Annals of the Academy of Romanian Scientists
Online Edition Series on Physics and Chemistry Sciences
ISSN 2559-1061 Volume **5**, Number **2**/**2020**

SUSTAINABLE ALTERNATIVES FOR HAZARDOUS WASTE MANAGEMENT

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Abstract. *In order to ensure a sustainable economic and social development and maintain the quality of the environment, adequate waste management and conservation of natural resources are required. It is therefore necessary to apply an integrated waste reprocessing and recycling system, based on specific technologies, which facilitate, in the first stage, the recovery of valuable waste materials and, subsequently, the recovery of all materials and energy. Among the waste generated, a significant quantity is classified as hazardous waste. This paper has as main objective the analysis of waste management alternatives with an emphasis on hazardous waste management. Small and large generators of hazardous waste and environmental impact are considered as well as options for reducing hazardous waste quantities. Following an algorithm proposed in literatureh, the decision of appropriate methods of treatment and disposal of hazardous waste is made based on three main factors: physical state of hazardous waste, hazard criterion, composition criterion. On this basis, specific schemes for hazardous waste processing and disposal were established. A special attention was paid to alternatives for the treatment and disposal of hazardous waste in the form of accumulators and spent batteries and recovery of critical metals as secondary critical metals.*

Keywords: batteries**,** hazardous waste, management alternatives, waste generation

https://doi.org/10.56082/annalsarsciphyschem.2020.2.93

1. Introduction

Human civilization is based on production and consumption, from which waste is generated, which is a huge loss of resources both in terms of materials and

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energy. Indeed, the quantities of waste can be seen as an indicator of the material efficiency of society. Excessive amounts of waste result from [1]:

- inefficient production processes;
- low durability of goods;
- unsustainable consumption patterns

The diagram in Fig. 1 shows that the most effective way to alleviate the problem of solid waste disposal is to reduce both the amount and toxicity of the waste generated, but while people are looking for a better life and a higher standard of living, they tend to consume more goods and generate more waste. Consequently, the company is looking for improved waste management methods and ways to reduce the volume of waste that is dumped.

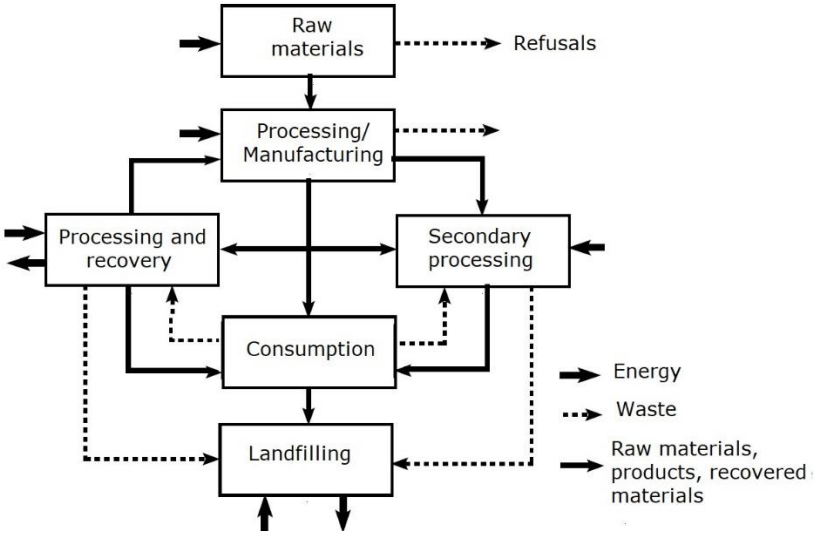

Fig. 1. The flow of materials and waste in an industrial society (adapted upon [1])

In order to ensure a sustainable economic and social development and maintain the quality of the environment, adequate waste management and conservation of natural resources are required. Initially, waste management aimed to dispose of waste and clean up cities. However, modern management looks at waste differently than in the past [2]. First of all, they are no longer considered losses, but a secondary source of raw materials and materials. Therefore, waste management is a complex process because it involves many technologies and disciplines. These include technologies associated with the control of the generation, handling, storage, collection, transfer, transport, processing and

disposal of solid waste. All these processes must be carried out in accordance with existing legal and social regulations, which protect public health and the environment and are aesthetically and economically acceptable. In order for the elimination process to respond to public attitudes, the disciplines to be considered also include administrative, financial, legal, architectural, planning and engineering elements. All these disciplines must communicate and interact with each other in a positive interdisciplinary relationship for an integrated waste management plan to be successful [3].

It is therefore necessary to apply an integrated waste reprocessing and recycling system, based on specific technologies, which will facilitate, in the first stage, the recovery of valuable waste materials and, subsequently, the recovery of all materials and the recovery of waste energy. biogas and / or incineration [1].

Waste management is a complex subject with a multitude of components. In particular, hazardous waste management in the European Union is a particular challenge. In principle, all waste incorporates a certain degree of hazard, if its management is poor. However, some of the waste is dangerous in the true sense of the word, and the negative effects generated by negligent management are direct and severe. Although the European Commission (EC) has undertaken a number of studies on the implementation of the WFD provisions on municipal waste, no recent studies have been carried out to assess the implementation of the provisions on hazardous waste.

Hazardous waste is represented by "materials, substances or products that the owner gets rid of, has the intention or obligation to dispose of, coming from households, institutions, companies, rural and urban areas and have hazardous properties - explode, oxidize, are strong flammable, irritating, harmful, toxic, rusty, infectious, carcinogenic or mutant" [4]. According to USEPA [5], waste is hazardous if it poses a substantial threat to human health or the environment. Hazardous waste poses a greater risk to the environment and human health than non-hazardous waste and thus requires a stricter control regime. This is specified in particular in Articles 17-20 of the Waste Framework Directive (WFD) [6], which specify additional obligations for labeling, record keeping, monitoring and control from "cradle to grave", ie from waste production to final disposal or recovery. In addition, the mixing of hazardous waste is prohibited to prevent risks to the environment and human health. Moreover, Article 24 allows for exemptions that can be granted to installations that are more restrictive when treating hazardous waste [6]. Technical norms on the management of hazardous waste activities "govern the separate collection, packaging, temporary storage, transport, treatment, recovery and disposal of hazardous waste, including the supervision of these

operations and the subsequent maintenance of the sites used, paying special attention to hazardous waste to prevent environmental contamination and damage to health ”(www.anpm.ro).

Classification into hazardous and non-hazardous waste is based on the system for classification and labeling of hazardous substances and preparations, which ensures the application of similar principles throughout the life cycle of materials. The hazardous waste properties are set out in Annex III to Directive CR 98 [6] and are further specified by Decision CE 532 [7] establishing a list of wastes, as last amended by Commission Decision 955 [8]. These properties are described in Fig. 2, according to the WFD provisions.

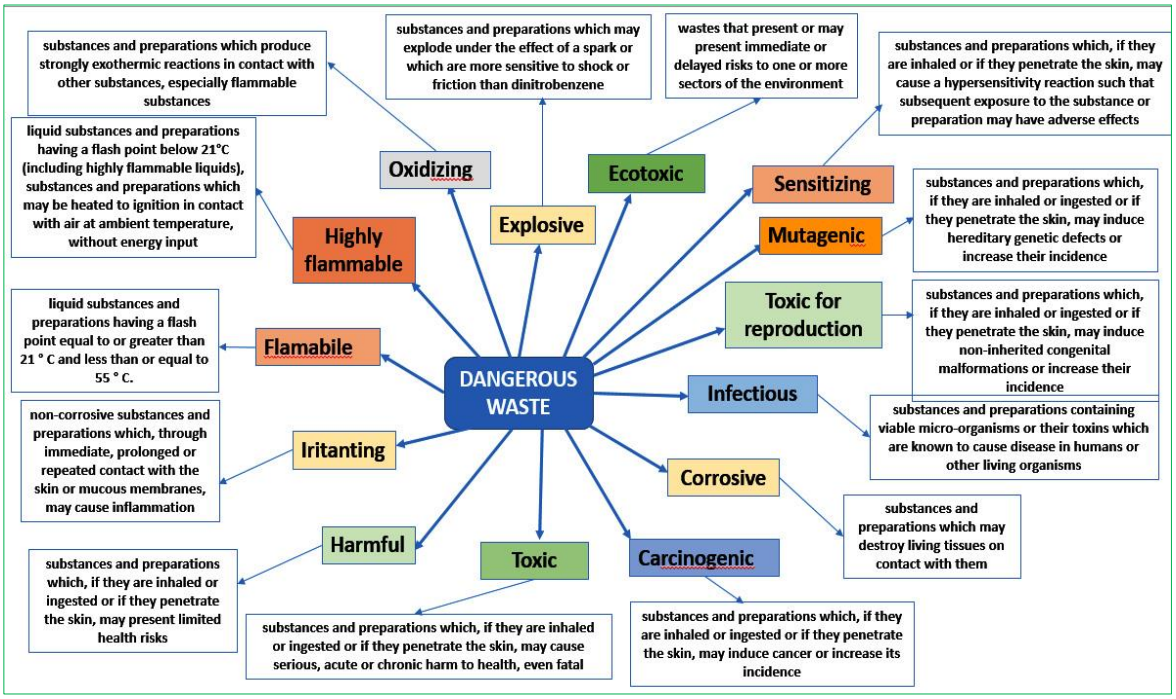

Fig. 2. Classification of hazardous waste according to the properties that determine its hazardousness

2. Generation and treatment of hazardous waste in the European Union

Among the waste generated in the EU-28 in 2016, a quantity of 100.7 million tons (4.0% of the total) was classified as hazardous waste [9].. Compared to 2010, 4.9% more hazardous waste was generated in the EU-2016, which represents an increase in the amount from 96.0 to 100.7 million tonnes. In 2016, the share of hazardous waste in total waste generation was below 10.0% in all EU

Member States, except Estonia and Bulgaria, where they accounted for 39.9% and 11.1% of the total, respectively (Fig. 3). The very large share for Estonia was mainly due to the production of energy from the oil shale. Among the non-member countries shown in Fig. 3, Serbia recorded the largest share of hazardous waste in total waste generation (35.2%) due to intense mining and quarrying, followed by Montenegro (19.4%) and Norway (14.6%)).

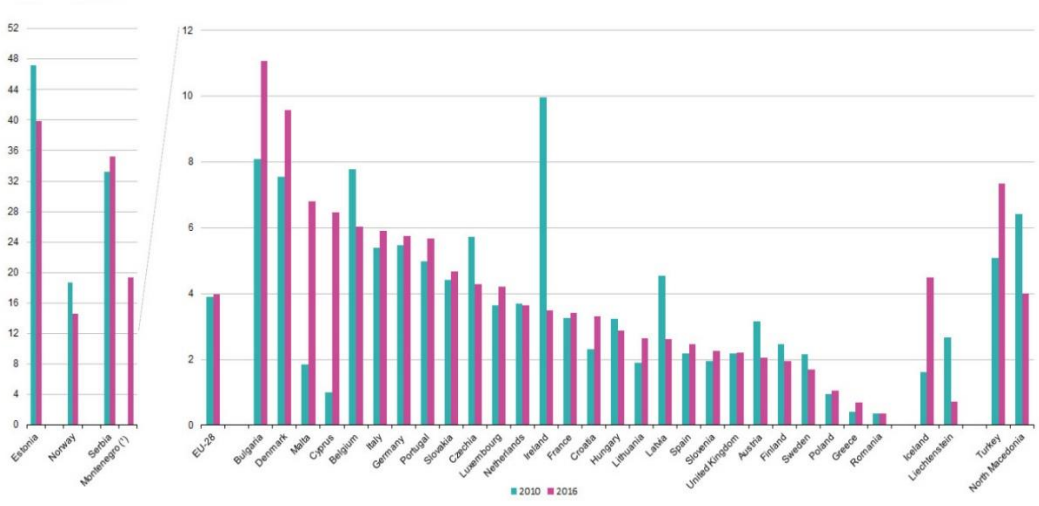

Fig. 3. Hazardous waste generated in 2010 and 2016 (% of total waste) [9]

In total, 76.8 million tonnes of hazardous waste were treated in the EU-28 in 2016, more than half of which were treated in only three EU Member States, Germany (28.0%), Bulgaria (17.2%).) and Estonia (12.5%) (Fig. 4). According to Eurostat data (2019), in 2016, 33.9% of hazardous waste treated in the EU-28 was landfilled, in other words deposited on the ground or released into bodies of water, equivalent to 51 kg per inhabitant (Fig. 5).

3. Characteristics of hazardous waste

The hazardousness of a waste is a property that refers to its ability to pose a sufficient threat to be included in the regulations on hazardous waste. The hazard must be detected using standard test methods. The characteristics that give hazardous waste are: **flammability, corrosion, reactivity, toxicity.** These wastes are also assigned codes as those in the list (example D00X) [10].

3.1. Flammability

Flammable waste ignites easily and supports combustion (for example: many paints, solvents and other industrial waste). The most flammable wastes are in the liquid state.

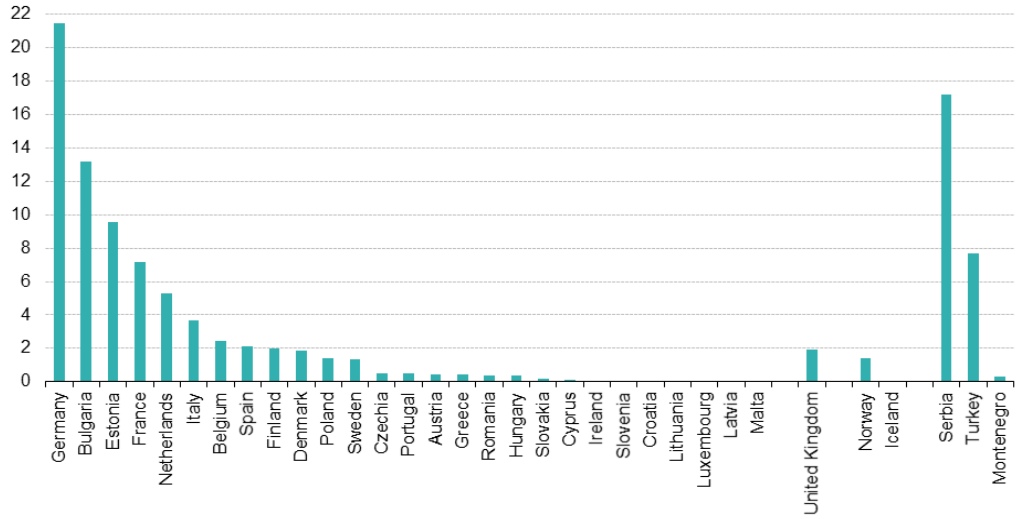

Fig. 4. Degree of hazardous waste treatment in European countries, 2016 (thousands of tons)

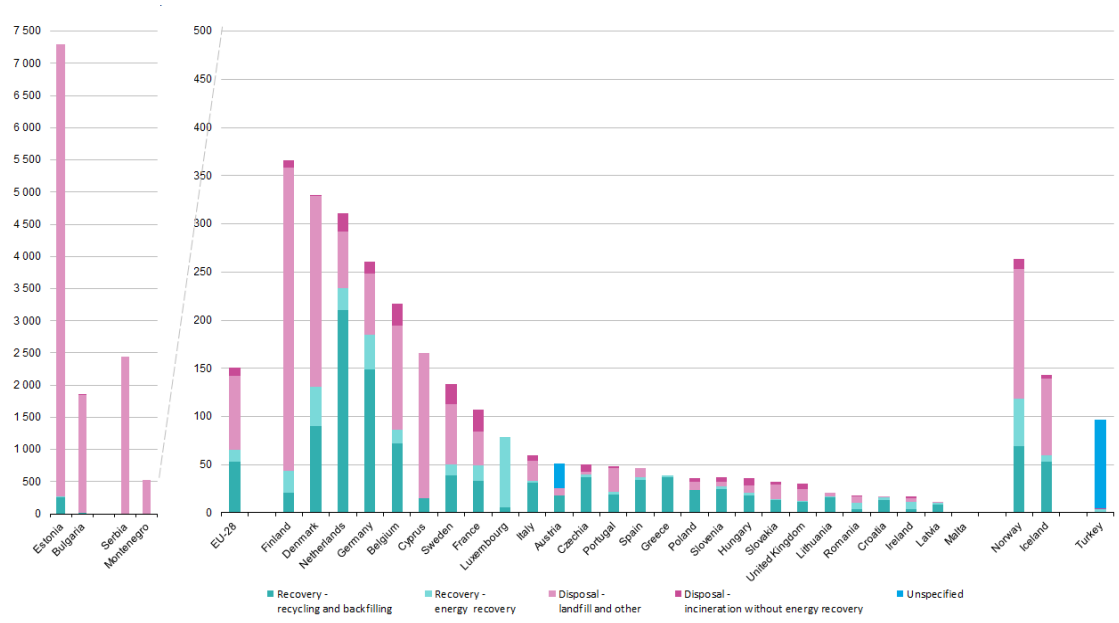

Fig. 5. Hazardous waste treatment processes, 2016 (kg per inhabitant)

There are three types of flammable forms [11, 12]:

- flash point liquids - the lowest temperature at which vapors ignite (600C) (examples: include alcohol, petrol and acetone).
- solids that burn spontaneously.
- oxidizing substances and compressed gases.

This property is highlighted by the flash point test which determines the lowest temperature at which a chemical compound ignites when exposed to a flame. An nonliquid waste can be dangerous due to flammability if it can ignite spontaneously and burn so strongly as to create a hazard.

3.2. Corrosivity

Corrosive waste is acidic or alkaline (basic) waste that can easily corrode or dissolve metals or other materials. They are among the most common hazardous waste streams. Sulfuric acid waste from car batteries is an example of corrosive waste. A waste is considered corrosive if it has a pH less than or equal to 2 or greater than or equal to 12.5 [12].

3.3. Reactivity

A reactive waste is one that explodes easily or is subjected to a violent reaction. Common examples are unloaded ammunition and explosives. There is no reliable test method for assessing the potential for waste to explode or react violently under normal handling conditions. Due to their instability, reactive waste can be very hazardous. USEPA recognizes that there are too many conditions and situations to identify all types of reactive materials. However, in order to support hazardous waste managers as well as users, USEPA [12] proposes the following criteria for characterizing the reactivity of hazardous waste:

- instability and usually produces violent changes without detonating
- potential for explosive mixture or violent reaction when combined with water
- when mixed with water releases toxic gases

3.4. Toxicity

Hazardous waste poses a threat to groundwater, which can have long-term effects on human health and the environment. This is different from the first three characteristic groups, which USEPA considers immediate hazards [12]. There are 60 contaminants on the toxicity list. These contaminants are only identified by a test method called the Toxicity Characteristic Leaching Procedure or TCLP. Hazardous waste will fall into one or more of these categories. As a generator of

the above, there are two options to determine which of the above characteristics best define the waste generated by testing or from the previous experience of the generator.

4. Small and large generators of hazardous waste and environmental impact

Hazardous waste is generated by two major categories of sources [13]:

- household consumers;
- economic agents and institutions.

In the area of household consumers, volumes are significant, but the selective collection and collection infrastructure is generally absent. Also, the lack or insufficiency of collection campaigns causes confusion among consumers, who do not know exactly which waste they generate falls into the category of hazardous. In addition, the authorities are not sufficiently involved in solving these problems [14].

In the case of economic operators and institutions as large generators of hazardous waste, things are better set up, because there is legislation in line with European regulations, and generators are obliged to ensure that hazardous waste is disposed of properly. Hazardous waste collection companies also ensure that the transport and disposal of hazardous waste is constantly monitored and invest in the technology required for disposal that meets the requirements of the law. The most important hazardous waste generated by households is shown in Fig. 6.

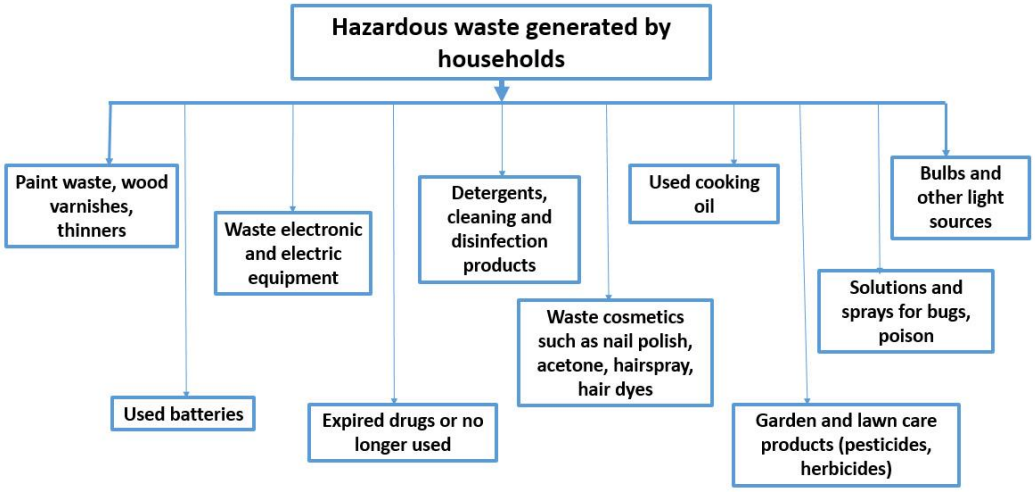

Fig. 6. The most common hazardous waste generated by households

The large generators of hazardous waste are: health system, pharmaceutical field, food industry, HORECA system, agriculture, chemical industry, automotive industry, printing houses, photo workshops, advertising production workshops, beauty salons etc. (Fig. 7).

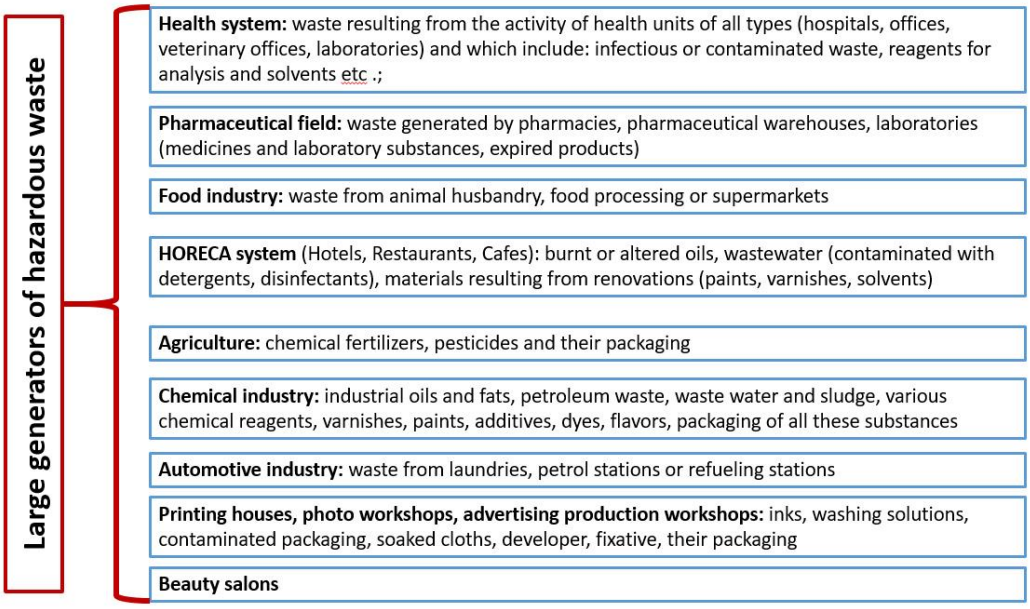

Fig. 7. Large hazardous waste generators

5. Options for reducing hazardous waste quantities

5.1. Methods for reducing hazardous waste quantities

Globally, four methods are agreed to reduce the amount of hazardous waste generated [14] (Table 1):

1. segregation or separation at source,
2. process modification,
3. substitution of the final product,
4. materials recovery and recycling.

One or more of these approaches are often used simultaneously or sequentially. However, reducing the amount of waste generated at source is not a new concept. Several industrial companies have set up internal incentive programs to achieve this. An example is 3M's 3P "Pollution Prevention Pays" program. By reducing waste and developing new substitutes for hazardous materials, 3M has saved $ 20 million over 4 years. Other companies have set up corporate working groups to investigate hazardous waste management solutions [15].

5.2. Selecting options

Treatment and disposal (**Tr & Di**) as well as direct disposal (**DDi**) are the most frequently applied among the hazardous waste management options. For example, injection into deep wells, discharge into ocean water, accumulation and filling of abandoned mines are known as alternatives to direct disposal or waste discharge; other technologies, such as precipitation, dehydration, phase separation, heat treatment etc. pre-treatment methods can be considered until the final disposal or precondition of the disposal methods.

Tables 1. Comparison of the four methods of reducing the volume of hazardous waste (HW) [15]

Advantages	***Disadvantages***
segregation or separation at source	
1) Easy to implement; usually low investment 2) Short-term solution	1) Lack of management of certain waste
process modification	
1) Potentially reduce both hazard and volume 2) Moderate solution 3) Potential savings in production costs	1) Requires research and development efforts and capital investments 2) It usually has no impact on the entire industry
substitution of the final product	
1) Impact throughout the industry - large volumes 2) Hazard reduction	1) It may require changing consumer habits 2) Major investments required - requires a growing market 3) Many sectors affected
materials recovery and recycling	
1) Medium term solution 2) Potential savings in manufacturing costs 3) Reduced liability compared to commercial	1) May require capital investment 2) It may not have a wide impact

Treatment and disposal include: physical treatment (**PhyT**), chemical treatment (**ChemT**), biological treatment (**BioT**), heat treatment (**TT**), stabilization / solidification (**S/S**), deep injection (**DWI**), controlled elimination (**CLD**) are accepted as direct disposal methods. Phase separation (**PS**) is considered as a preparation process, especially for sludge and liquid waste [16]..

To determine the appropriate treatment and disposal options for each hazardous waste, various approaches can be proposed, such as, for example, the methodology of multicriteria analysis, following an algorithm proposed in Fig. 8 [17]. According to this approach, the decision of appropriate methods of treatment and disposal of hazardous waste is made based on three main factors with the

algorithm presented in Fig. 9: physical state, hazard criterion (hazard), composition criterion. On this basis, specific schemes for hazardous waste processing and disposal can be established on the basis of waste physical state, combined with criteria regarding composition and hazard [17].

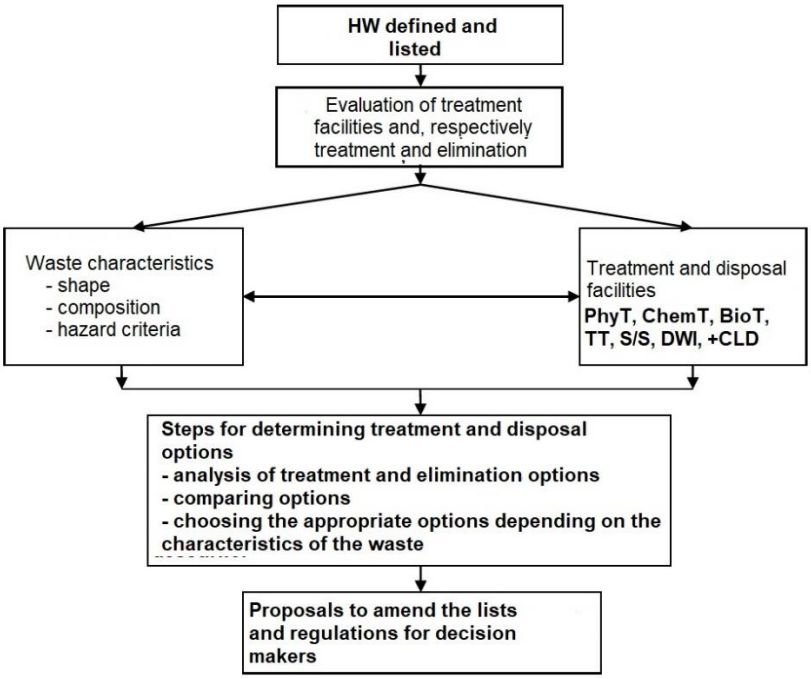

Fig. 8. Algorithm for determining hazardous waste treatment / disposal options [17].

5.3. Alternatives for the treatment and disposal of hazardous waste in the form of accumulators and spent batteries (AB) and recovery of critical metals (Li, Co, Pb, Al)

Waste batteries are defined as hazardous waste, but the metals contained in them, such as lead, cobalt, lithium, aluminum, and other materials, are usually recovered and used as secondary raw materials in the metallurgical or other industries [18, 19]. In this hazardous waste management alternative, the first process is to remove the lid, then the removal of the plastic separators and the cover, as well as the battery / accumulator body. These separate parts can be recycled, reused or disposed of for controlled disposal (CLD). On the other hand, the mostly acidic solution is decanted and then sent to the WWTS after neutralization (Fig. 10).

The remaining material containing metal parts is sent to the furnace for smelting and metal production. In this process a slag is generated and the new waste is

directed to the alternative for slag treatment. All the mentioned processes can constitute a profit-oriented industrial installation. The project is best achieved for large batteries, such as car batteries, which ensure efficient recovery, by the so-called urban mining [20].

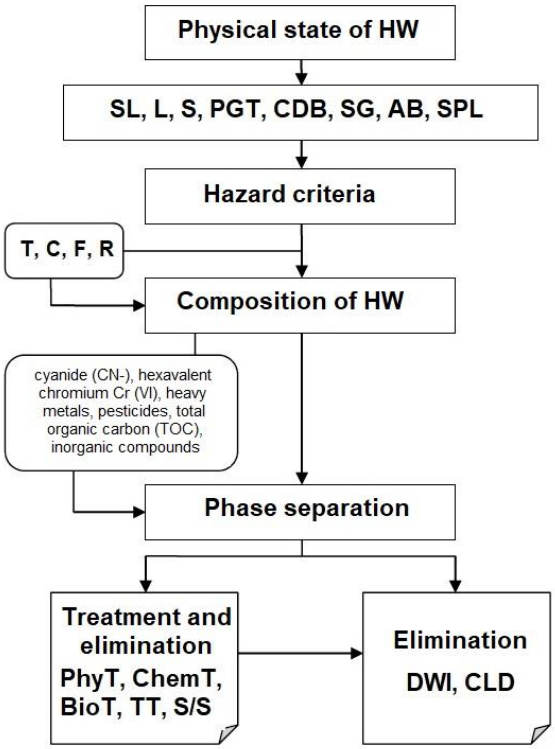

Fig. 9. Algorithm for determining hazardous waste (HW) treatment / disposal options, based on three main criteria: *Physical state*: sludge (SL), liquid (L), solid (S), pressurized gas pipes (PGT), container, drum, barrel (CDB), slag (SG), accumulator, battery (AB), leakage (SPL); *Hazard criteri*a: toxicity (T), corrosivity (C), flammability (F), reactivity (R); *Hazardous waste composition*: cyanide (CN-), hexavalent chromium Cr (VI), heavy metals, pesticides, total organic carbon (OCD), inorganic compounds (adapted upon [17])

The final stages of hazardous waste management, namely the treatment and disposal stages, are perhaps the most complex and technologically demanding. There are a multitude of options for treating and disposing of hazardous waste [21]. However, selecting the best choice for a particular category of hazardous waste is both difficult and crucial for the proper management of that waste. The purpose of treating and disposing of hazardous waste is to mitigate the characteristics that make such waste hazardous.

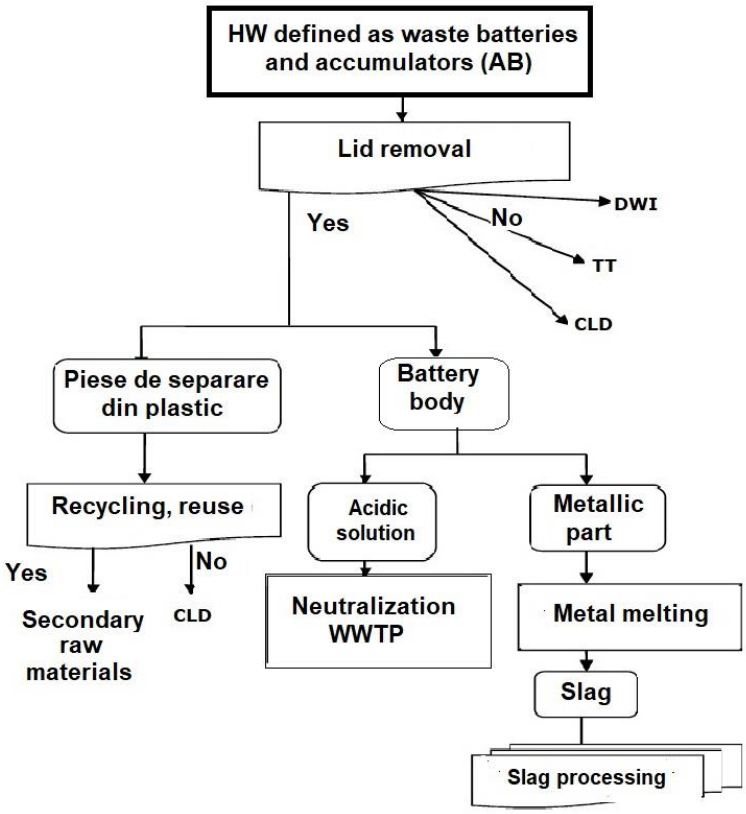

Fig. 10. Treatment of HW defined as used batteries and accumulators (AB) (adapted upon [17])

Often, hazardous waste is disposed of without prior treatment in the hope that, in the end, the waste will turn into less hazardous waste. In addition, these treatment and disposal strategies usually seek to reduce the volume of waste and concentrate the waste for more efficient storage.

Conclusions

Waste is a key environmental, social and economic issue, as the amount of waste generated in Europe and along the world increases every year. In order to ensure a sustainable economic and social development and maintain the quality of the environment, adequate waste management and conservation of natural resources are required.

Hazardous waste is material, substance or product from households, institutions, companies, rural and urban areas and has hazardous properties - explodes, oxidizes, is highly flammable, irritating, harmful, toxic, rusty, infects, is

carcinogenic or mutant, and which the owner gets rid of, has the intention or obligation to eliminate them. Hazardous waste poses a greater risk to the environment and human health than non-hazardous waste and thus requires a stricter control regime.

By their nature, hazardous waste usually does not allow recycling and therefore the generation rate must be reduced and the waste generated is disposed of by neutralization or destruction. Recycling is only used for certain categories of hazardous waste, such as batteries or electronics and appliances. Hazardous waste has major negative effects on the environment. The quality and health of air, soil, water and wildlife are affected by the amount of hazardous waste generated each day by business and industry.

Among the hazardous waste management options, treatment and disposal as well as direct disposal are the most frequently applied. Treatment and disposal include: physical treatment, chemical treatment, biological treatment, heat treatment, stabilization/solidification, deep injection, controlled disposal are accepted as direct disposal methods. Phase separation is considered as a preparation process, especially for sludge and liquid waste. To determine the treatment/disposal options for hazardous waste, three criteria are taken into account: physical state (mud, liquid, solid, pressurized gas pipes, container, drum, barrel, slag, accumulator, battery, leaks); hazard criteria (toxicity, corrosivity, flammability, reactivity); hazardous waste composition (cyanide, hexavalent chromium, heavy metals, pesticides, total organic carbon, inorganic compounds).

Acknowledgements

This work was supported by a grant of the Romanian Ministry of Education and Research, CCCDI - UEFISCDI, project number PN-III-P2-2.1-PED-2019-5239, Contract no. 269PED/2020, within PNCDI III.

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