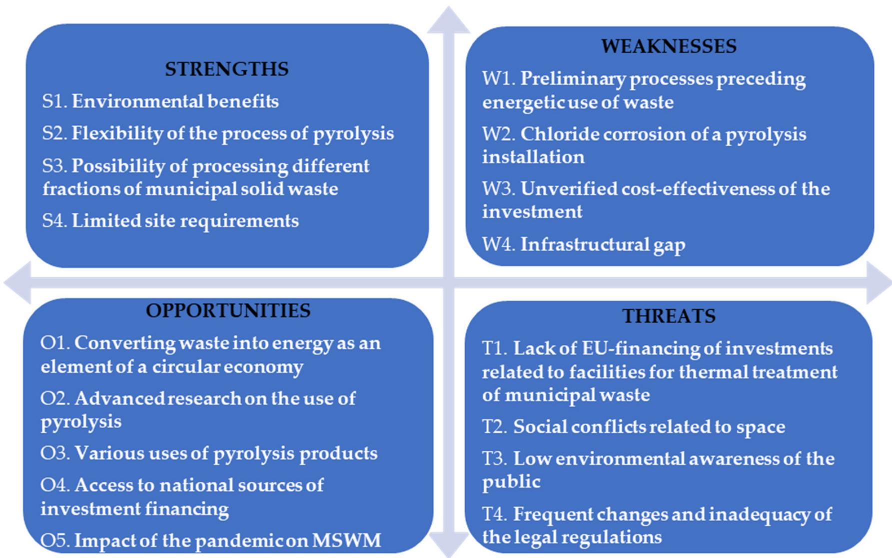

Figure 4. SWOT factors affecting the possibilities of using MSW pyrolysis in Poland.

All the examined strategic factors, which may be important for the application of pyrolysis in Poland, are characterized below.

4.1. Strenghts

4.1.1. Environmental Benefits (S1)

Porteous [40] presented key factors connected with the use of the energy from thermal treatment of waste as part of a waste management strategy. The author provided a detailed description of the used rigorous regime of the thermal treatment of waste and related emissions. It turned out that thermal treatment of wastes is a low-risk, environmentally friendly method after municipal waste recycling. It eliminates the environmental impact of landfill and helps to mitigate global warming thanks to the green energy rate and reduction of landfill gas emissions. Continental Europe and Scandinavia have successfully adopted composting, recycling, and energy recovery as a unified goal in integrated waste management. As early as 2005, the researcher [40] stressed that it is high time for other countries to adopt a similar policy and get rid of unsustainable landfills and their harmful impact on the environment [40]. Comparison of pyrolysis and incineration as methods for thermal treatment of waste shows that pyrolysis is usually characterized by a lower temperature of the process compared to incineration, as well as lower emission of air pollutants, including polybrominated diphenylethers (PBDEs) [41,42]. Furthermore, as Saffarzadeh et al. write, the energy produced in pyrolysis-based processes is cleaner than that from conventional waste incineration plants. Due to the neutral atmosphere of the process, lower amounts of nitrogen oxides (NO_x) and sulphur oxides (SO_2) are released during pyrolysis [43].

4.1.2. Flexibility of the Process of Pyrolysis (S2)

A strength of pyrolysis as a method for thermal treatment of waste is high flexibility of this process. By changing such parameters as temperature or heating rate, different yields and quality of solid, liquid, and gaseous products can be received [44–47].

The process of pyrolysis is affected by a number of parameters that determine the quality and quantity of resulting products. The most important factor impacting the properties of pyrolysis products is the type of the waste used. However, there is a huge number of factors affecting the effectiveness of pyrolysis. The other parameters are: reactor type, heating method, process temperature, heating rate, pressure, method of feedstock preparation, particle size, how long the fuel stays in the reactor, the intensity of the flowing medium and catalyst in the case of biomass pyrolysis. Depending on these parameters, different yields of biochar, oil, or pyrolytic gas can be obtained. Controlling these parameters is important, if the aim is to obtain, e.g., a larger share of oil fraction. Proper selection of the parameters produces the intended effect of pyrolysis [48].

4.1.3. Possibility of Processing Different Fractions of Municipal Solid Waste (S3)

An unquestionable advantage of the process of pyrolysis is the possibility of thermal treatment of various types of waste, both industrial and household [45]. Defining a single mechanism of pyrolysis with respect to all types of waste is practically impossible. This is because waste constitutes a highly diversified group of materials in terms of the types of chemical substances. The mechanism of pyrolysis can be applied to various types of municipal waste such as: plastics, including foil, PCV, PCB; rubber waste (e.g., car and bicycle tyres); textiles, multi-material waste; sewage sludge (e.g., from small-scale sewage treatment facilities), biomass and waste of biomass nature, cellulose waste (paper, cardboard) [49–51]. The fuel that is mostly used in pyrolysis is a selected combustible fraction of municipal solid waste, RDF—composed of plastics, paper, rubber, wood, and textile wastes among other things—is mainly used in pyrolysis [51–53]. The input raw material in the production of fuel from municipal solid waste (RDF) can be both homogeneous and mixed waste. The composition and contamination level of the resulting RDF will vary depending on the source of the waste used for processing. However, the major advantage of RDF is the fact that it is possible to impact its quality in the process of production by selecting the waste raw material or using appropriate waste treatment techniques [51].

4.1.4. Limited Site Requirements (S4)

An unquestionable advantage of a pyrolysis installation is its small size. An installation for utilizing the high-calorie fraction of municipal waste should be placed on a ground of around 12 × 30 m. It should be located at a place where it will not be exposed to atmospheric factors [23].

Given the above, such an installation can be successfully located on the premises of a regional facility for municipal waste treatment, which is a relatively convenient and cheap solution. Researchers stress that gasification and pyrolysis processes are more suitable for smaller installations [54].

4.2. Weaknesses

4.2.1. Preliminary Processes Preceding Energetic Use of Waste (W1)

The amount of energy produced using the method of pyrolysis depends on waste parameters (in particular, caloric value). Waste that is best suited for pyrolysis is waste with caloric value of over 6 MJ/kg of dry mass, ground and dried [23]. The preliminary processes preceding energetic use of waste (sorting, grinding, drying, condensing, and mixing) increase not only the duration of energy recovery but also the overall costs of the process [26]. Usually, fractions are dried at the temperature of around 110 °C and ground by milling to a granule size of around 10 mm [51]. Due to a relatively small bulk density, the raw material also requires an additional preparation stage aimed at material densification [55].

Unprocessed mixed municipal waste (so-called trommel fines, undersize fraction) is characterized by high moisture content of above 40%, therefore in order to ensure appropriate conditions for thermal recovery, it should be dried. Usually, the raw material is dried at the temperature of 60 °C for 24 h to achieve the minimum moisture content at 2.69%. Then, non-combustible parts (stones, concrete, glass, bones, etc.) are removed, and the material is ground to a granule size of 0.5–2 mm [56,57].

Municipal waste is characterized by huge inhomogeneity and changeability of physicochemical properties, therefore in order to improve its combustion properties (including caloric value and quality), after removal of the recyclable fraction, it is subjected to the process of multiple grinding, mixing, and removal of non-combustible parts (e.g., metals, glass). Next, it is dried (with undersize fraction—pre-RDF). For that purpose, waste heat from thermal waste treatment processes is most often used. The resulting product—both pre-RDF and RDF—is characterized by a relatively stable moisture content, more homogeneous physicochemical structure, and higher caloric value. At the same time, it is easier to transport, load, and store, it involves lower pollution emission and reduces the demand for air during combustion [53,58,59].

4.2.2. Chloride Corrosion of a Pyrolysis Installation (W2)

One of the threats—limiting the lifetime of a pyrolysis installation—is the presence of chlorine compounds, which lead to corrosion of the installation and, under certain conditions, to the formation of dioxins and furans. Knowledge of the chemical mechanisms causing corrosion is vital for assessment of the threat of corrosion during the pyrolysis of municipal solid waste [10,60]. The level of the risk of corrosion can be preliminarily assessed by determining the chlorine content in the fuel. In the literature, such an approach is called the 'fuel chloride corrosion index', and it is estimated that with Cl < 0.02% there is no risk of corrosion [61]. In the case of fuel with inhomogeneous chemical composition that comes from oversize fraction of municipal solid waste (RDF), chlorine content varies significantly [62,63]. The shares of sulfur (<0.02–0.30%) and chlorine (0.1–1.10%) in RDF correspond to the levels registered for 'raw' municipal waste, (0.08–0.30%) and (0.47–1.02%) respectively. A noticeable share of chlorine in the waste processed in water-to-energy plants

(WTE Plants), as well as mutual relations with other key elements (S, Na, K, Zn and Pb), contributes significantly to corrosion of the installation in question [44,64].

4.2.3. Unverified Cost-Effectiveness of the Investment (W3)

There are no referential local installations for the thermal treatment of municipal waste using pyrolysis in operation in Poland. The ones being constructed are prototypical, which makes it difficult to discuss average investment expenditure and operational costs. Analysis of the data made available by an entity using a prototypical pilot RDF installation shows that it can be a profitable investment (costs related to CO_2 emission charges and employed staff were not taken into account). With the following assumptions:

1. Potential profit from obtaining RDF waste (1 t) = 50 PLN;
2. Electricity demand = 1.1 MWh/t;
3. Value of electricity obtained from 1 t of RDF = 2 MWh;
4. Value of thermal energy obtained from 1 t of RDF = 4 MWh (14.4 GJ);
5. Energy needs of the process = 1.1 MWh;
6. Energy surplus = 0.9 MWh;
7. Electricity price by C11 rates (energy rates—2019) = 0.5535 PLN/kWh;
8. Heat energy price (energy rates—2019) = 24.39 PLN/GJ;
9. Installation performance = 1 t RDF/h;
10. System operation time = 8640 h/year;
11. Calorific value RDF = 23 MJ/kg;
12. Potential revenue = 12,074,572.80 PLN;

Parameters assumed the following PLN values:

1. Amount of investment outlays incurred 25,000,000 PLN;
2. Annual cost of operation and maintenance 1,200,000 PLN;
3. Annual straight-line depreciation (20% rate) 5,000,000 PLN;
4. Annual unexpected expenses related to the operation of the installation 787,500 PLN;
5. Total annual cost (excluding investment outlays) = 6,987,500 PLN.

An economic analysis of the obtained results suggests that the investment is profitable with the assumed technical and economic parameters as follows:

1. NPV = 14,786.83 (NPV > 0);
2. PI = 1.0006 (return on investment > 1);
3. CIF = 72,447,436.8 (sum of revenues, inflows or positive cash flows);
4. COF = 66,925,000 (sum of investments, costs, expenses—i.e., negative cash flows);
5. CF = 5,522,436.8 (total cash flow).

As the installation is a prototype created for research purposes, the results should be treated with a certain margin of uncertainty [27].

4.2.4. Infrastructural Gap (W4)

When analysing the situation of Poland against the EU, one should look, on the one hand, at those countries that have already invested in the installations for thermal treatment of waste and the number and processing capacity of these installations reached saturation (e.g., Germany, France, Italy, Spain) and they do not need access to finance, and, on the other hand, at the countries—such as Poland—that lack such capacity and need significant investment to develop it. In the case of countries such as Poland, the processing capacity of the installations for thermal treatment of waste is still insufficient. Due to many years of investment gaps, in 2021, Poland had only 1.1 million Mg/year of the existing processing capacity of the installations for thermal treatment of waste (1.4 million—including those planned and underway), while the present demand is at the level of at least 3.8 million Mg/year [65]. These numbers were calculated with the following assumptions: (1) In Poland—according to Statistics Poland's data [22]—12.5 million Mg/year of municipal waste is produced; (2) the target of recycled municipal waste is 65%; and (3) instead of land-filling, waste is referred to thermal treatment—with the limit of 30% of the municipal waste stream produced in the country [65]. Comparing the capacity of the existing installations in European countries, in 2021 in Poland only around 0.3 million Mg of waste per 10 million inhabitants was thermally treated, whereas in other countries, such as Germany or Holland, the figures were 3.3 and 3.6 million Mg/10 million inhabitants respectively [65].

In order to achieve the landfill reduction target to the extent observed, e.g., in Germany or Holland, Poland must support investments in such installations, including, in particular by qualifying them as sustainable investments and providing access to funds that will be used for developing such projects [65]. According to current forecasts, the heating sector in Poland requires investments of PLN 53–101 billion over the next 10 years. One of the major challenges is the need to change the fuel structure. Currently, the share of coal is still 74%, whereas that of renewable energy sources and natural gas—only around 8% each—and the remaining 10% is heating oil and other energy sources. In the process of transformation, the issues that are very likely to be analyzed are: increasing the share of waste heat and the possibility of building installations for thermal treatment of municipal waste [66].

4.3. Opportunities

4.3.1. Converting Waste into Energy as an Element of a Circular Economy (O1)

Pyrolysis is part of a chain of waste management measures that is consistent with the assumptions of a circular economy. This is evidenced by the fact that the products resulting from pyrolysis of solid fuel have practical applications, and thus can be managed in a rational way [51]. Experts stress that waste-to-energy plants play an important role in a circular economy with respect to the management of the residual fraction of mixed municipal waste that cannot be reused or recycled [65]. Results of 2018 research by Malinowski and Chwiałkowski [19] confirmed high availability of proper quality RDF in Poland. Analysis of the parameters of an installation for municipal waste pyrolysis developed by Metal Expert Group in 2018 confirmed that from 1 tonne of RDF with the caloric value of 24 MJ/kg it is possible to achieve 0.6 MWh of electric energy on average and 1.2 MWh of thermal energy [23]. Moreover, the results of research conducted by Malinowski and Chwiałkowski [19] showed that, in 2017 in Poland, the cost of producing 1 kWh of electric energy in a traditional power plant was PLN 0.60, whereas the cost of 1 kWh of energy produced from gas in the process of pyrolysis was PLN 0.20.

One should stress the specific situation of Poland in the context of energy changes and emission reduction. Evolution of the heating system is difficult without using waste as fuel.

Thermal treatment of waste with energy recovery is a component of a circular economy that is complementary to recycling [67]. According to 2018 data from CEWEP (Confederation of European Waste-to-Energy Plants), 96 million tonnes of waste in Europe are annually subjected to thermal treatment with energy and heat recovery. There is still a need for installations—for example in Poland—capable of thermal treatment of 41 million tonnes of waste per year. According to Pająk, thermal treatment of municipal waste is the only method of waste handling that is able to close the waste management system as required by the circular economy. The municipal waste thermal treatment plants operating in Poland are effective, but their network is too small to meet the requirements of a circular economy by 2035 [65].

4.3.2. Advanced Research on the Use of Pyrolysis (O2)

Research on the use of pyrolysis as a method for thermal treatment of selected types of waste is conducted worldwide. The results of such research, as presented in numerous scientific studies, provide solid foundations for economic practice and are perceived as a strength of this method. The research covered the use of pyrolysis for thermal treatment of such wastes as: carbon fiber and glass fiber composites [68–70], waste from olive farms [71], waste plastics from agricultural production [72], waste plastics from landfills [73], waste from citrus fruit processing [74], used car tyres [51,75,76], paper production waste [77,78], sunflower-seed oil waste [79], sewage sludge [51], as well as biogas production waste [80].

4.3.3. Various Uses of Pyrolysis Products (O3)

Products of solid fuel pyrolysis (including waste) are usually as follows: [51]

- pyrolytic gas, which usually contains CO_2, CO, CH, CnHm, H_2, H_2S, dust, and other trace impurities;
- liquid water–tar–oil fraction;
- biochar containing inorganic components of processed fuel.

Products from the process of pyrolysis represent a very good alternative to fossil fuels. The process of waste pyrolysis has many benefits to the natural environment, such as reduction of the use of fossil raw materials and reduction of the volume of landfill waste. Observation of pyrolysis parameters and their impact on pyrolysis products provides specific information on the possibilities of using the resulting products.

The findings of the research by Saffarzadeh et al. [43] suggest that, despite a significantly inhomogeneous feedstock of the waste, high temperature pyrolysis (above 1300 °C) of MSW yields slag with quite homogeneous characteristics and composition. Research by Stelamch [51], among others, confirmed that solid products of municipal waste pyrolysis can be used for energy purposes. Biochar produced in a not very high final temperature of pyrolysis (500–700 °C) has a relatively high caloric value, and because it is a fragile material, it can be easily ground to smaller particles. This allows a homogeneous batch of such a product to be obtained for easier combustion in special technological systems [51]. The biochar received as a result of the pyrolysis of RDF is characterized by moderately high content of ash, but markedly lower than the biochar received as a result of pyrolysis of mixed municipal waste [51].

4.3.4. Access to National Sources of Investment Financing (O4)

Although new investments in the installations for thermal treatment of waste—including pyrolysis—were not included in the EU budget for the years 2021–2027, such installations can be funded from national sources. The largest institution supporting such investments in Poland is the National Fund for Environmental Protection and Water Management (NFEPWM). Under the programme "Rational waste management", investors may apply for substantial subsidies—up to 50% of the eligible costs, with the amount of non-repayable aid not exceeding PLN 50 million. The programme (since August 2020) supports projects to build new installations, or develop or modernize the existing installations, for thermal treatment of waste produced from municipal waste with cogeneration, i.e., ones that in addition to producing heat from waste incineration, generate power as well [67].

Currently, over 1.1 million tonnes of waste are incinerated, which accounts for around 10% of the whole stream. The regulations permit utilization of 30% of waste, which is a better solution than sending waste to landfill sites—a practice that will have to be significantly reduced by 2030 [67]. Additionally, the policy of the Ministry of Climate in Poland states that fuel from waste, the excess of which currently poses a problem to local government units, should be sent to local heating plants more frequently, where it would be incinerated to produce heat [81].

However, the current support programmes in Poland such as "Energy Plus" or "Rational Waste Management" have a relatively short investment horizon [67]. This makes it difficult to develop financial models, both for building new incineration plants and modernizing the heating plants so that they can use waste as fuel. Heating companies tend to finance investments from their own funds [81].

4.3.5. Impact of the Pandemic on Municipal Solid Waste Management (O5)

COVID-19 pandemic caused problems to the functioning of waste management. The literature highlights challenges related to increased waste disposal during the pandemic. There was a huge increase in used personal protective equipment (face masks, gloves, and other protective means) and a wide distribution of infectious waste from hospitals, health care facilities and households under quarantine. The pandemic also saw an increase in the amount of food and plastic waste [82]. The literature presented evidence that the lockdowns imposed due to the pandemic led to an increase in the consumption level in households and resulted in changes in waste amount and recycling. Increased consumption was initially caused by mass purchase of food or panic. Many citizens were forced to stay at home. As a result, there was a significant increase in the purchase of frozen and packaged food since March 2020. Many consumers preferred buying durable food products and changed their habits: they bought online more or built food stocks. As a result, more waste was recorded, especially plastic packaging and food waste [83].

The most cited reasons for the potential change in waste generation are follows: decreased socialization, eating at home instead of eating out, wearing masks, children staying at home instead of going to nurseries/kindergartens, which leads to more cooking activities and thereby waste generation (effect in households: increased use of masks, gloves, toilet paper, food). Example data (increased waste): [83]

- the biggest increase was recorded for plastic packaging and food waste (53% and 45% respectively);
- other types of packaging (e.g., metal, paper packaging), glass bottles, garden waste are also among goods with higher rate of generation;
- no changes in the production of electronic waste;
- food wastage: during the pandemic, products that were most often thrown away were fruit and vegetables (2.63%), whereas those thrown away least often were tomatoes (1.08%);
- in March 2020, Italy saw increased consumption and purchase of bread (180.7%), yeast (189.6%) and cereal/grain (131.4%);
- Great Britain recorded an increased consumption of preserved meat (143%);
- purchase of dried potatoes increased in Germany by around 202%;
- online delivery of meals increased by 73% during the pandemic in Singapore.

Due to the epidemic, tonnes of medical waste—such as masks, gloves, and aprons—are generated every day. According to South China Morning Post reports, the amount of medical waste produced daily during the pandemic increased from 40 to 240 tonnes. During the COVID-19 pandemic, the production of medical waste grew significantly in different countries. Irresponsible management of this type of waste may contribute to disease transmission. In general, SARS-CoV-2 remains active on the surface of the material for 2 to 9 days [84].

The risk of contamination from plastic waste has been increasing exponentially since the World Trade Organization announced the coronavirus pandemic. There are many factors contributing to this increasing risk, including increased consumption of disposable plastics in society, insufficient or no infrastructure for plastic waste management, and urbanization. Another factor is plastic-based personal protective equipment—including millions of surgical masks, medical aprons, face shields, protective glasses, protective aprons, containers for disinfectants, plastic shoes, and gloves—which are widely used to reduce the risk of exposure to severe acute respiratory syndrome coronavirus (SARS-CoV -2) [85–87].

Proper handling and removal of such waste in hospitals, households, municipal centers, and quarantine centers is vital to stopping the public spread of the disease. According to the waste management policy, each piece of such contaminated waste should be properly identified, collected, segregated, stored, transported, processed, and disposed of. Managing such material is very difficult, as people are not as well-trained as the employees of hospitals or municipal centers. Because of the risk of being mixed with other household waste, contaminated waste should be handled separately before final disposal. It should be stored separately from other streams of household waste and collected by local authorities or waste management entities. In addition to training programmes and social awareness, strict observance of the principles of identification, separation, disinfection, transportation, and safe disposal is key to effective and safe management of COVID-19-related waste [88]. Manual sorting and recycling of such waste was reported as restricted for security reasons [89].

4.4. Threats

4.4.1. Lack of EU-Financing of Investments Related to Facilities for Thermal Treatment of Municipal Waste (T1)

In accordance with EU regulations [90], Poland adopted a regulation establishing the waste management hierarchy [91]:

1. Prevention of waste generation;
2. Preparation for reuse;
3. Recycling;
4. Other processes of recovery;
5. Disposal.

The implementation of this hierarchy became a stumbling block to the financing of investments into the construction of facilities for thermal treatment of municipal waste, including pyrolysis. This is because the EU law treats the processes of incineration, gasification, and pyrolysis identically. This is evidenced by the definition contained in Directive 2000/76/EC [92], which states that "an incineration plant" means any stationary or mobile technical unit and equipment dedicated to the thermal treatment of wastes, with or without recovery of the combustion heat generated. This includes the incineration by oxidation as well as other thermal treatment processes such as pyrolysis, gasification, or plasma process [92].

As a result of these regulations, financing of new investments related to facilities for thermal treatment of municipal waste, including by pyrolysis, was not included in the EU's seven-year budget for 2021–2027, recently approved by the European Parliament [93]. This significant change in the ability to partly finance such investments from EU funds may have a negative effect on the process of development of such installations. It will be more difficult for local government units responsible for waste management to finance such capital-intensive projects from their own budgets.

4.4.2. Social Conflicts Related to Space (T2)

The location of facilities for thermal treatment of waste in modern cities poses an increasing problem to city planners and decision makers. Although incineration plants are generally desirable and beneficial to the society, people generally do not want the land in their vicinity to be used for that purpose. Local communities often resort to various social movements—from petitions to protests and demonstrations—in order to object to or overturn the state's location decisions. Through social movements, people may also call for a radical reform of the decision-making related to the location of such facilities. In many cases, location conflicts are so controversial and intense that the projects they concern are suspended or even abandoned. The findings of research by Liu et al. [94] confirm that the sense of injustice is a strong predictor of inhabitants' engagement in this type of activism.

Recent decades have seen an increasing global public objection to the location of new infrastructure [95]. For instance, the protests in Italy in 2012 against waste disposal installations (mainly landfill sites and incineration plants) accounted for 28.3% of all the studied cases of space-related social conflicts [96]. The names NIMBY, LULU, BANANA, NOOS, NOPE, and CAVE seem mysterious at first glance, but all of these acronyms refer to a similar, widespread phenomenon whereby local communities object to having facilities that may impact their quality of life located in their neighbourhood [97].

The name NIMBY ('not in my backyard'), which represents the most common variant of such protests at present, appeared in the USA as early as 1980 and became widespread in Great Britain in the late 1980s. The effect of NIMBYism can be defined as social rejection of the location of facilities, infrastructure, and services that are necessary for the society but have negative connotations. Other acronyms found in the literature, though similar, suggest various degrees of rejection, for instance, LULU's effect ('locally unwanted land use'), BANANA's effect ('build absolutely nothing anywhere near anything'), including the more radical NIABY's effect ('not in any backyard'), which means total opposition to a development project or type of projects irrespective of intended location, or the new phenomenon called YIMBY ('yes in my backyard'), which involves seeking benefits from having a facility in the area [98].

The location literature identifies a range of environmental, social, and psychological factors that may be conducive to a negative reaction to unwanted facilities [96]. They include:

- aesthetic effect of the facility and relations with outsiders [99];
- facility type and transparency of the available opinion [100];
- values related to environmental injustice and integrity of the location process [101];
- unwanted consequences, such as health and material problems, as well as adverse changes to life quality [102];
- perceived risk related to the facility [103];
- trust in the authorities, decision makers, and development organizations [104].

The long process of searching for an appropriate location of an incineration plant can be easily observed in Poland. In the beginning of the 20th century, there was only one municipal waste incineration plant in Poland, and social approval of further development of this technology was very limited. This becomes particularly apparent when compared with such countries as Germany, Austria, Holland, Sweden, or France, where such facilities are quite common in waste management systems and no obstacles exist in obtaining permission to build new ones. A good example is a facility in Dürnrohr in Austria, where social consultations were conducted for two years, resulting in a referendum in which the residents could express their consent or lack thereof. Over 60% of those eligible for voting participated in the referendum, and the project was approved by 74% of the population [105]. The process of the new approach to locating municipal waste management facilities, with a particular focus on incineration plants, was described extensively by Pająk [106].

In Poland, no local community wants to have an incineration plant in its vicinity. Wesołowska [105] stresses that investors must remember the importance of the acceptance by the local community. Properly conducted social consultations shorten the investment process and minimize protests at the stage of plant operation. In Austria and a few other EU countries, it is not possible to make a final decision to build a waste incineration plant without gaining approval through a referendum. Persuading the local residents takes around 2–3 years.

Lu et al. [107] confirmed that the rapid rise in waste incineration caused the stakeholders to pay more attention to the environmental and social impact. Sustainable social development is of key importance to social acceptance and helps to turn NIMBY claims into 'beauty in my backyard' (BIMBY) synergy. The researchers stressed that aesthetic appearance of municipal waste incineration plants plays a part in winning social acceptance for the location of this type of facilities.

Summing up, targeted and deliberate communication aims to use early information measures in a reasonable way and thus prevent a full-scale conflict. However, the waste management system in Poland must change regardless of social resistance. This is dictated by the necessity of alignment with EU standards on the one hand, and practical reasons on the other hand—i.e., problems with acquiring new areas for landfills, shrinking reserves of raw materials, including energy-producing ones (use of the combustion properties of waste), and, simultaneously, a constantly growing demand for energy. Thus, the authorities face a huge challenge—they need to convince the public to accept a certain course of action, conduct a wide-scale educational initiative addressed at children, youth, and the elderly, who are often disappointed by their own economic situation, do not believe in any assurances from the so-called 'authority' and are reluctant to any changes. This will also involve overcoming the stereotypes that have persisted over many years of negligence.

4.4.3. Low Environmental Awareness of the Public (T3)

The process of pyrolysis involves the necessity of waste separation. For many years, various analyses of waste management have pointed out insufficient environmental education among Poles with respect to proper handling of waste. One of the effects of that is low effectiveness of waste separation "at source". In 2020, 13.1 million tonnes of municipal waste were collected, of which only 4.97 million tonnes in a selective manner (37.9%), and as many as 8.14 million tonnes were mixed waste (62.1%) [20]. Based on the results of a 2019 study by [108], only 66% of the Poles surveyed declared waste separation, and 15% of the respondents would know how to segregate exemplary packaging when throwing it away.

The biggest problem with waste separation was recorded among the residents of housing estates with multi-family houses. However, the fact that this problem concerned single-family houses to a smaller degree does not mean that their occupants handle waste properly. Residents of single-family houses often incinerate waste intended for separation in home heating installations [109]. High caloric value of such waste and the cost of its treatment 'encourage' residents to use it for energy generation.

4.4.4. Frequent Changes and Inadequacy of the Legal Regulations (T4)

Waste management using thermal methods is regulated by detailed, increasingly strict legal regulations. Pyrolysis installations are treated under the Polish law as plants for thermal treatment of waste (incineration or co-incineration plants). The Waste Act [91] defines thermal treatment of waste as incineration by oxidation as well as other processes of thermal treatment of waste—i.e., pyrolysis, gasification and plasma process. This process can be conducted exclusively in waste incineration or co-incineration plants.

As law systematically evolves, there is a connection between legal regulations and the possibility of a practical execution of a specific technological process as part of the thermal treatment of waste, and the possibility of using the substances produced in the process of the pyrolysis of specific waste. The unpredictability of law and the change in the financing rules do not encourage potential new investments into installations for thermal treatment of waste. Legislative changes have a negative impact on the profitability of investments in progress and may even block them. However, it is changes in national legislation that will have the strongest impact on the condition of the industry. An example is the plan to lift the prohibition of landfilling high-caloric waste, which will be one of the foundations of a new reform in Poland. The temporary lifting of the prohibition may open up another, cheaper way of waste management: waste will be sent to landfills rather than for energy recovery [81].

Constant changes impact the industry's financial situation. What is particularly concerning is the new tax on unprocessed plastic, which can substantially increase the now-competitive costs of waste incineration. From 1 January 2021, a new fee on non-recycled plastic packaging produced in a member state is paid into the EU budget. With a mandatory surcharge on every tonne of plastics (estimated at PLN 3–3.5 thousand) sent to an incineration plant, the profitability of such plants may drastically decrease. Due to the necessity of ratifying the regulations concerning EU budget financing [110], payments on plastic will be applied retroactively. This means that regardless of the date of the implementation of the EU regulation by member states, the charge will be automatically applied at the beginning of the year. The amount of payment by member states will be EUR 0.80 per each kilogram of non-recycled plastic waste in a given year. The member states with GDPs below the EU average negotiated reduction of the payment. In the case of Poland, this means annual savings of EUR 117 million. Each EURO above this amount will be paid into the EU budget [110].

5. Results of SWOT Analysis

Continuing with the third stage of the study, the authors asked the experts to analyze the interrelationships among the four seemingly independent groups of strategic factors and to assign values to the characteristics. For this purpose, the experts assigned weights in the numerical range (0–1) to particular factors which might affect the application of the pyrolysis process of municipal solid waste in Poland. The sum of the weights in the factor group was 1.0. In a further step, this allowed the following questions to be answered: (1) Will the strengths of pyrolysis allow the opportunities to be taken advantage of? (2) Will the strengths of pyrolysis overcome the threats? (3) Will the weaknesses in pyrolysis hinder the opportunities from being seized? (4) Will the weaknesses in pyrolysis compound the impact of the existing threats? Then the experts identified the interactions between the studied factors—the occurrence of interaction was marked with a value equal to 1, while the absence of interaction with a value equal to 0. The results are presented in Tables 5–8.

Table 5. Key questions of SWOT analysis. Will the strengths of pyrolysis allow the existing opportunities to be used?

Strengths/Opportunities	O1	O2	O3	O4	O5	Weights	Number of Inteactions	Product of Weights and Interactions
S1	1	0	0	1	1	0.22	3	0.66
S2	1	0	1	1	1	0.3	4	1.2
S3	1	1	1	1	1	0.3	5	1.5
S4	1	1	0	0	1	0.18	3	0.54
Weights	0.31	0.15	0.2	0.14	0.2			
Number of inteactions	4	2	2	3	4			
Product of weights and interactions	1.24	0.3	0.4	0.42	0.8			
Sum of interactions							30	
Sum of products								7.06

Table 6. Key questions of SWOT analysis. Will the strengths of pyrolysis overcome the threats?

Strengths/Threats	T1	T2	T3	T4	Weights	Number of Inteactions	Product of Weights and Interactions
S1	0	1	1	0	0.22	2	0.44
S2	0	0	0	0	0.3	0	0
S3	0	0	0	0	0.3	0	0
S4	0	1	0	0	0.18	1	0.18
Weights	0.26	0.13	0.31	0.3			
Number of inteactions	0	2	1	0			
Product of weights and interactions	0	0.26	0.31	0			
Sum of interactions						6	
Sum of products							1.19

Table 7. Key questions of SWOT analysis. Will the weaknesses of pyrolysis be an obstacle to taking advantage of the emerging opportunities?

Weaknesses/Opportunities	O1	O2	O3	O4	O5	Weights	Number of Inteactions	Product of Weights and Interactions
W1	0	0	0	0	1	0.17	1	0.17
W2	1	0	0	1	1	0.24	3	0.72
W3	1	0	0	1	1	0.28	3	0.84
W4	1	0	0	0	1	0.31	2	0.62
Weights	0.31	0.15	0.2	0.14	0.2			
Number of inteactions	3	0	0	2	4			
Product of weights and interactions	0.93	0	0	0.28	0.8			
Sum of interactions							18	
Sum of products								4.36

Table 8. Key questions of SWOT analysis. Will the weaknesses of pyrolysis compound the impact of the existing threats?

Threats/Weaknesses	T1	T2	T3	T4	Weights	Number of Inteactions	Product of Weights and Interactions
W1	0	1	0	0	0.17	1	0.17
W2	0	0	0	0	0.24	0	0
W3	1	0	0	0	0.28	1	0.28
W4	0	0	0	0	0.31	0	0
Weights	0.26	0.13	0.31	0.3			
Number of inteactions	1	1	0	0			
Product of weights and interactions	0.26	0.13	0	0			
Sum of interactions						4	
Sum of products							0.84

In the fourth step of the study the authors calculated the number of interactions occurring between the links, the value of the weights assigned to them and then the value of the product of the weights and the interactions. The received results were assigned to the corresponding fields of the matrix and are presented in Table 9.

Table 9. List of the answers to the questions of SWOT analysis.

Combination	Results of SWOT Analysis	
	Sum of Interactions	Sum of Products of Weights and Interactions
Strengths/opportunities	30	7.06
Strengths/threats	6	1.19
Weaknesses/opportunities	18	4.36
Threats/weaknesses	4	0.84

The obtained results made it possible to determine the most desirable strategy of pyrolysis application in Poland. Based on the results, the recommended strategy for using pyrolysis of municipal solid waste in Poland is an aggressive strategy (Table 10).

Table 10. Matrix of basic strategies in management.

	Opportunities	**Threats**
Strengths	aggressive strategy number of interactions 30 weighted number of interactions 7.06	conservative strategy number of interactions 6 weighted number of interactions 1.19
Weaknesses	competitive strategy number of interactions 18 weighted number of interactions 4.36	defensive strategy number of interactions 4 weighted number of interactions 0.84

The result of the research is the identification of an aggressive strategy. According to the literature [33,34], aggressive strategy recommendation refers to a venture for which strengths and opportunities prevail in the environment. The aggressive strategy of implementing MSW pyrolysis as the leading method in Poland is to maximize the synergies between the strengths of the method and the opportunities from the environment. It is a strategy characterized by strong expansion and diversified development, with the primary goal of taking advantage of emerging opportunities for waste management and simultaneously strengthening its position in the energy market. The identification by the authors of an aggressive strategy for the management of municipal solid waste in Poland using the pyrolysis method represents the most favorable situation possible because in the current economic conditions the strengths of the pyrolysis process prevail and the environment is full of opportunities. As a result, the considered implementation of MSW pyrolysis in Poland has a great potential for expansion and strong, dynamic development based on its own strengths and market opportunities.

At the same time, another result of the SWOT analysis is the identification of existing weaknesses. However, it is extremely important in this process to understand the distinction between weaknesses that are the result of ineffective management and those that are derived from strategy. In the case of management weaknesses, they should be systematically mitigated as they threaten the use of pyrolysis. In turn, weaknesses associated with the chosen strategy should be treated as independent. Summing up the considerations on the SWOT analysis, it should be mentioned that the intention of the authors was to identify the key factors that may influence future situations in the studied area, to give them appropriate weights and only on this basis to assess their significance. Indication of the most important advantages and disadvantages of pyrolysis as a method of MSW management in Poland and analysis of the environment may provide important foundations for making effective decisions regarding selection of the most efficient waste management strategy in Poland.

6. Conclusions

Lack of scientific publications addressing the possibility of using pyrolysis in Poland based on SWOT analysis lends the research conducted by the authors an exploratory character, but on the other hand it prevents a substantive discussion with other researchers. The authors hope that they will make at least a small contribution to filling the research gap in that area.

Wide-scale use of pyrolysis in Poland as a method for thermal treatment of municipal solid waste would help to not only partially solve the problem of the excessive amount of landfilled waste, but also to recover a valuable energy. Pyrolysis of municipal waste is the only thermochemical process in which liquid, solid, and gaseous fractions can be obtained for direct use in various power plants or for production of value-added chemicals. At the same time, the process is more environmentally friendly compared to conventional waste incineration systems, as lower amounts of NO_x and SO_x can be released thanks to the neutral atmosphere used in that process. Moreover, it is possible to purify the resulting pyrolytic gas before its use, with reduced size and costs of such systems compared to the cutting-edge cleaning technology used in incineration plants.

Based on the SWOT analysis, in order to improve the Polish municipal solid waste management indices, the authors recommend that pyrolysis should be used on a wider scale as a thermal method for waste treatment. The following arguments substantiate this recommendation:

1. Advanced research on the use of pyrolysis is conducted in Poland and worldwide, constituting a valuable information base on that process.
2. The proposed method is characterized by a lower emission of pollution, i.e., SO_2 and NO_x compared to an incineration plant.
3. Pyrolysis results in valuable solid (biochar) and gaseous (high caloric pyrolytic gas) products that can be reused, thus reducing the total costs of pyrolysis.
4. The process of waste pyrolysis can be associated with generation of electricity on-premise in regional facilities for municipal waste treatment, preventing the contamination of the environment as a result of transporting RDF to the disposal destinations.
5. Pyrolysis is a very flexible process, which means that the quality of outputs can be shaped by regulating heating speed and temperature.
6. Pyrolysis can be applied to various fractions of municipal waste.
7. Pyrolysis installations can be located in the grounds of a regional facility for municipal waste treatment.
8. The energy recovered from waste can be used for the own needs of a regional facility for municipal waste treatment, and the surplus sold to the power grid, providing an additional source of revenue.

It is also very important to take advantage of the opportunities existing in Poland to implement pyrolysis, namely: movement towards the circular economy and EU-imposed requirements that need to be met, access to national sources of financing investments and the SARS-CoV-2 pandemic, resulting in an increased amount of waste. A variety of applications of pyrolysis products may also help to increase the popularity of pyrolysis in Poland.

A key task to be addressed by the Polish waste management strategy should be raising public awareness of environmental issues. Increased environmental awareness may contribute to wider acceptance of municipal waste management measures, reducing the scale of social conflicts. A huge problem is posed by the instability of the Polish law and the fact that it is inadequate for the present conditions. At the same time, the strategy for municipal waste management should focus on overcoming the weaknesses of pyrolysis. This means, among other things: filling the infrastructural gap by initiating the development of new installations, seeking to verify investment profitability, seeking to increase spending on the research concerning chloride corrosion of installations with a view to reducing or eliminating this phenomenon. The process of pyrolysis should be a subject of further research focused not only on identifying its effects and environmental impact, but, above all, minimizing chloride corrosion of pyrolysis installations and estimating investment profitability for a wider scale implementation of pyrolysis. Based on the analysis, the authors see potential for future research on:

- the development of a biodegradable, solid pyrolysis product, i.e., biochar for the production of building materials, which will reduce the total cost of pyrolysis;
- the possibility of obtaining cheap energy raw material in the form of high-calorific pyrolytic gas, e.g., to fuel metallurgical heating furnaces, as a substitute for natural gas;
- the possibility of developing the technology for use in small municipal utilities plants, allowing the calorific fraction of municipal solid waste to be managed efficiently and cost-effectively;
- the possibility of using pyrolysis for the thermal treatment of a new category of municipal waste, i.e., municipal waste mixed with medical waste generated during the pandemic, with an above-average proportion of plastics;

- the impact of pyrolysis on the environment, in particular the formation and destruction of polycyclic aromatic hydrocarbons (PAHs) and polychlorinated dibenzodioxins and dibenzofurans (PCDD, PCDF), precursors of chloride corrosion;
- promotion of the principles of sustainable development and implementation of pro-ecological solutions being a marketing asset in the market activity of enterprises.

Moreover, the expected increase of power consumption as a result of electro mobility development and the expected gradual shutdown of coal power plants will contribute to the search for alternative methods of generating energy from waste [111]. The implementation of the solutions of thermal treatment of waste using pyrolysis, as proposed in the paper, will help to promote the principles of sustainable development and implement environmentally friendly solutions as a marketing asset in the market activities of enterprises. With a limited number of available solutions in that area, there is a large demand for innovations, which should involve overcoming the key challenges in the area of waste management, especially plastic waste generated during the pandemic, and incorporating new technologies for thermal treatment of waste into the existing system of waste management.

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