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Efficient thermal solutions in the management of hazardous medical waste

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Abstract. The transformation of medical waste into energy requires the implementation of specialized technologies and expertise in the composition of hazardous medical waste, both at the point of generation and as a result of its treatment through various disposal/recovery methods. This study emphasizes the necessity of recycling medical waste, a determining factor in the efficient execution of services such as collection, transportation, storage, and final disposal of hazardous medical waste. The technology of low-temperature thermal treatment of medical waste is a business model that can be utilized in combination with various factors, such as the capabilities of companies, specialists in the field of medical waste, , and the amount of waste generated in the service area. The sustainability of business models based on these eco-friendly technologies in the field of medical waste recovery depends on the supply chain of medical waste, the monitoring of transport costs for these special categories of medical waste, and the access chain to the final market for hazardous medical waste recovery.

Keywords: sterilization, circular economy, pollution, alternative methods, recycling, hazardous medical waste.

1. Introduction

To maintain a healthy environment, selective waste collection is a priority and a legislative requirement. Materials that may initially appear to be waste can be treated and reused in various greener ways, which help avoid unnecessary waste. Recycling and reuse are the easiest measures to implement in order to help the environment. Optimal waste recycling means applying all necessary operations before disposing of treated waste in landfills, thus reducing or avoiding negative impacts on natural ecosystems. [1]

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Through environmental auditing processes and environmental impact assessments, the negative effects of each phase of the life cycle of hazardous waste disposal technologies are identified. This paves the way for more eco-friendly technologies, which generate environmental benefits and cost savings related to the operation of hazardous medical waste disposal technologies. Green procurement stimulates the demand for recycled materials and the production of raw materials to introduce all waste, both produced and generated, into the technological cycle.[2] The market value of recycled products and goods plays an important role in evaluating the costs for the continuous implementation of hazardous medical waste recovery methods. [3]

Selective collection at the source determines the choice of an optimal final disposal method for hazardous medical waste and is the main priority of the EU. Landfills should be the last option for final disposal. Hazardous medical waste refers to those categories of medical waste that require special handling, collection, storage, transport, and disposal measures. The implementation of management processes directly proportional to the category of hazardous medical waste, depending on the specifics of the generating healthcare unit, is only achieved through awareness of the importance of proper hazardous medical waste management. [4]

Extended producer responsibility for waste is an essential tool for transitioning to a circular economy, as it provides an effective framework for the proper management of waste, including hazardous medical waste. Extended Producer Responsibility (EPR) shifts the responsibility for post-consumer product generation from the government and consumers to producers. Producers are obliged to manage their products throughout their entire life cycle, including final waste disposal, driving them to design more durable, reusable, and recyclable products. [5] The challenges faced by an operator in implementing new technologies are due to the high costs of the recovery and recycling system. Infrastructure and investments are part of the efficient and effective operation of hospital hazardous medical waste disposal technologies, as described in Fig 1.

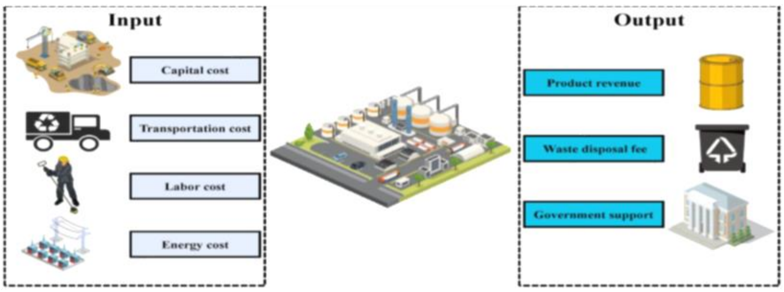

Fig. 1. Inputs and Outputs of Medical Waste Recovery & Recycling Systems (Su et al., 2021).

The efficiency of hazardous medical waste disposal technology depends on numerous factors, including the nature and composition of the medical waste, equipment and facilities, availability of operations and physical maintenance, spaces allocated for the proper functioning of the technologies, access to utilities, the possibility of implementing photovoltaic panels, the skill set of the employed personnel, regulatory requirements, public acceptability, costs, and the volume of hazardous medical waste (85% non-hazardous medical waste, 15% hazardous medical waste)[6].

2. Methods

2.1. International situation

The specialized literature and European legislation place significant importance on the classification of hazardous medical waste and the use of standard codes. Depending on the nature of the medical waste and the presence of harmful content, an adapted final disposal method, accepted by the World Health Organization, is applied [7].

The literature analyzes the environmental impact factors of 8 final disposal technologies for medical waste and has found that 94% of the carbon in medical waste is released as CO_2 in both incineration and sterilization—MSW technologies. Sterilization of medical waste followed by its disposal results in carbon being stored as organic matter in landfill residues.

Based on the specialized literature, the analysis of the 8 disposal methods has a significant effect on the development of the Medical Waste Management Strategy at both national and international levels, according to the results in Table 1—centralized data. [8]

Table 1. Carbon Flows for One Ton of Medical Waste Disposed of Through 8 Technologies (source Ji et al., 2024)

Medical waste 300,86 kg	Medical waste pretreatment 300,86 kg	Incineration 326,6 kg	Carbon dioxide emissions 326,34 kg	CO_2 1196,59 Kg	TECHNOLOGY PI
	Disel 25,74 kg		Carbon monoxide emissions 0,34 kg	CO 0,61 Kg	
Medical waste 300,86 kg	Medical waste pretreatment 300,86 kg	Incineration 303,9 kg	Carbon dioxide emissions 303,62 kg	CO_2 1132,72 Kg	TECHNOLOGY RKI
	Diesel 30,04 kg		Carbon monoxide emissions 0,29 kg	CO 0,68 kg	
Medical waste 300,86 kg	Medical waste pretreatment 300,86 kg	Medical residues 293,05 kg	Landfill residue 290,31 kg	CH_4 3,65 Kg CO_2 123,02 Kg	TECHNOLOGY SSL
	Diesel 25,74 kg	Carbom dioxide emission 33,53 kg	Biogas 2,74 kg		

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<table>
<tr><td rowspan="2">Medical waste 300,86 kg</td><td rowspan="2">Medical residues 284,51 kg</td><td colspan="2">Landfill residue 281,69 kg</td><td colspan="2" rowspan="2">CH_4 3,76 Kg</td><td colspan="2" rowspan="2">TECHNOLOGY MS-L</td></tr>
<tr><td colspan="2">Biogas 2,82 kg -</td></tr>
<tr><td rowspan="2">Medical waste 300,86 kg</td><td rowspan="2">Medical residues 330,76 kg</td><td colspan="2">Landfill residue 327,48 kg</td><td colspan="2" rowspan="2">CH_4 4,37 kg</td><td colspan="2" rowspan="2">TECHNOLOGY CD - L</td></tr>
<tr><td colspan="2">Biogas 3,28kg</td></tr>
<tr><td rowspan="3">Medical waste 300,86 kg</td><td>Medical waste pretreatment 300,86 kg</td><td colspan="2">Medical residues 293,05 kg</td><td>Incinerations 293,05 kg</td><td>Carbon dioxide emissions 292,96 kg</td><td>CO_2 966,78 Kg</td><td rowspan="3">TEH. SS-MSWI</td></tr>
<tr><td rowspan="2">Diesel 25,74 kg</td><td colspan="2">Carbon dioxide emissions 33,55 kg</td><td>Diesel 0,022 kg</td><td>Carbon monoxide emissions 0,11 kg</td><td>CO 0,24 Kg</td></tr>
<tr><td colspan="4">CO_2 123,02 kg</td><td></td></tr>
<tr><td rowspan="2">Medical waste 300,86 kg</td><td colspan="2" rowspan="2">Medical residues 284,51 kg</td><td colspan="2">Incineration 284,51 kg</td><td>Carbon dioxide emissions 284,42 kg</td><td>CO_2 933,6 kg</td><td rowspan="2">TEH. MS-MSW1</td></tr>
<tr><td colspan="2">Diesel 0,023 kg</td><td>Carbon monoxide emissions 0,11 kg</td><td>CO 0,25 kg</td></tr>
<tr><td rowspan="2">Medical waste 300,86 kg</td><td colspan="2" rowspan="2">Medical residues 330,76 kg</td><td colspan="2">Incineration 330,76 kg</td><td>Carbon dioxide emissions 284,42 kg</td><td>CO_2 1030,56 kg</td><td rowspan="2">TEH. CD-MSW1</td></tr>
<tr><td colspan="2">Diesel 0,027 kg</td><td>Carbon monoxide emissions 0,13 kg</td><td>CO 0,29 kg</td></tr>
</table>

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TECHNOLOGY PI	Pyrolysis
TECHNOLOGY RKI	Rotary Kiln Incineration
TECHNOLOGY SSL	Thermal Sterilization Followed by Landfilling
TECHNOLOGY MS-L	Microwave Sterilization Followed by Landfilling
TECHNOLOGY CD-L	Chemical Disinfection Followed by Landfilling
TECHNOLOGY SS-MSWI	Thermal Sterilization Followed by Incineration
TECHNOLOGY MS-MSW1	Microwave Sterilization Followed by Incineration
TECHNOLOGY CD-MSW1	Chemical Disinfection Followed by Incineration

Without a proper environmental performance assessment of an investment, we cannot promote eco-friendly technologies.[9] Harmful greenhouse gas emissions must fall within the limits imposed by legislation. The monitoring of emissions from the transportation of medical waste takes into account an energy consumption of 1362 kJ/t·km, according to research, with a fuel mix of 68% diesel and 32% gasoline, and an engine efficiency of 30%. [10]

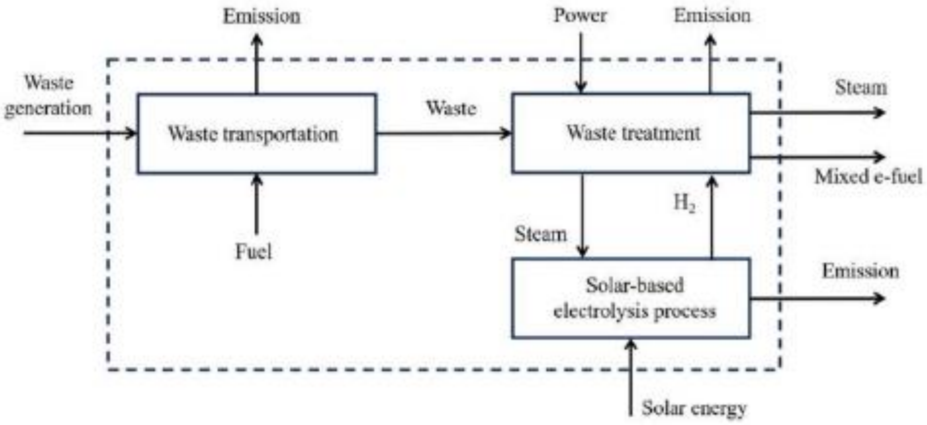

Fig. 2. System Boundary for Environmental Analysis Source: Zhou et al., 2024

2.2. National situation

According to environmental reports published by the National Institute of Public Health Bucharest, in the past 4 years, 4 low-temperature thermal treatment technologies using microwaves for hazardous medical waste have been put into operation, as opposed to the existence of incinerators. This is also reflected in the data centralized on the website www.insp.ro.[11]
Selective collection of medical waste is the determining factor in choosing the final disposal technology. The typology of regions provides information on the implementation of waste management strategies in compliance with the proximity principle [12] —waste generated should be disposed of at final disposal facilities located as close as possible. [13]

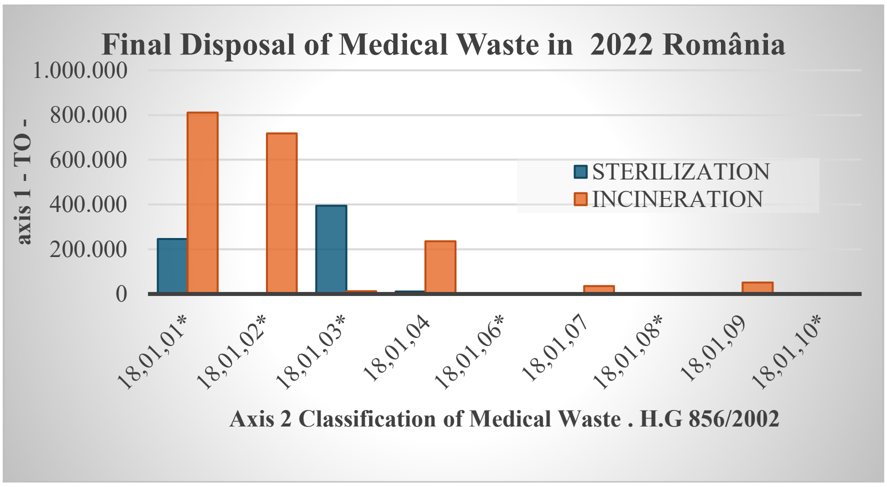

Fig. 3. Final Disposal of Medical Waste by Waste Codes at the National Level – Processed Data Source: www.insp.ro[14]

Microwave sterilization is based on high-frequency electromagnetic waves at 2450 MHz. The principle of treatment with electromagnetic waves is characterized by their absorption by water, fats, and proteins. It is identified by the selective energy absorption characteristics of microbial cells, placing them in the high-frequency oscillation field of electromagnetic waves. The vibration of the electric field causes energy to be transferred to the membrane. causing rapid growth, leading to cell death and killing the pathogens in the medical waste.

Fig. 4. Microwave Thermal Treatment Equipment www.ecosteryl.com

Moisture content in medical waste has a significant impact on microwave treatment. Similarly, the exposure time and mixing intervals of medical waste also affect the treatment process. Analysis of hazardous medical waste disposal technologies at a national level reveals that a closed, automated, and easy-to-operate system with minimal environmental pollution is required. According to the technical specifications provided by the authorized national economic operator, the technology is dismountable, designed to be assembled in enclosed spaces as close as possible to the waste generation site. Access to utilities can be adjusted based on the area. Potable water supply can be sourced from a nearby well if there is no distribution network in the vicinity. Electrical power supply can be supplemented with the installation of photovoltaic panels.[15]

After electromagnetic treatment, the resulting medical waste can be stored in landfills as municipal waste, according to analysis reports showing that the treated medical waste is inert. This technology is not suitable for treating blood or chemical substances and may produce an unpleasant odor [16].

Biomass is the primary carrier of liquid waste, as most medical materials in biomass are cotton dressings, with cellulose being their main component. During medical procedures, most bodily fluids, including blood and other liquids, are absorbed and stored in gauze dressings, making them the largest moisture carriers in medical waste. In conclusion, the bulk density of medical waste is 249 kg/m³, and the moisture content is 44.75%. Without information on the density of medical waste, it is not possible to calculate an efficient cost per transport unit and final

processing capacity of medical waste. Information about the characteristics of medical waste is essential for defining the type of equipment required for hazardous medical waste treatment. Moisture content is one of the key parameters in the disposal process of hazardous medical waste.[17]
The presence of a high moisture percentage reduces calorific value. Increased moisture in waste leads to the proliferation and spread of bacteria and infection sources (see Fig.5).[12]

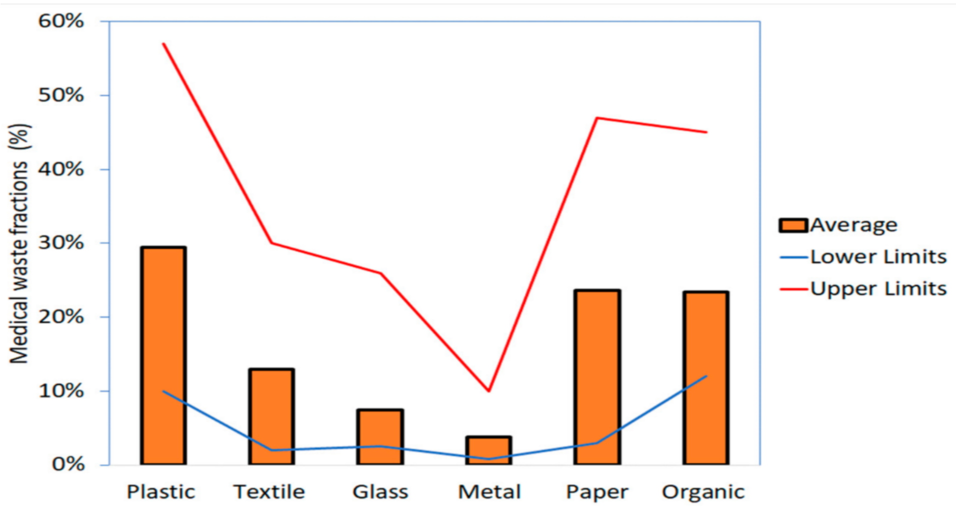

Fig 5. Average values, upper limits, and lower limits of the main medical waste fractions[12]

3. Results and discussion

As demonstrated by the comparative analysis of the 8 final disposal technologies for medical waste, emissions are environmental indicators that show higher values when using processes such as semi-dry treatment, acid absorption, dust removal, residual gas treatment, and wastewater treatment. Adopting and exploring composite materials with physical absorption properties for toxic elements is a potential strategy to reduce dependence on chemical agents and minimize pollutant emissions. [10]

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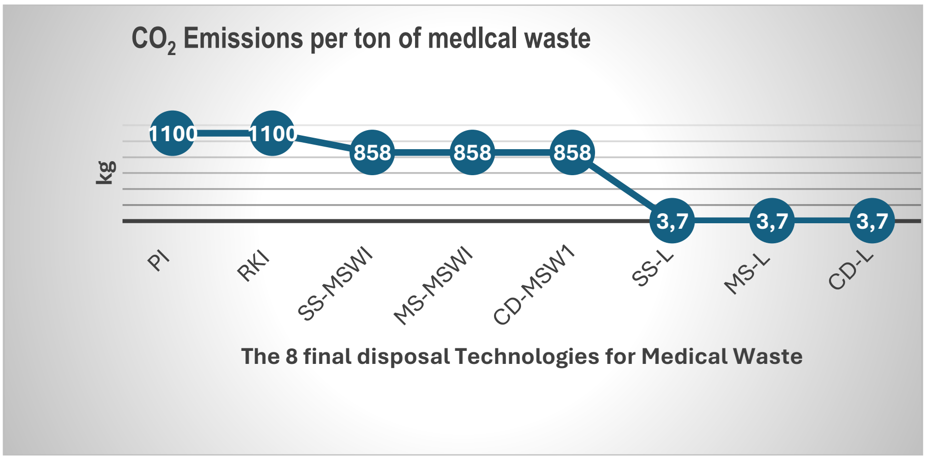

Fig. 6. CO_2 Emissions of the 8 Analyzed Technologies - Processed Data Source (Zhou et al., 2024)

The comparative analysis of hazardous medical waste final disposal installations helps identify optimal integrated solutions for implementing and promoting systems that support and advance the circular economy. For Pyrolysis (PI) and Rotary Kiln Incineration (RKI), it is noted that one ton of disposed medical waste produces 1.1 tons of CO_2. Processing one ton of medical waste using technologies such as SS-MSWI (thermal sterilization followed by incineration), MS-MSWI (microwave sterilization followed by incineration), and CD-MSWI (chemical sterilization followed by incineration) results in only 78% of the CO_2 emissions produced by PI and RKI technologies. Specifically, PI (pyrolysis) and RKI (rotary kiln incineration) technologies produce approximately 1617-1655 kg of CO_2 per ton of medical waste, while the other technologies emit only 18.6-36% of this amount. Greenhouse gases emitted by SS-L (thermal sterilization followed by landfilling), MS-L (microwave sterilization followed by landfilling), and CD-L (chemical sterilization followed by landfilling) technologies are only 3.7 kg. [9]
The quality of thermally treated medical waste is constantly monitored throughout the entire treatment process, with temperature recordings for continuous monitoring. To achieve high-performance technology status, periodic analysis reports are conducted. [18] Contamination reduction is assessed through microbiological evaluation of both untreated raw waste and treated waste. During testing, the total bacterial flora of untreated waste before treatment ranged from 22,000 CFU/g to 17,000 CFU/g (CFU = colony-forming units). After treatment, bacterial content was significantly reduced, with their presence no longer detectable (below 4 CFU/g)[19].
For the optimal implementation of hazardous medical waste disposal systems, technologies that combine lower CO_2 emissions with high effectiveness in contamination reduction should be prioritized, thus supporting circular economy goals and protecting public health.

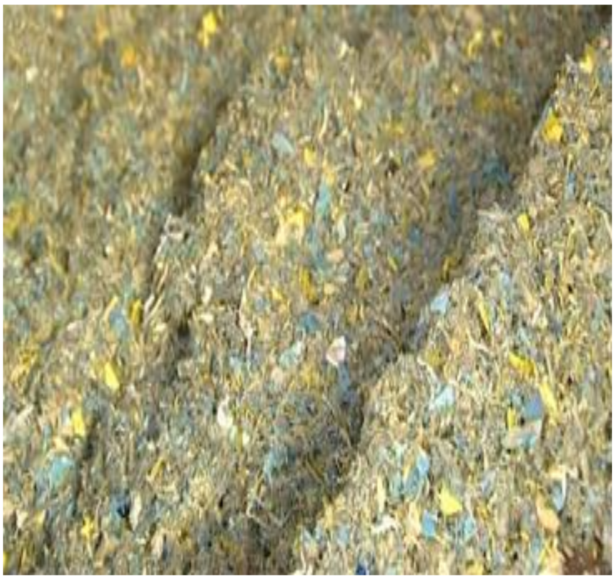

Fig. 7. Medical waste treated thermally with microwaves. Source: www.ecosteryl.com

The quality of thermal treatment is monitored using a test sample introduced into the neutralization flow at the entry point and retrieved at the exit of the sterilized waste. Decontamination quality is checked in real time, with operational parameters recorded every 30 seconds. This technology does not generate wastewater or emissions. The microwave treatment of medical waste produces a specific odor related to the heating and moisture of plastic, which is within legal limits. (www.ecosteril.com)

From an environmental protection perspective, the air extraction system in the thermal treatment facility prevents dust from being released from both the feed and discharge hoppers. Air treatment through washing, disinfection, deodorization, and filtration with activated carbon maintains air quality. Noise levels are below the minimum standards in force.

The efficiency of the thermal treatment technology flow is between 90-99%. After thermal treatment, medical waste becomes inert, with a volume reduction of up to 80%-90%. [19] During incineration, only about 4-6% ash is produced[13]

Calorific value is a determining factor in selecting final waste valorization operations. Table 3 calculates the calorific value of each component in the structure of medical waste to develop a disposal recipe, taking into account their combination in the process.[20]The technical datasheet of the equipment presents a functional cost of 0.40 kW/kg of medical waste processed thermally by microwave (for a source of 270 kg of waste - 40 minutes of operation).[21]

0,40 kw = 0,40 lei (ron)
1 kg medical waste Thermally Treated [22]

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Economic barriers faced by a company aiming to enter the market include high costs associated with the acquisition of equipment, as well as costs related to operation, maintenance, and upkeep.[22] The cost of medical waste recovery and recycling systems is a major obstacle that puts the promotion and implementation of new technologies on hold. [23]

Fig. 8. Metal recovery equipment. Source: www.ecosteryl.com

According to the data presented in the Trial Report (2022) from the company that authorized the use of data on the chemical analysis of a 250 kg waste sample diluted with distilled water at a ratio of 1/10, the metal content complies with the parameters set by national legislation. Consequently, waste treated thermally by microwave is acceptable for disposal at non-hazardous waste landfills. As indicated in the analysis report of medical waste treated by microwave technology, heavy metals can be recovered and valorized through a technological assembly following the microwave technology, a procedure that is conducted internationally.[24] (www.ecosteryl.com)

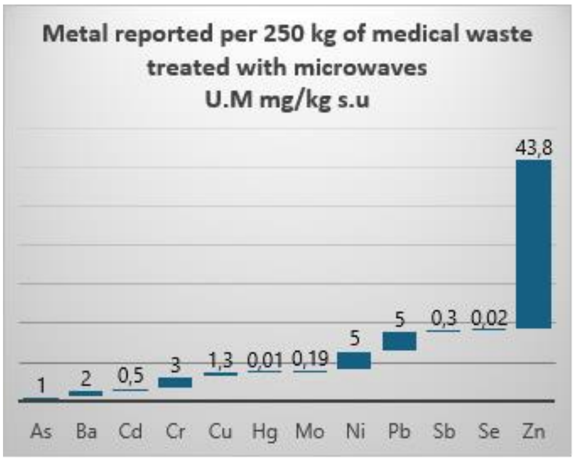

Fig. 9. Metal content in 250 kg of medical waste treated thermally by microwave – Processed Report 2022

The promotion of support and funding policies for industries at the regional level represents the confidence that economic operators can have in innovative investments, which contribute to medium- and long-term development.[25]
At the national level, according to the website www.anpm.ro and the annual reports issued by INSP Bucharest, [26] inert medical waste is transported to authorized final waste landfills, despite their calorific value. This waste can be reused as raw material for co-incineration or other technologies, such as molecular waste disintegration technology for converting waste into electricity, according to the project implemented in 2024 in Tarnăveni. Specifically, from 1 ton of shredded and dried waste, approximately 400 m³ of gas can be obtained, with the exact quantity depending on the calorific value of the waste. The gas produced, which has a calorific value similar to that of methane gas, can generate approximately 1.1-1.15 MW/h of electric current, of which up to 10% will be used for operating the facility. Thus, by generating gas over the course of a year, the County Council aims to produce approximately 18,240 MWh. www.monitorulcj.ro

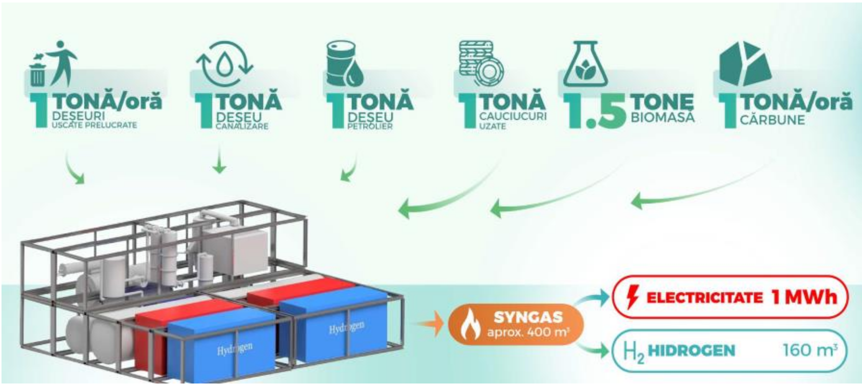

Fig. 10. Molecular disintegration technological flow. Source: www.wpowertech.ro

4. Conclusions

The microwave thermal treatment technology for hazardous medical waste is easy to assemble and operates with minimal utility connections. The cost of equipment for the recovery and recycling of treated medical waste is the primary obstacle that puts the promotion and implementation of new technologies on hold. [27] Effective management of medical waste requires specialized personnel with solid knowledge of the relevant market.
To properly manage all hazardous medical waste generated by public and private healthcare facilities, it is important that the authorized operator in this field has both thermal treatment methods and backup equipment to avoid losses that may occur during maintenance periods, technical failures, or the inability to dispose of all categories of medical waste. [28]HG [29]Typically, especially in the case of

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hazardous waste, a well-executed mixing recipe (by percentage) based on medical waste codes minimizes the need to add auxiliary fuel, according to the calorific value calculation. [30]

Microwave thermal treatment technology is an eco-friendly model for managing medical waste and a development point in transforming it into raw material for other industries due to the following aspects:

1. Efficiency: Microwave technology can efficiently treat hazardous medical waste without requiring pre-treatment or sorting stages, due to the medical waste codes being subject to final disposal via this technology. [31]
2. Safety: Microwave treatment is conducted in a closed circuit, protecting operators from accident risks associated with other methods, such as incineration or gasification[32].
3. Environmental Protection: The use of microwave technology does not generate toxic gas emissions and particles into the atmosphere, compared to other medical waste treatment methods, such as steam sterilization.[33]
4. Flexibility: This technology can be adapted to various capacities, depending on the amount of medical waste generated/collected over time, and can be installed in different locations, including areas with limited space, within an enclosed hall.
5. Energy Efficiency: Microwave thermal treatment requires only electrical energy, eliminating the need for gas or other fuels. Electricity can also be provided by photovoltaic panels.[34]

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