The Handbook of Environmental Remediation
Classic and Modern Techniques

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CHAPTER 2

Hazardous Wastes – Types and Sources

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2.1 Introduction

All around the globe, the economic and social status of people is changing very rapidly. Especially in developing countries, the need for a better economic state is a prerequisite for better social status. The economic growth and development of a country result in many adverse effects on the environment, *viz.* waste generation, greenhouse gas emissions, deforestation, land degradation, *etc.* Waste can be described in the most characteristic way as unwanted material generated in any production process. Although the definition of waste and its categorization may vary slightly in different countries, waste and waste management represent a significant global issue. The never-ending race towards urbanization and modern lifestyle to become a developed country has a serious disadvantage, namely the generation of hazardous waste. With a paradigm shift in economy with the goal of industrialization, the number of industries, particularly those which produce

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hazardous wastes, has increased dramatically. During the past few decades, the generation of hazardous waste has increased alarmingly around the globe[1–3] and there is an urgent need to develop comprehensive strategies for hazardous waste management. In order to do so, proper guidelines, classification practices and the promotion of reuse and recycling need to be developed. Hazardous waste accounted for about half of the environmental consultation market worth $8.2 billion in 1991,[4] which makes it very evident that hazardous waste was also of great significance nearly 30 years ago. What makes it so concerning is its toxicity, which is why the scientific and practical definition of hazardous waste and its proper treatment and disposal have been dominant over other environmental issues. This chapter attempts to address these issues and provide a comprehensive strategy for the storage, treatment and proper disposal of hazardous waste.

2.2 Management of Hazardous Waste

Initially, officials around the globe were not concerned about the consequences of hazardous waste for environmental and human health. Gradually, with the advances and developments in science and the advent of many interdisciplinary fields, researchers across the world started to recognize the looming threat of chemicals and the consequences for society. Accident episodes were now increasingly associated with chemicals and these accidents attracted attention throughout the world, hence a need to define hazardous waste became evident.

2.2.1 Identification and Classification

Various countries have their own classification system pertaining to hazardous waste and there are multiple levels of sophistication and complexities involved in the identification of hazardous waste. Therein lies a very basic difficulty for government and industrial organizations engaged in hazardous waste control programs, namely to define hazardous waste realistically within the scientific and practical domains. Correct identification and subsequent classification are essential to ensure that the collection, transportation, storage, and treatment of waste and its proper disposal are carried out in a manner that not only protects human health but also provides protection for the environment, and in compliance with legal requirements. This chapter presents the classification system adopted by United States Environmental Protection Agency (EPA) and also by the European Union Environmental Protection Agency, which is accepted across the European Union.

First, correct classification depends mostly on correct identification, and to address this issue the Resource Conservation and Recovery Act (RCRA) describes the four steps necessary for preliminary identification of hazardous waste.[5] These steps are summarized in Figure 2.1. Moreover, the RCRA[5] defines hazardous waste as "a solid waste or combination of solid waste, which because of its quantity, concentration or physical, chemical or

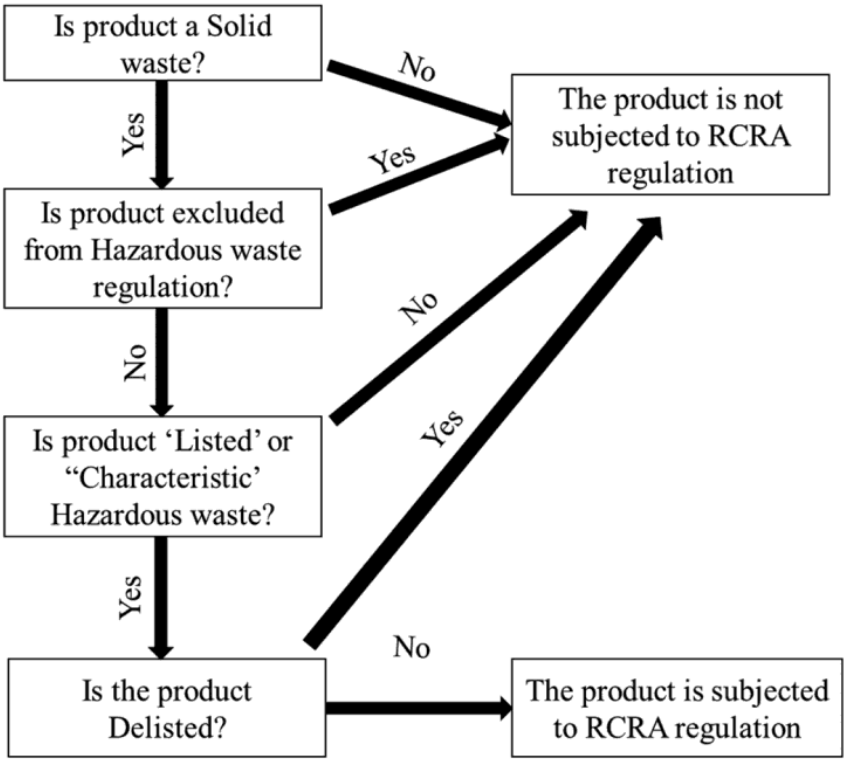

Figure 2.1 Identification process for hazardous waste. See also ref. 5.

infectious characteristics may (a) cause, or significantly contribute to, an increase in mortality or an increase in serious irreversible or incapacitating reversible, illness; or (b) pose a substantial present or potential hazard to human health or the environment when improperly treated, stored, transported or disposed of or otherwise managed''. This classification is based on the fact that ''such wastes are non-degradable or persistent in nature or they can be biologically magnified or because they can be lethal or because they may otherwise cause or tend to cause detrimental cumulative effects''.[6]

The definition provided by the RCRA is very broad one and does not clearly indicate the threats posed by the waste(s). This issue was therefore addressed by classifying the waste through (1) listing of hazardous wastes and (2) identification of certain specific characteristics which, when present in a waste, makes it hazardous.

2.2.1.1 Listed Hazardous Waste

Hazardous waste listings by the EPA specifically describe the specific types of waste that are dangerous enough to warrant regulatory action. Hence it becomes very important that, before the final listing, the EPA conducts comprehensive studies regarding threats posed by a particular waste and waste stream to human and environmental health. If a waste or stream is found to be threatening enough, it can be listed in one of the lists and be classified as hazardous. Thereafter, any waste that conforms to the listing criteria is considered hazardous, regardless of its chemical composition or any such variable. The four criteria that the EPA may use to list a waste are as follows:

1. The waste typically contains harmful chemicals and other factors indicate that it could pose a threat to human health and the environment in the absence of special regulation. Such wastes are known as toxic listed wastes.
2. The waste contains such dangerous chemicals that it could pose a threat to human health and the environment even when properly managed. Such wastes are known as acutely hazardous wastes.
3. The waste typically exhibits one of the four characteristics of hazardous waste described in the hazardous waste identification regulations (ignitability, corrosivity, reactivity or toxicity).
4. When the EPA has to cause to believe for some other reason that the waste typically fits within the statutory definition of hazardous waste developed by Congress.

The EPA may list any waste using one or more of the criteria mentioned above. Based on these, four lists were prepared by the EPA, with each list designating from about 30 to a few hundred waste streams as hazardous. Each waste is assigned a waste code consisting of the letter associated with the list followed by three digits. For example, the wastes on the F list are assigned the waste codes F001, F002 and so on. The four lists prepared by the EPA are as follows:[5]

- *The F list:* since the processes producing industrial solid waste vary greatly across the sectors, the F list wastes are considered to be wastes from non-specific sources. The list designates particular solid wastes from certain common industrial or manufacturing processes as hazardous. The F list is codified in the regulations at §261.31.
- *The K list:* the K list labels a particular solid waste from certain specific industries. Wastes in this list are known as wastes from specific sources. The K list is found at §261.32.
- *The P and the U lists:* these two lists are similar in the sense that both have listings of pure or commercial grade formulations of certain specific unused chemicals as hazardous. Both the P and U lists are codified in §261.33.

2.2.1.2 Characteristic Hazardous Waste

Successful identification and subsequent classification are mainly governed by some characteristic features and these sets of characteristic feature can very well be used to classify hazardous waste. Even though unanimous definitions of hazardous waste have not been formulated across the globe, there is a universal acceptance towards these characteristic features. According to the EPA,[7] if a substance shows one or many of the following characteristics upon self-reaction or reaction with other compounds, it may be classified as a hazardous substance. These characteristic features are defined as follows:[5]

1. *Ignitability:* Any waste product that can create fire under certain conditions, has a flash point of less than 60 °C and shows spontaneous combustible characteristics can be called an ignitable product.
2. *Corrosivity:* All the acids or bases ($2 \leq pH \geq 12.5$) and/or any waste product that are capable of causing corrosion in metal containers (such as storage tanks, drums, *etc.*).
3. *Reactivity:* If any material is unstable under normal conditions, it can be considered a reactive hazardous waste. "These products may cause explosions, undergo violent reactions, generate toxic fumes, gases or vapors or explosive mixtures when heated, compressed or mixed with water".[5]
4. *Toxicity:* A waste product is referred to as toxic when its proven to be harmful or fatal upon ingestion or adsorbed. Determination of toxicity is carried out through a laboratory test known as the "Toxicity Characteristic Leaching Procedure" (TCLP).

2.2.1.3 Wastes Listed Solely for Exhibiting the Characteristic of Ignitability, Corrosivity and/or Reactivity

The regulation of wastes listed solely for exhibiting the characteristic of ignitability, corrosivity and/or reactivity does not work in the same way as that of other listed hazardous wastes under RCRA. Hence, according to RCRA (66 FR 27266), "When wastes are generated that meet a listing description for one of the 29 wastes listed only for exhibiting the characteristic of ignitability, corrosivity and/or reactivity, the waste is not hazardous if it does not exhibit a characteristic".[9]

2.2.1.4 The Mixture and Derived-from Rules

Through the listing of hazardous waste and characterization, most of the bases for identification of such wastes were considered to be covered. However, some key concerns were subsequently raised regarding the identification process. One such concern was "what if the hazardous waste is changed chemically or physically in some way, will it still be considered hazardous?" To resolve this issue, the EPA quickly came up with a very simple and strict guideline. This guideline was broadly presented in mixture and derived-from rules. These rules operate differently for listed and characteristic hazardous wastes.

2.2.1.4.1 Listed Hazardous Waste. The mixture rule for listed wastes states that "a mixture made up of any amount of a non-hazardous solid waste and any amount of a listed hazardous waste is considered a listed hazardous waste. In other words, if a small vial of listed waste is mixed with a large quantity of non-hazardous waste, the resulting mixture bears the same waste code and regulatory status as the original listed component of the mixture''. Similarly, the derived-from rule for listed wastes states that ''any material derived from a listed hazardous waste is also a listed hazardous waste. Thus, ash produced by burning a listed hazardous waste bears the same waste code and regulatory status as the original listed waste, regardless of the ash's actual properties''.[5]

2.2.1.4.2 Characteristic Wastes. As mentioned earlier, norms for listed waste and characteristic wastes are different. The EPA decided that since the waste mixture does not exhibit any of the four characteristics, it shall no longer be considered hazardous. Hence ''a mixture involving characteristic wastes is hazardous only if the mixture itself exhibits a characteristic. Similarly, treatment residues and materials derived from characteristic wastes are hazardous only if they themselves exhibit a characteristic''.[5]

2.2.1.4.3 Waste Listed Solely for Exhibiting the Characteristic of Ignitability, Corrosivity and/or Reactivity. It is mentioned that ''if a hazardous waste listed only for the characteristics of ignitability, corrosivity and/or reactivity is mixed with a solid waste, the original listing does not carry through to the resulting mixture if that mixture does not exhibit any hazardous waste characteristics''.[5] Similarly, for derived-from it states that ''if a waste derived from the treatment, storage or disposal of a hazardous waste listed for the characteristics of ignitability, corrosivity and/or reactivity no longer exhibits one of those characteristics, it is not a hazardous waste''.[5]

Another major guideline (valid from 2015) followed across the European Union is given by the Environmental Protection Agency (EPA) Ireland, which mentions two very critical elements for hazardous waste classification:[5]

1. Preparation of List of Waste (LoW): ''The LoW provides a harmonized list for coding all waste. The different types of waste in the list are fully defined by the six-digit entry for the waste including the respective two-digit and four-digit chapter headings''.[8]

   As per the LoW, waste can be categorized in any one of the following three entry types:
   (i) non-hazardous;
   (ii) hazardous (marked with an asterisk);
   (iii) mirror – either hazardous or non-hazardous.

   One very important and notable point here is that, without any prejudice, if a waste has been entered in a non-hazardous category, no further assessment is required and the entry is finalized as non-hazardous. Similarly, if a waste has been entered in a hazardous category, it is hazardous without any further assessment. However,

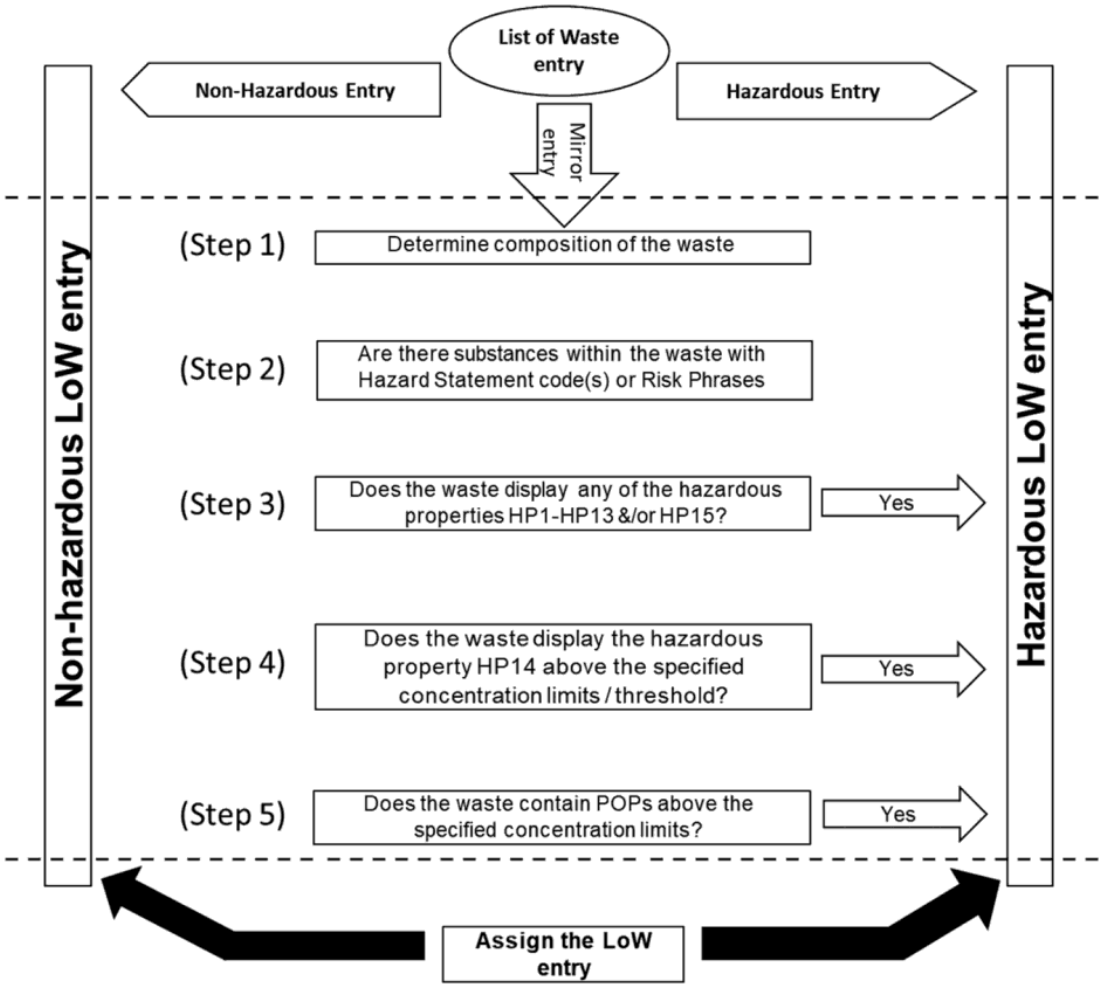

Figure 2.2 Steps for determination of hazardous waste entry. Reproduced with permission from: EPA Ireland.[8]

provisions and directives are in place to rectify any entry based on evidence.

Moreover, if the list has a mirror entry, it is dealt with in accordance with the second element:

2. Determining if waste is hazardous or non-hazardous: ''If the waste has a mirror entry, it must be subject to further assessment to determine if it is hazardous or not''. The necessary steps are outlined in Figure 2.2.

Various classes of hazardous waste and a few examples are compiled in Table 2.1.[10,11] This table illustrates the similarity between UN class number and EPA identification number of hazardous waste classification.

2.2.1.5 Tests for Hazardous Wastes

Various physical and chemical tests are required to identify several waste characteristics so that optimum and efficient treatment and disposal guidelines can be formulated. These test method numbers, listed by the

Table 2.1 Various classes of hazardous waste with EPA Ireland identification number.

UN class number (1989)	Characteristics	Types	Examples	Similar EPA identification number
1	Explosives	Projection, mass explosion, minor hazard	Ammonium perchlorate, cyclonite, explosive articles	D003
2	Gases	Poisonous, flammable gas, non-flammable gas	Compressed oxygen, butane, ammonia	D001
3, 4	Flammable solids and liquids	Low flash point range, medium flash range, high flash range	Acetone, alcohol, diethyl ether	D001
		Flammable solids, spontaneous combustion, emitting flammable gases when wet	White phosphorus, yellow phosphorus, alkali metals	
5	Oxidizing substances	Oxidizing compounds of all types	Sodium peroxide, potassium permanganate, potassium superoxide	D002
6	Infectious substances	Poisonous agents, infectious agents	Arsenic, clinical waste	D003
7	Radioactive materials	Radioactive compounds of all kinds	Uranium	D003
8	Corrosives	Corrosive in nature	Mineral acids, organic acids, strong bases	D002
9	Toxic	Toxic to the ecosystem or society	Environmentally hazardous chemicals	D004–D043

EPA,[12] are summarized in Table 2.2. The choice of appropriate method depends upon the detail of the information sought for final treatment/disposal. Moreover, to choose the correct method, some basic information is necessary, which includes the following:

1. Physical state of the sample: aqueous, solid, volatile, sludge, multiphase sample.
2. Analytes of interest: organic (carbon compounds) or inorganic (metals and anions).
3. Analytical sensitivity required.
4. Analytical objective: screening methods/composite sampling, *etc.*
5. Purpose of testing: quantitation or monitoring.
6. Information regarding sample containers and holding time.

Table 2.2 Applicable method numbers for various tests of hazardous waste.

Applicable determinative method numbers for:		
Organic analyses	Inorganic analyses	Miscellaneous methods
8000D, 8011, 8015C, 8021B, 8031, 8032A, 8033, 8041A, 8061A, 8070A, 8081B, 8082A, 8085, 8091, 8095, 9100, 8111, 8121, 8131, 8141B, 8151A, 8260B, 8261, 8270D, 8275A, 8276, 8280B, 820A, 8310, 8315A, 8316, 8318A, 8321B, 8325, 8330A, 8331, 8332, 8410, 8430, 8440, 8520	6010D, 6020B, 6200, 6500, 6800, 7000B, 7010, 7061A, 7062, 7063, 7195, 7196A, 7197, 7198, 7199, 7470A, 7471B, 7472, 7473, 7474, 7580, 7741A, 7742	5050, 9000, 9001, 9010C, 9012B, 9013A, 9014, 9015, 9016, 9020B, 9021, 9022, 9023, 9030B, 9031, 9034, 9035, 9036, 9038, 9056A, 9057, 9060A, 9065, 9066, 9067, 9070A, 9071B, 9075, 9076, 9077, 9131, 9132, 9210A, 9211, 9212, 9213, 9214, 9215, 9216, 9250, 9251, 9253, 9320

2.3 Waste Generators

A waste generator may be any person who produces a hazardous waste. As the quantity of generated waste may vary, the EPA has categorized generators in three different categories, based on the quantity of hazardous waste generated each month,[13] as follows:

1. very small quantity generators (VSQGs);
2. small quantity generators (SQGs); and
3. large quantity generators (LQGs).

Identification of the generator category is essential for all of the generators. The criteria for determining the category are given in Table 2.3.

There are certain requirements for all waste generators, as described in 40 CFR Part 262,[13] and some of those regulations are as follows:

1. Very small quantity generators (VSQGs):
   - VSQGs must identify all the hazardous waste generated.
   - VSQGs may not accumulate more than 1000 kg of hazardous waste at any time.
   - VSQGs must ensure that hazardous waste is delivered to the authorized person or facility only.
2. Small quantity generators (SQGs):
   - SQGs may accumulate hazardous waste on-site for 180 days without a permit (or 270 days if shipping a distance greater than 200 miles).
   - The quantity of hazardous on-site waste must never exceed 6000 kg.
   - As SQGs are not required to have detailed contingency plans, there must always be at least one employee available to respond to an emergency, who is responsible for coordinating all emergency response measures.

Table 2.3 Generator categories based on quantity of waste generated in a calendar month. Source: Electronic Code of Federal Regulations.[13]

Quantity of acute hazardous waste generated in a calendar month	Quantity of non-acute hazardous waste generated in a calendar month	Quantity of residues from a cleanup of acute hazardous waste generated in a calendar month	Generator category
>1 kg	Any amount	Any amount	Large quantity generator
Any amount	≥1000 kg	Any amount	Large quantity generator
Any amount	Any amount	>100 kg	Large quantity generator
≤1 kg	>100 kg and <1000 kg	≤100 kg	Small quantity generator
≤1 kg	≤100 kg	≤100 kg	Very small quantity generator

3. Large quantity generators (LQGs):
   - LQGs may only accumulate waste on-site for 90 days. Certain exceptions apply.
   - LQGs do not have a limit on the amount of hazardous waste accumulated on-site.
   - LQGs must submit a biennial hazardous waste report.

Both SQGs and LQGs must manage their hazardous waste in tanks or containers and must comply with the manifest requirements mentioned in 40 CFR Part 262.

2.4 Sampling and Analysis of Hazardous Waste

One of the most basic and important foundations of the RCRA hazardous waste program is the need presented to waste generators for treatment, storage and disposal facilities first to conduct a proper analysis and identification for all the hazardous wastes that are generated, treated, stored or disposed of at their facility, through waste testing and/or acceptable knowledge related to the waste. Waste analysis refers to both testing and application of acceptable knowledge and it involves the identification and subsequent verification of the chemical and physical characteristics and composition of the waste by performing a detailed physicochemical analysis on a representative sample of the waste.[8]

Major stakeholders are (a) waste generators and (b) treatment, storage and disposal facilities (TSDFs), and the majority of the RCRA's waste analysis requirements are applicable to these hazardous waste generators and TSDFs. These clients may pose or have various concerns relating to the quality of waste, which in turn may help in identifying suitable disposal mechanisms, *etc.* The analysis of waste fulfils many such objectives concerning the client. Some such concerns are as follows:

1. Waste producers may want to assess the kind of recovery/disposal that is possible.
2. Managers of waste treatment plants need to know if they can accept and will be able to treat the waste.
3. Authorities are interested in the environmental effects related to a particular waste type.

Hence ‘‘waste analysis’’ and subsequent development of a ‘‘waste analysis plan’’ (WAP) become a pivotal activity which ensures that the treatment and disposal facility complies with the applicable regulations. However, there are certain analytical and other related requirements that must be fulfilled by both the generators and TSDFs. The RCRA generator standards are generally applicable for LGQs and SGQs only.

2.4.1 Waste Analysis Requirements for Generators

Anyone who generates a solid waste is obligated to determine if the waste is hazardous or not. The preparation of a WAP is not mandatory for generators unless they are required to manage and treat the waste or contaminated soil in tanks, containers or containment buildings to meet applicable treatment standards.[13] Figure 2.3 provides a summary flowchart of waste analysis and analytical requirements that are applicable for generators.

2.4.2 TSDF Waste Analysis Requirements

As a TSDF, compliance with the applicable §§264/265.13 requirements for waste analysis and WAPs is a necessity. Part 264 of the CFR covers the requirements for permitted facilities/units, whereas Part 265 covers interim status facilities/units.[13]

If the TSDF relies on generator-supplied information only, it is important for the TSDF concerned to review and verify the supplied information and ensure its adequacy.

Hence the transformation of waste-related information among the TSDFs, the generators and other stakeholders becomes very important. For example, if a generator or TSDF ships out the waste to an off-site facility, it is mandatory to provide the waste profile data (analytical data, source of waste, *etc.*). These data are important for the treatment facility to accept the waste in their facility. One very important stakeholder, other than generators and TSDFs, is ‘‘hazardous waste transporters’’, who also have to have detailed data pertaining to the waste they are handling. It is advantageous for all the stakeholders to provide detailed information among themselves to ensure compliance (Figure 2.4).

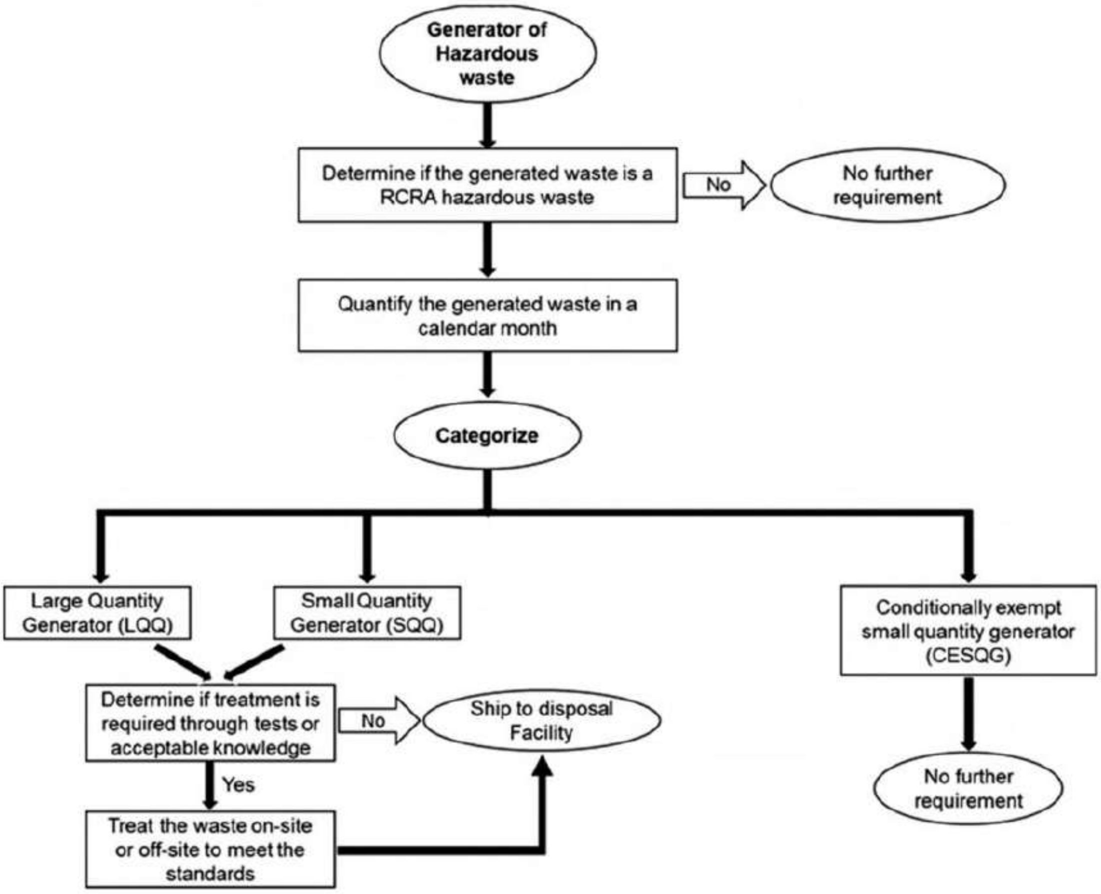

Figure 2.3 Waste analysis requirements for generators.

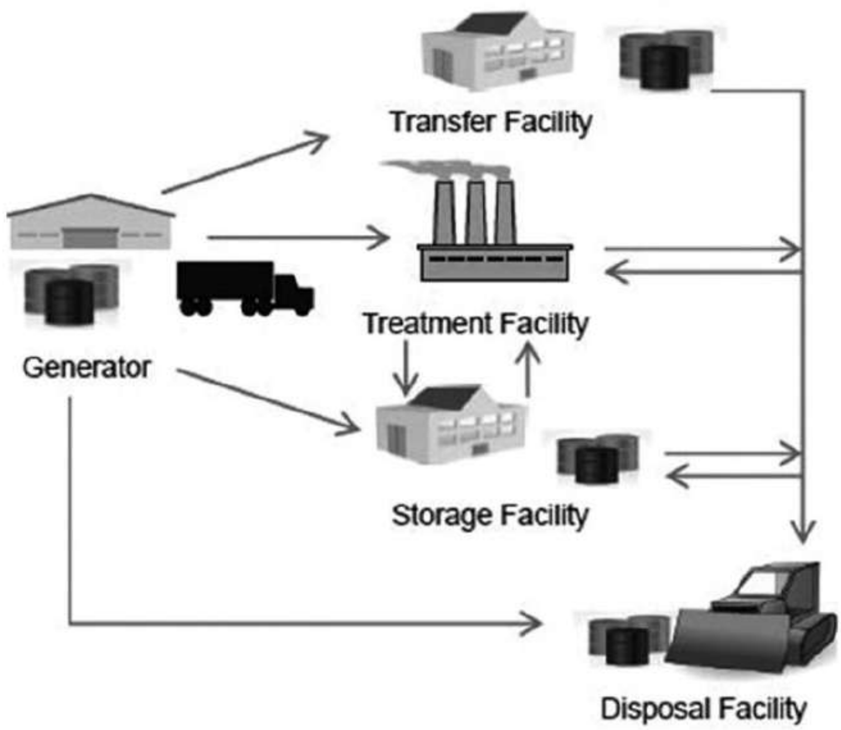

Figure 2.4 Waste analysis data transformation.
Reproduced with permission from: EPA Ireland.[8]

2.4.3 Sampling and Analysis for TSDFs

For a TSDF, all the waste analysis requirements can be satisfied through waste sampling and analysis. Moreover, for a new facility or in the absence of detailed information by the generator, there is a need for frequent sampling and a higher quality of analysis. Sampling and analysis reports may be used to document compliance at the facility.

2.4.3.1 Pre-acceptance Sampling and Analysis

A TSDF receiving waste from any facility must confirm various waste characteristics at the time of pre-acceptance. This will ensure that the TSDF would not accept any waste that it is not permitted to handle. Moreover, this ensures that the TSDF can manage the accepted waste effectively and in accordance with the regulations.

2.4.3.2 Waste Acceptance (Fingerprint Analysis) Sampling and Analysis

Fingerprint analysis can include detailed instrumental analysis in laboratories, may make use of field testing kits and screening instruments or may involve visual observations (as in the case of color identification, *etc.*), although the specific information sought for acceptance of the waste may vary according to the waste type, accuracy and permission required to fulfill the permit requirements and the primary objective of waste acceptance.

There are two vital objectives of all the waste acceptance sampling and analysis:

- making sure that the parameters which are being tested (*e.g.* pH) meet all the permit requirements and are well within the acceptable limits required for effective treatment and management; and
- verifying that the waste that is being shipped in is the same waste that was approved during pre-acceptance.

2.4.3.3 Use of Acceptable Knowledge

There are times when acceptable knowledge proves to be very useful in providing information before pre-acceptance of the waste and also checking the compliance with permit regulations. However, some situations may arise where dependence on acceptable knowledge alone may prove to be fatal. Furthermore, the EPA has recognized that, since accuracy in waste identification is essential, acceptable knowledge may prove to be more economical and convenient than sampling and analysis, it is prudent to go through the rigorous process of ''waste analysis''.

2.4.4 Conducting Waste Analysis

Conducting waste analysis and preparing a WAP constitute a very rigorous exercise that helps a facility to conduct and document its analytical methods and procedures. Based on an EPA Ireland document,[8] the various stages involved in waste analysis conduction are summarized in Figure 2.5.

2.4.5 Quantifying the Data Uncertainty

Waste handlers make use of analytical data to make certain decisions and determine if these decisions are supported with sufficient data evidence. For example, if the waste to be managed has elevated levels of a certain pollutant, this could cause potential damage to the managing unit and consequentially may incur regulatory penalties. Hence the unit is likely to minimize the uncertainty behind the decision and increase the confidence level behind the decision taken.[8,14,15]

2.4.6 Need for Re-evaluation and Record Keeping

"The RCRA regulations require that waste analysis performed under 40 CFR 264/265.13(a)(1) be repeated as necessary to ensure that it is accurate and up to date".[8] The important decision to make is determining the re-evaluation frequency and the EPA Ireland document[8] discusses various approaches for this purpose. However, it is important that the facility keeps accurate records of the previous data, which can be accessed whenever necessary for comparison with the present data. Hence "record keeping is an essential aspect of waste analysis, as it documents whether the analyses were done in accordance with required and acceptable procedures".[8]

2.5 Storage, Transport and Disposal of Hazardous Waste

Once the characterization and identification are complete, waste is sent to the storage facility, where it is kept temporarily and subsequently transferred to the disposal or treatment facility.

2.5.1 Storage of Hazardous Waste

The waste resides in the storage facility for a limited time period, after which it is treated and sent to the disposal facility. Generally, the storage facility shall not be provided at the place of generation; however, it might be allowed if the waste is kept in special storage tanks. The primary task of segregation of waste must be carried out with extreme caution and attention. The containers must be kept clean along with the storage facility. Leakages must be

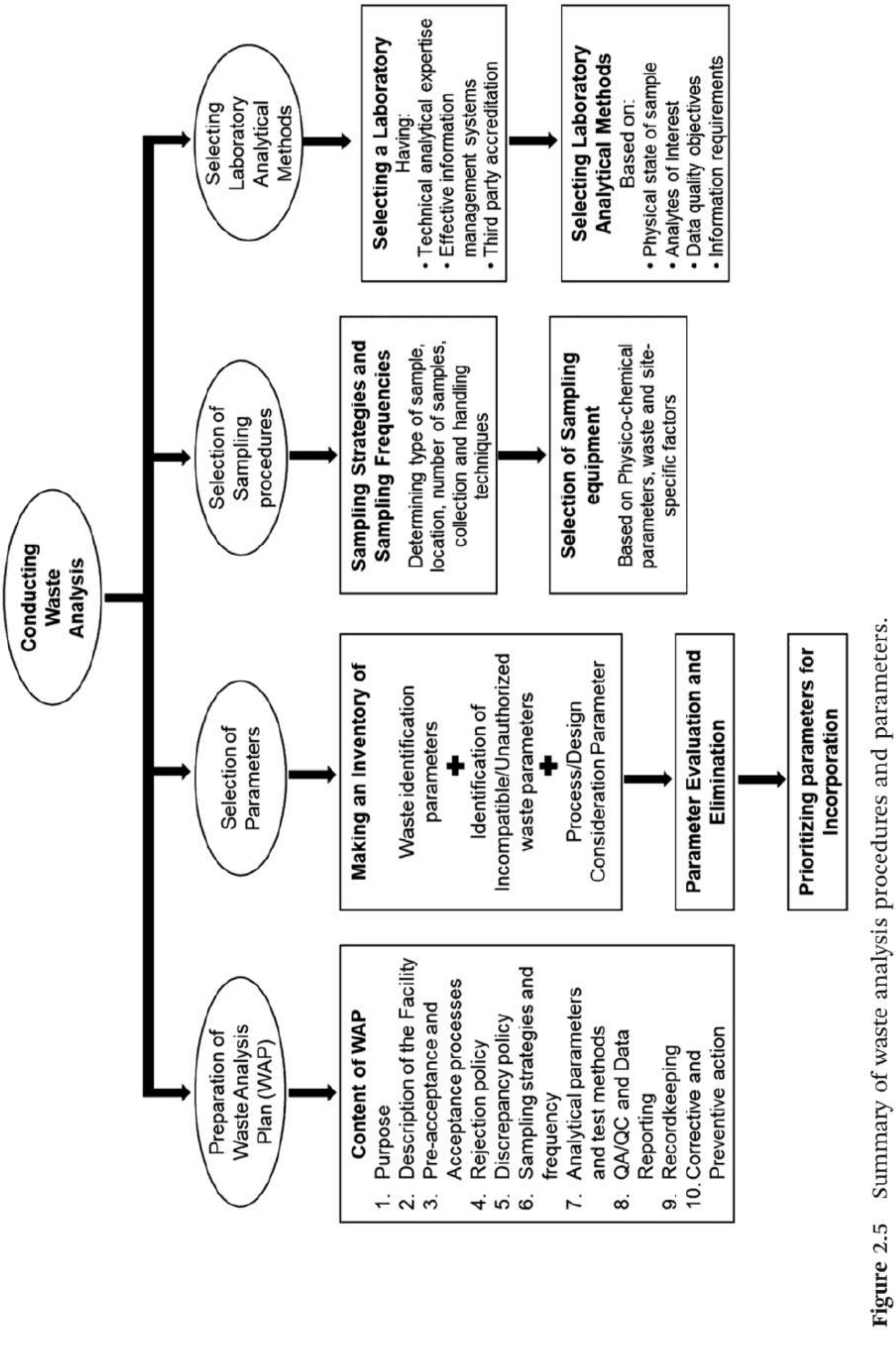

Figure 2.5 Summary of waste analysis procedures and parameters.

carefully checked for and avoided. Some important points that must be kept in mind are the following:

- Pollution control equipment such as water spray systems, masks, *etc.*, must be kept at the storage facility.
- The storage facility must have all the necessary guidelines in case any accident occurs.
- The facility must be inspected regularly to keep a check on any deficiency and subsequently avoid any potential accidents.
- There must always be additional containers and workers present or kept at standby as an additional safety measure.
- Proper labeling and regular cleaning of containers must be ensured.
- The maximum storage period is 90 days.
- Special care must be taken when storing hazardous chemicals, as they are subject to further reactions and may undergo explosions. The content of containers having hazardous chemicals must be clearly mentioned along with a mention of any special storage or handling requirement, if any.
- The quality of containers must not be compromised.
- Cover to protect against rain must be provided.

2.5.2 Transport of Hazardous Waste

Transportation of hazardous waste is a very important and crucial aspect in the complete hazardous waste management system, since it requires precise practices to ensure safe transfer and disposal of wastes. Hence it is prudent for the transfer facilities to make sure that they have the required level of expertise and conform to the mandatory registration and other licensing requirements of the state authority in question. This would in turn also enable the governing authorities/bodies to ensure safe and secure transport of hazardous wastes. Some key considerations are as follows:

- As a transporter it is prudent to ensure that the waste generators transport their hazardous waste only in the specified transport vehicles.
- Moreover, it is customary to train the drivers and attendants of the transport vehicles to handle any emergency situations.
- The vehicles must be dedicated for transport of hazardous waste only and must be leak-proof and covered.
- Vehicles must have a license and a no-objection certificate from the governing authorities.
- The containers must be sealed, especially if they contain liquid waste.
- It must be ensured that reactions must proceed inside the containers, hence the stability of the base will be maintained.
- The containers should be able to bear the shocks and jerks resulting from vibrations and undulations of the road, *etc.*
- The emptying process must be easy and risk free.

- Mechanical loading and unloading procedures must be designed to minimize the risks.
- Labels must be waterproof and marked clearly in both English and the regional language. It must also withstand the effects of sunlight.
- The label of the previous contents must be removed to avoid any confusion or mishandling.
- The label must include the waste code number, the type of waste, its origin (basic information of the generator), hazardous properties (*e.g.* flammable, explosive) and the symbol stating the hazardous properties (symbol for biohazard, flammability, *etc.*). Some common labels are presented in Figure 2.6.
- A no-objection certificate for interstate transfer of the waste must be obtained beforehand to avoid any delay.
- For ease of identification of vehicles carrying hazardous waste, they must be painted differently to the regular vehicles, to prevent unfortunate accidents.

2.5.3 Technologies for Hazardous Waste Management

The treatment of hazardous waste can be broadly classified into physical, chemical and biological methods of treatment followed by disposal of waste and residues.

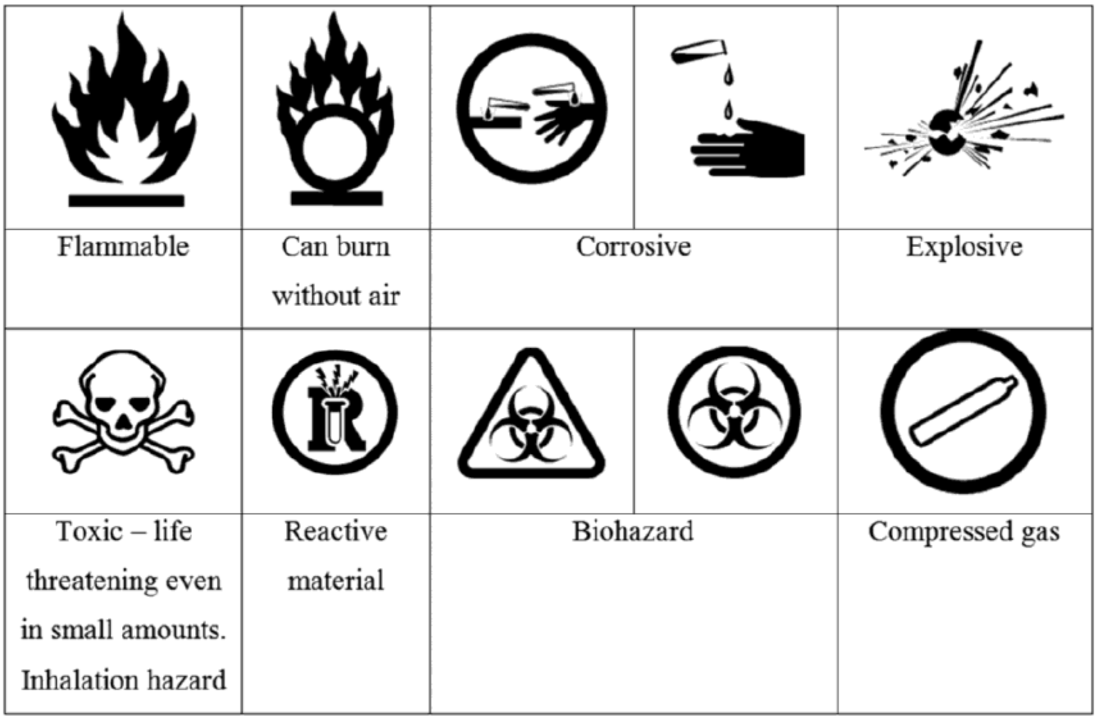

Figure 2.6 Some hazardous waste property symbols. Reproduced with permission from: US EPA.[16]

2.5.3.1 Physical Methods of Treatment

Physical methods of treatment make use of the physical characteristics of the waste constituents to separate the hazardous constituents in a waste stream, wherein residues are further treated and ultimately sent to ultimate disposal. Some of the key methods are discussed in the following subsections. Table 2.4 presents a summary of physical treatment technologies and processes.

2.5.3.1.1 Separation Through Sedimentation. Sedimentation is a Type I settling process in which gravity causes heavier particles to settle and they are collected at the bottom of the sedimentation tank.[17] Sedimentation can be adopted only when there is a difference in the specific gravities of the constituents in the mix of wastes.

2.5.3.1.2 Separation Through Centrifugation. Components of a fluid mixture can be separated using the process of centrifugation, where the use of centrifugal and centripetal force is used to collect the heavier particles through the center of the equipment. Centripetal forces are much stronger than gravitational forces and hence are better for separating waste mixtures. However, centrifugation is generally limited to dewatering

Table 2.4 Physical treatment operations and processes. Reproduced from ref. 26 with permission of Elsevier. Copyright 2019.

No.	Type of technology	Operations[a]	State of waste[b]	Waste constituents[c]
1	Aeration process	Se	L	1, 2, 3, 4
2	Air stripping process	Se	S, L	3, 4
3	Ammonia stripping	VR, Se	L	1, 2, 3, 4
4	Carbon absorption process	VR, Se	L, G	1, 3, 4, 5
5	Centrifugation process	VR, Se	L	1, 2, 3, 4, 5
6	Dialysis process	VR, Se	L	1, 2, 3, 4
7	Distillation process	VR, Se	L	1, 2, 3, 4, 5
8	Electrodialysis	VR, Se	L	1, 2, 3, 4, 6
9	Encapsulation	St	L, S	1, 2, 3, 4, 6
10	Evaporation process	VR, Se	L	1, 2, 5
11	Filtration process	VR, Se	L, G	1, 2, 3, 4, 5
12	Flocculation process	VR, Se	L	1, 2, 3, 4, 5
13	Flotation process	Se	L	1, 2, 3, 4
14	Ion-exchange process	Se	L	2, 4
15	Reverse osmosis process	VR, Se	L	1, 2, 3, 4, 6
16	Sedimentation process	VR, Se	L	1, 2, 4, 6
17	Steam stripping process	Se	S, L	3, 4
18	Thickening process	Se	L	1, 2, 3, 4, 5
19	Vapor scrubbing process	VR, Se	L	1, 2, 3, 4

[a]Se, separation; St, storage; VR, volume reduction.
[b]S, solid; G, gas; L, liquid.
[c]1, Inorganic chemical without heavy metal; 2, inorganic chemical with heavy metal; 3, organic chemical without heavy metal; 4, organic chemical with heavy metal; 5, radiological; 6, biological.

of sludge, separation of oils from water and clarification of viscous gums and resins.[18]

2.5.3.1.3 Coagulation and Flocculation. Coagulation and subsequent flocculation aid the sedimentation process, wherein a coagulant (polymer, alum, *etc.*) is added, which helps with the agglomeration of particles and a floc is formed that becomes heavy and settles. Flocculation is used primarily for inorganics. Various studies have reported the use of coagulants to remove the characteristic wastes successfully. Peng and Wang[19] successfully treated pulp mill effluent with a hydraulic retention time of 16.3 min. Fox *et al.*[20] made use of ferric salts with cactus mucilage as a coagulant and removed up to 96% of arsenic within 30 min.

2.5.3.1.4 Filtration. Filtration is another suitable technique for physical treatment and many advanced filtration methods have evolved over the years. Abdullah *et al.*[21] achieved the successful removal of lead using a polysulfone–hydrous ferric oxide nanoparticles ultrafiltration mixed-matrix membrane. Mondal and De[22] used hollow-fiber nanofiltration membranes and successfully treated textile plant effluent for dye removal.

2.5.3.1.5 Adsorption. Adsorption is used for the removal of pollutants in many environmental systems. Grover *et al.*[23] studied the uptake of arsenite by layered double hydroxides, hydrotalcite and hydrocalumite and achieved a removal efficiency of 80%. Xu *et al.*[24] achieved a removal efficiency of 99% under optimal conditions to remove copper using ZnS nanocrystals. Similarly, Cheng *et al.*[25] reported a removal efficiency of 99% of As(III) using an Fe–Al bimetallic composite.

2.5.3.2 Chemical Methods of Treatment

The basic principle behind the chemical treatment process is alteration of the chemical structure of the constituents, which produces residues that are less hazardous than the original waste. Various operations and processes are summarized in Table 2.5 and are discussed in the following subsections.

2.5.3.2.1 Neutralization. Neutralization is a pH adjustment procedure to make a balance between hydrogen ions (H^+) and hydroxyl ions (OH^-). Some of the applicable wastes are pickle liquors, plating wastes, mine drainage and oil emulsion breaking.[27] It is the least expensive form of chemical treatment.

2.5.3.2.2 Chemical Precipitation. This is also a pH adjustment process, in which acid or base is added to adjust the pH such that the constituent that needs to be removed is at its lowest solubility and is precipitated out. This method is mostly used for dissolved metals.

Table 2.5 Chemical treatment operations and processes. Reproduced from ref. 26 with permission of Elsevier. Copyright 2019.

No.	Type of technology	Operations[a]	Waste constituents[b]
1	Alkali metal dechlorination	De, Se	1, 2, 3, 4
2	Calcination	VR	1, 2, 5
3	Neutralization process	De	1, 2, 3, 4
4	Oxidation process	De	1, 2, 3, 4
5	Chemical precipitation	VR, Se	1, 2, 3, 4, 5
6	Reduction process	De	1, 2, 3, 4
7	Solvent extraction process	Se	1, 2, 3, 4
8	Sorption	De	1, 2, 3, 4, 5
9	Ozonation	De	4, 6

[a] De, detoxification; Se, separation; VR, volume reduction.
[b] 1, Inorganic chemical without heavy metal; 2, inorganic chemical with heavy metal; 3, organic chemical without heavy metal; 4, organic chemical with heavy metal; 5, radiological; 6, biological.

2.5.3.2.3 Chemical Hydrolysis. Hydrolysis can be achieved through adding chemicals (acid hydrolysis), irradiation (photolysis) or biologically (enzymatic bond cleavage) where cleavage of bonds takes place, in a molecule that is generally insoluble in water such that it goes into ionic solution with water. Special care must be taken that the heavy metals are not mobilized.

2.5.3.2.4 Ultraviolet Photolysis. The process of detoxification or destruction of hazardous chemicals in aqueous solutions with the help of ultraviolet (UV) radiation is known as UV photolysis (*e.g.* degradation of dioxins in waste sludge). However, since UV radiation cannot penetrate soil or opaque solutions, this method cannot be used for pollutants in such media.

2.5.3.3 Biological Methods of Treatment

Biological degradation of hazardous constituents is one of the most practicable and feasible options in a comprehensive waste management process and makes use of microorganisms to degrade and detoxify the hazardous wastes from water and soil. In recent times, a large number of studies have been focused mainly on identifying new such species and re-engineering the processes.

2.5.3.3.1 Aerobic Treatment. Generally, microorganisms break down hydrocarbons into simpler compounds through aerobic respiration, anaerobic respiration and fermentation. However, aerobic degradation processes are preferred as they are rapid and more complete and hence do not produce a large quantity of by-products. Amanatidou *et al.*[28] found low solid accumulation while observing the degradation of particulate organic chemicals. In a study by Chamorro *et al.*,[29] it was found that more than 85% of BOD_5 and 100% removal of stigmasterol took place in Kraft mill effluents.

Such methods, however, are limited to low levels of halogenated organics (BOD $<10\,000$ mg L^{-1}).

2.5.3.3.2 Activated Sludge. There are number of modifications along with the conventional process. In this process, activated sludge (one with aerobic microorganisms) is recirculated back into the aeration tank to achieve higher degradation of organic compounds. This process is not suitable for streams containing highly chlorinated organics, amines and aromatic compounds. Moreover, volatile hazardous compounds may also escape during the process.[18]

2.5.3.3.3 Rotating Biological Contactors. This is another aerobic treatment method especially used for waste streams containing alcohols, phthalates, phenols, ammonia and cyanides. Solids are also removed in this process as part of the primary treatment. Similarly to the activated sludge process, streams containing highly chlorinated compounds are not suitable for treatment by this method.

2.5.3.3.4 Bioreclamation. This process makes use of aerobic microbial degradation to treat contaminated areas, easily adopted through *in situ* treatment (either through injection/extraction walls or an excavation process). The applicability of this process is limited by the site geology and hydrological conditions.[18]

2.5.3.3.5 Anaerobic Digestion. The primary end products of all anaerobic digestion processes (achieved through bacteria that survive in an oxygen-free environment) are methane and carbon dioxide. Systems operating with this process generally require long retention times. Many variants of this technology are commercially available but the basic principle remains the same. The applicability is limited by the concentration of organics.

It can be seen that almost all the bioremediation methods work with liquid waste that does not have high heavy metal concentrations and are generally detoxifying processes.

2.5.3.4 Thermal Treatment

Thermal treatment methods are generally applicable to all kinds of wastes and are considered to be a good energy recovery option compared with other methods. Some of these methods are discussed in the following subsections.

2.5.3.4.1 Incineration. Combustion is one of the non-hazardous and energy recovery options pertaining to the management of hazardous waste. The various such processes include liquid injection incineration (special nozzles introduce the liquid waste into the incineration chamber), rotary kiln incineration (rotation is used to cause agitation in the solid waste to achieve maximum burning) and fluidized bed incineration (use of an inert granular bed material for efficient transfer of heat). Among these, the fluidized bed reactor requires high maintenance and frequent cleaning and is not ideal for bulky materials, whereas most types of waste can be incinerated in a rotary kiln. In addition, industrial kilns are also used but require much longer times due to lengthy retention durations. Blast furnaces use very high temperatures (~1649–1872 °C) and hazardous waste with a high heat content acts as a fuel for these furnaces. Infrared radiators are also used for the destruction of hazardous waste, which results in low particulate emissions and low fossil fuel usage. The end product of most of the incineration processes is ash, which can be used in filling of low-lying areas and is also being used as a replacement for sand, soil, cement, *etc.* by many researchers across the globe.[30–32]

2.5.3.4.2 Pyrolysis. When the waste is chemically decomposed by heating the material under anaerobic conditions, the process is called pyrolysis. Direct and indirect methods of heating are practiced, with temperatures ranging between 500 and 800 °C; the direct methods produce a combination of combustion gases and volatiles from the waste and the indirect methods allow product recovery, but it is more complex and expensive. The limitation of this process is that the input waste capacity is small and it requires an auxiliary fuel.[18,26]

Advanced electric reactors also pyrolyze waste using electrically heated fluid walls, which results in thermal radiation causing pyrolysis of the organic constituents of the waste fed into the system. The primary advantage with this type of reactor is its portability.

2.5.3.4.3 Wet Air Oxidation. This process uses elevated temperature and pressure to oxidize dissolved or finely divided organics that are too dilute to be incinerated economically. Off-gas treatment is also necessary in this process and it cannot be used to treat large volumes of waste. A modification to this process is supercritical water oxidation, where supercritically heated water (above 500 °C), which acts as an excellent solvent for organic materials, is used.

2.5.3.4.4 Molten Salt Destruction. This method simultaneously burns the organics while sorbing the objectionable by-products from the effluent stream, accomplished through mixing air and waste in a pool of sodium carbonate. It is used in the treatment of wastes with low ash or high chlorine contents.[18]

A molten glass pool is also used as a mechanism to transfer heat for the destruction of organics while capturing ash and inorganics. Most wastes can be treated using this technology and a significant volume reduction is obtained. However, waste with a high ash or soil content cannot be treated by this method and it also requires off-gas treatment.

2.5.3.4.5 Plasma Torch. In this process, the waste is brought into contact with a gas, energized to its plasma state by an electrical discharge. The temperature in the centerline of the torch reaches up to ~5000 °C, which ionizes the gas and subsequently the ionized gas molecules transfer the energy to the waste and cause pyrolysis. This method can destroy refractory compounds.[18]

2.5.4 Disposal of Hazardous Waste – TSDF

The final and most vital step in any hazardous waste management plan is the suitable and efficient disposal of the waste. However, efficient disposal is very dependent on other stages since its effectiveness depends largely upon the process of collection, transfer and treatment. Based on the disposal pathway suggested by fingerprint analysis, the waste is taken for its final disposal. In general, the easiest and most practiced option for disposal is to dump the waste in landfills. However, in recent years many countries have started to think along the line of "zero landfill". Incineration is also a disposal practice that is safe provided that there are dedicated waste incinerators. Hence a comprehensive hazardous waste management facility must consist of waste stores, laboratories, dedicated incinerators, reuse/recycling plants, arrangement for transfer and a secure landfill (especially for inert waste).

The selection of a particular disposal option depends upon several factors, such as the capital investment required, operational and maintenance expenses, technical requirements, *etc.* However, it is advisable to adopt more than one disposal option.[33] Since incineration has already been discussed, the other suitable options for waste disposal are briefly considered in the following subsections.

2.5.4.1 Immobilization

When the toxic waste is mixed with certain materials that tend to form an impermeable solid matrix around the waste, it is called immobilization, as the waste is fixed/trapped inside the matrix. This can be achieved through physical, chemical or physicochemical mechanisms. Cement, polymeric sulfur and resins are some of the substances used to immobilize wastes containing organic compounds. Immobilization can be achieved through solidification techniques or stabilization techniques.[33] A comparative analysis of these techniques is presented in Table 2.6.

2.5.4.2 Landfills

A secure landfill is one that contains hazardous waste, but without any seepage/percolation of leachate into the ground. To fulfill this requirement, the basic design considerations involve the following:

- a layer of natural mineral liner followed by synthetic liner;
- a well-designed drainage system to collect leachate;

Table 2.6 Comparison of immobilization techniques.

	Cement-based solidification	Lime-based solidification	Organic polymer technique (urea–formaldehyde process)	Thermoplastic encapsulation
Brief description	Formation of a monolithic, rock-like structure around the waste using Portland cement and additives (fly ash, *etc.*)	Mixing of inorganic sludge with lime and additives (fly ash, kiln dust, *etc.*) to form pozzolanic concrete	Mixing of an organic monomer with the waste using a catalyst resulting in a hardened polymerized mass that entraps the solids while permitting some liquid to escape	Dewatered solid waste is mixed with a thermoplastic polymer (asphalt. bitumen, *etc.*) and heated followed by cooling, allowing the formation of a coating over the waste
Applicable waste	Waste sludge contaminated with heavy metals or traces of radioactivity is present	Commonly used for inorganic hazardous compounds	Both wet and dry sludge	
Advantages	• Cost-effective • Simple operation • Tolerant of chemical variations	• Cost-effective • Simple operation • Ease of availability	• Drying of polymer mass is not necessary	• Sludge is completely isolated • Secondary container is not required
Limitations	• Increased bulkiness • Organic matter hinders the settling process • Low-strength cement may cause leaching	• Bulky products • Increased chances of leaching	• Catalyst is a strong acid, hence waste may escape with liquid because of increased solubility	• Expensive materials • Polymers used are flammable, hence special care is required

- provision for a layer of some impervious material (*e.g.* clay) blanketing the landfill and its slopes (this results in minimizing infiltration, permits adequate runoff and avoids spooling of water in the surrounding areas).

Moreover, there must be provision for surveillance or monitoring bore wells, which must be constructed in both the upstream and downstream directions of the landfill used to monitor the quality of groundwater. However, the leachate collected from the landfill and other areas such as waste storage units and laboratories must be treated and disposed of in a "leachate treatment facility" using one of the following options:

- solar evaporation;
- forced evaporation;
- treatment in common effluent treatment plants.

Landfills can have different standards, such as having a single liner, double liner, above the ground or below the ground (based on the groundwater table). Consequently, the site selection for secure landfill must include identifying the soil strata, soil and rock characteristics, groundwater profile, flood levels and access to transportation, *etc.*

2.6 Monitoring Procedure for Treatment, Storage and Disposal Facility/Prevention of Environmental Hazard Risks

In this section, various potential environmental hazard risks at disposal sites are discussed. These hazards emphasize the need for frequent monitoring procedures at TSDF facilities.

2.6.1 Fire

There may be several natural reasons that may cause fire at a landfill site that may not always be monitored. However, the primary anthropogenic reasons may involve following:

- disposing of two or more non-compatible wastes together;
- wastes having high ignitability and calorific value;
- wastes having high reactivity with water, air, acids and bases.

The chances of fire due to other operations are very small.

2.6.2 Rain/Storm

Rains or storms create the potential for leachate generation and subsequently may hamper the drainage and leachate collection efficiency.

Hence, if the landfill is located in areas with heavy or frequent rainfalls, provision of temporary or permanent cover arrangements must be made. Moreover, storm water drains must be constructed and must be efficiently maintained to keep them operational. Waterlogging in the surrounding areas must be avoided, especially in areas with high groundwater levels.

2.6.3 Air Emissions

The major problem emanating from air emissions is the management of "dust", which can be managed through spraying of leachate over the landfill and surrounding areas (especially in the summer season), which not only suppresses the dust but also helps in evaporation of leachate. Moreover, depending upon the stack height and the presence of a geologically sensitive site, the locations to install air-quality monitoring stations must be decided. These stations will monitor the total volatile organic compounds (VOCs), suspended particulate matter (SPM), respirable suspended particulate matter (RSPM), NO_x, SO_x, *etc.*, in the ambient air. Moreover, unpleasant odors may be controlled through (a) restriction of the organic content in the wastes and (b) proper compaction and cover. This will also enhance the esthetic appeal of the landfill.[34]

2.6.4 Groundwater and Surface Water Quality Monitoring

In the worst-case scenario of failure of the landfill liner system, the seepage may leach into the groundwater or reach the surface water, which would degrade the quality of the groundwater and surface water. Hence proper care and attention must be exercised during the design, construction and operation of a landfill site. Moreover, activities that may damage the liners must not be allowed at the landfill or nearby areas. It is strongly recommended that the quality of groundwater (through hand pumps, tube wells or monitoring wells) and surface water (through drains and rivers) is regularly monitored. Parameters to be analyzed must include pH, color, electrical conductivity, turbidity, solids concentration, total organic carbon, biological oxygen demand (BOD), chemical oxygen demand (COD), chlorides, nitrates, sulfates, total Kjeldahl nitrogen, total alkalinity, total hardness, pesticides and heavy metals.[34]

2.6.5 Soil Quality Monitoring

Soil samples must be regularly monitored, the recommended parameters being pH, electrical conductivity, color, total dissolved solids, total organic carbon, polycyclic aromatic hydrocarbons (PAHs) and heavy metals. It is strongly recommended that this monitoring is performed on a seasonal basis, *i.e.* in each season through the year. Moreover, any spillage on the roads must be immediately disposed of into the landfill and surrounding areas must be continuously monitored for effective functioning.[34]

Further Reading Online

http://www.theworldcounts.com/counters/waste_pollution_facts/hazardous_waste_statistics
https://www.graphicproducts.com/articles/hazardous-waste-symbols/
https://www.epa.gov/hw
https://www.epa.gov/hw/learn-basics-hazardous-waste
http://www.dtsc.ca.gov/HazardousWaste/
http://www.environment.gov.au/protection/hazardous-waste/what-hazardous-waste
http://ec.europa.eu/environment/waste/hazardous_index.htm
http://uppcb.com/hazardous_waste_brief.htm
https://archive.epa.gov/epawaste/hazard/web/html/hwid-intro2.html
http://www.environmentalpollution.in/waste-management/hazardous-waste/how-to-treat-hazardous-waste-physical-chemical-and-biological-treatment/6741

References

1. H. Ozaki, K. Sharma, C. Phanuwan, K. Fukushi and C. Polprasert, Management of hazardous waste in Thailand: present situation and future prospects, *J. Mater. Cycles Waste Manag.*, 2003, **5**(1), 0031–0038.
2. N. T. K. Thai, Hazardous industrial waste management in Vietnam: current status and future direction, *J. Mater. Cycles Waste Manag.*, 2009, **11**(3), 258–262.
3. T. Öztürk, Generation and management of electrical–electronic waste (e-waste) in Turkey, *J. Mater. Cycles Waste Manag.*, 2015, **17**(3), 411–421.
4. M. D. LaGrega, P. L. Buckingham and J. C. Evans, *Hazardous Waste in Hazardous Waste Management*, Waveland Press, Illinois, 2nd edn, 2010.
5. US EPA, *Introduction to Hazardous Waste Identification,* 40 CFR Part 261, Solid Waste and Emergency Response, 5305W, US Environmental Protection Agency, Washington, DC, EPA/530/K/05-012, 2005. https://www.epa.gov/sites/production/files/2015-09/documents/hwid05.pdf. Accessed January 2018.
6. J. Pichtel, *Waste Management Practices: Municipal, Hazardous and Industrial*, 2nd edn, Taylor & Francis Group, USA, 2014.
7. US EPA, *EPA's Report on the Environment (ROE) (2008 Final Report)*, US Environmental Protection Agency, Washington, DC, EPA/600/R-07/045F (NTIS PB2008-112484), 2008. https://cfpub.epa.gov/ncea/risk/recordisplay.cfm?deid=190806. Accessed 15 February 2018.
8. EPA Ireland, *Waste Classification List of Waste & Determining if Waste Is Hazardous or Non-hazardous*, Environmental Protection Agency, Ireland, 2015, https://www.epa.ie/pubs/reports/waste/stats/wasteclassification/EPA_Waste_Classification_2015_Web.pdf. Accessed January 2018.

9. US EPA, *Hazardous Waste Identification Rule (HWIR): Revisions to the Mixture and Derived-From Rules*, 40 CFR Parts 261 and 268, 2001. https://www.gpo.gov/fdsys/pkg/FR-2001-05-16/pdf/01-11411.pdf. Accessed January 2018.
10. H. E. M. Saleh, Introductory Chapter: Introduction to Hazardous Waste Management, in *Management of Hazardous Wastes*, ed. H. E. M. Saleh and R. O. A. Rahman, InTech, 2016, DOI: 10.5772/62208.
11. S. Nair and J. Abraham, Hazardous Waste Management with Special Reference to Biological Treatment, in *Handbook of Environmental Materials Management*, ed. C. Hussain, Springer, Cham, 2018.
12. US EPA, *Test Methods for Evaluating Solid Waste, Physical/Chemical Methods (SW-846)*, US Environmental Protection Agency, 2014, https://www.epa.gov/hw-sw846/sw-846-compendium. Accessed November 2018.
13. US EPA, *United States Environmental Protection Agency*, Standards Applicable to Generators of Hazardous Waste (40 CFR Part 262), 2018, https://www.ecfr.gov/cgi-bin/text-idx?SID=12dbfa31159667c702e5ee735c5b06f8&mc=true&node=pt40.28.262&rgn=div5#se40.28.262_114. Accessed November 2018.
14. US EPA, *RCRA Waste Sampling Draft Technical Guidance, Planning, Implementation and Assessment, EPA 530-D-02-002*, US Environmental Protection Agency, Washington, DC, 2002. Accessed November 2018.
15. US EPA, *Calculating Upper Confidence Limits for Exposure Point Concentrations at Hazardous Waste Sites, OSWER 9285.6-10*, US Environmental Protection Agency, 2002. https://www.epa.gov/sites/production/files/2016-03/documents/upper-conf-limits.pdf. Accessed November 2018.
16. US EPA, *Procedures for Transportation Workplace Drug and Alcohol Testing Programs* (49 CFR Part 40), US Environmental Protection Agency, 2018. https://www.ecfr.gov/cgi-bin/text-idx?SID=44edbc0e557a4cc5ff03365810ee5b1c&mc=true&node=pt49.1.40&rgn=div5.
17. G. Tchobanoglous, F. L. Burton and H. D. Stensel, *Wastewater Engineering: Treatment and Reuse*, McGraw-Hill, Boston, 4th edn, 2003.
18. US EPA, *A compendium of technologies used in the treatment of hazardous wastes*, EPA/625/8-87/014, 1987.
19. Y. S. Peng and E. I. Wang, Treatment of Pulp Mill DStage Bleaching Effluent Using a Pilot-Scale Electrocoagulation System, *Water Environ. Res.*, 2016, **88**(3), 257–263.
20. D. I. Fox, D. M. Stebbins and N. A. Alcantar, Combining Ferric Salt and Cactus Mucilage for Arsenic Removal from Water, *Environ. Sci. Technol.*, 2016, **50**(5), 2507–2513.
21. N. Abdullah, R. J. Gohari, N. Yusof, A. F. Ismail, J. Juhana, W. J. Lau and T. Matsuura, Polysulfone/Hydrous Ferric Oxide Ultrafiltration Mixed Matrix Membrane: Preparation, Characterization and its Adsorptive Removal of Lead(II) from Aqueous Solution, *Chem. Eng. J.*, 2016, **289**, 28–37.
22. M. Mondal and S. De, Treatment of Textile Plant Effluent by Hollow Fiber Nanofiltration Membrane and Multi-Component Steady State Modeling, *Chem. Eng. J.*, 2016, **285**, 304–318.

23. K. Grover, S. Komarneni and H. Katsuki, Uptake of arsenite by synthetic layered double hydroxides, *Water Res.*, 2009, **43**(15), 3884–3890.
24. J. Xu, Z. Qu, N. Yan, Y. Zhao, X. Xu and L. Li, Size-Dependent Nanocrystal Sorbent for Copper Removal from Water, *Chem. Eng. J.*, 2016, **284**, 565–570.
25. Z. Cheng, F. Fu, D. D. Dionysiou and B. Tang, Adsorption, Oxidation and Reduction Behavior of Arsenic in the Removal of Aqueous As(III) by Mesoporous Fe/Al Bimetallic Particles, *Water Res.*, 2016, **96**, 22–31.
26. R. Prakash and M. Gowtham, *Hazardous Waste and Its Treatment Process in Energy from Toxic Organic Waste for Heat and Power Generation*, Woodhead Publishing Series in Energy, 2019.
27. M. N. Rao, R. Sultana and S. H. Kota, *Hazardous Waste in Solid and Hazardous Waste Management*, Butterworth-Heinemann, 2017, DOI: 10.1016/B978-0-12-809734-2.00005-5.
28. E. Amanatidou, G. Samiotis, E. Trikoilidou and L. Tsikritzis, Particulate Organics Degradation and Sludge Minimization in Aerobic, Complete SRT Bioreactors, *Water Res.*, 2016, **94**, 288–295.
29. S. Chamorro, J. P. Vergara, M. Jarpa, V. Hernandez, J. Becerra and G. Vidal, Removal of Stigmasterol from Kraft Mill Effluent by Aerobic Biological Treatment with Steroidal Metabolite Detection, *J. Environ. Sci. Health, Part A*, 2016, **51**(12), 1012–1017.
30. R. Cheerarot and C. Jaturapitakkul, A study of disposed fly ash from landfill to replace Portland cement, *Waste Manage.*, 2004, **24**, 701–709.
31. G. D. O. Okwadha, Partial replacement of cement by plant solid waste ash in concrete Production, *IOSR J. Mech. Civil Eng.*, 2016, **13**(5), 35–40.
32. D. A. Rubinos and G. Spagnoli, Utilization of waste products as alternative landfill liner and cover materials – A critical review, *Crit. Rev. Environ. Sci. Technol.*, 2018, **48**(4), 376–438.
33. C. Visvanathan, Hazardous waste disposal, *Resour., Conserv. Recycl.*, 1996, **16**, 201–212.
34. US EPA, *Waste Analysis at Facilities that Generate, Treat, Store and Dispose of Hazardous Wastes*, Solid Waste and Emergency Response (5303P), EPA530-R-12-001, 2015.