Chapter 5
Medical Waste Management and Treatment Technologies

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5.1 Introduction

Medical waste refers to the waste generated as a result of healthcare activities at hospitals, blood banks, veterinary clinics, medical research laboratories, or any other healthcare facilities. It includes any discarded material that is involved in the diagnosis and treatment of humans and animals, and it is usually contaminated with blood, body fluids, or any other infectious material. Figure 5.1 shows typical generated medical wastes in a hospital. Medical waste can be generally classified into general waste, infectious waste, hazardous waste, and radioactive waste (Hulley 2020). According to the Medical Waste Tracking Act of 1988, EPA defined medical waste as any type of solid waste that is created in the diagnosis, treatment, or immunization of human beings or animals, or in related research studies, or in the production or testing of biologicals (Chartier et al. 2014). The main components of medical waste are plastics, paper, and textiles, and these primary materials are used in hospitals for sanitary consumables such as bottles, drug packaging, bedsheets, toilet papers, face masks, and gloves. The bulk density of medical waste is typically 249 kg/m^3 with a moisture content of 44.75 wt.% (Zhang et al. 2016).

Medical waste poses a serious risk to the health and to the environment because it contains several pathogenic microorganisms and hazardous chemicals. Improper handling of medical waste could lead to the exposure to pathogens or hazardous material through inhalation, ingestion, or cuts or punctures by infected sharps.

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Fig. 5.1 Typical medical wastes found in hospitals (Medical wastes n.d.)

Underdeveloped and developing countries lack efficient medical waste management systems and establishments. For instance, a study was conducted in Bangladesh, which is a developing country with rapidly rising urban population and numerous health issues, and it was observed that the limited medical waste management systems were attributed to lack of education on medical waste management. Only four major cities (Dhaka, Chittagong, Gazipur, and Khulana) implemented some type of healthcare waste management methods. In other cities, the collected medical wastes are transferred to open waste dumping sites. Typically, hospital and domestic waste are mixed together and discarded or buried, without accounting for any rules or restrictions. Furthermore, it is reported that there are no specific waste treatment practices or guidelines in government hospitals within the country. The hospital employees treat all wastes as general solid wastes, without paying much attention to the possibility of the infectious nature of medical wastes (Md. Yousuf and Rezaul 2018). Due to the lack of education and awareness on the dangers of medical wastes and due to the absence of adequate waste management and control technologies or equipment, this trend will continue to persist. However, a study which focused on 900 private healthcare facilities show that the medical waste is 16.18% of the total waste, which falls within the acceptable World Health Organization (WHO) range of 10–25%. In the private healthcare sector, the average daily hazardous healthcare waste generation rate per patient was found to be 0.17 kg per bed per day. Even with the low hazardous waste generation rates in private sectors, the personnel involved in waste disposal and treatment are subject to health hazard issues, as a result of massive accumulation of medical wastes over time (Md. Yousuf and Rezaul 2018).

The objective of this chapter is to provide an overview of medical waste constituents, environmental laws related to medical wastes, management and control techniques, and medical waste management during COVID-19 pandemic.

5.2 Categories of Medical Wastes

The World Health Organization (WHO) categorized medical wastes into several groups:

- *Infectious wastes*: wastes that have a large concentration of substances or pathogens that can cause infections to humans. It includes cultures of infectious agents, as well as wastes from patients with infections. For instance, these types of wastes come from the following contaminated sources: used swabs, bandages, surgical gloves, masks, dressing, and any disposable medical equipment (Chartier et al. 2014).
- *Sharps*: wastes that do not pose an infectious hazard but a physical one instead (i.e., cut, abrasion). Sharp waste includes syringes, needles, scalpels, blades, broken glass, etc.
- *Pathological wastes*: wastes that consist of body parts of humans or animals (i.e., organs, tissues, body parts, blood, body fluids).
- *Chemical wastes*: wastes that result from cleaning or medical diagnosis processes. They include chemical solvents, disinfectants, and reagents used for cleaning and disinfecting medical laboratories.
- *Radioactive wastes*: wastes that consist of radioactive material such as radionuclides that are used for diagnosis and treatment.
- *Pharmaceutical wastes*: wastes that include unused, expired, contaminated drugs, and vaccines.
- *Cytotoxic wastes*: waste that includes genotoxic substances which can be categorized as one of the three: carcinogenic, mutagenic, or teratogenic. Cytotoxic waste can include expired or unused cytotoxic drugs used in the treatment of cancer and devices contaminated with cytotoxic substances.
- *General nonhazardous wastes*: wastes that do not possess infectious or radioactive nature and do not result in physical or chemical hazards. They are not dangerous to humans. This type of waste includes plastics, paper, and textiles.
- *Other categories of medical wastes*: these wastes include pressurized containers (gas cylinders) and waste containing heavy metal content such as broken thermometers, blood pressure gauges, and batteries.

In general, infectious waste, pathological waste, and sharps are the predominant waste types among the medical wastes generated. The WHO reported that around 85–90% of the total medical waste generated falls within the general nonhazardous waste category, while the rest of the medical waste generated is hazardous. If the waste is not segregated properly, the total volume of the medical waste generated would increase, as a result of contamination due to contact, hence increasing the overall waste management and treatment costs (Chartier et al. 2014).

Health hazards of medical wastes are mainly caused by the infectious pathogenic microorganisms that the waste contains. Other hazards are usually caused by hazardous nature of chemicals and pharmaceuticals, the radioactivity of the waste, and the cuts from sharps. The exposure to medical wastes could cause harm to anyone including medical staff, medical waste handlers, workers of waste treatment facilities, patients, and general public. Exposure to the waste can occur through direct or indirect contact with a help of a carrier like air, water, or the environment or direct contact through inhalation, ingestion, or by skin cuts or punctures. Improper management of medical waste poses significant risks on the human health and the environment.

5.3 Quantities of Medical Wastes

The quantities of medical wastes in three different developed countries including the United States, Australia, and Greece are discussed here to illustrate the enormous rate of medical waste generation.

The United States is one of the world's top contributing nations, toward prominent solid waste generation, equivalent to 624,700 metric tons in 2011 (Van Demark 2018). In terms of annual waste generation, the healthcare industry is second only to the food industry, which is known as the primary contributor in waste generation. Each year, healthcare facilities in the United States produce 4 billion pounds of trash (660 tons per day), in which their operating rooms generate up to 70%, or approximately 2.8 billion pounds (Van Demark et al. 2018).

Similarly, the Australian healthcare system has grown into being one of the greatest contributors of wastes in the country, generating up to 236 million kilograms of waste per year. According to the United Nations Environmental Program (UNEP), a single patient hospital bed can produce up to 0.87 kg of infectious waste each day. The daily output of CO_2, from incinerating the medical waste alone, is estimated to be in excess of 235,000 kg per day. Hence, the incineration process by itself releases a significant amount of greenhouse gases (GHG). To put that in perspective, 1 kg of clinical waste creates around 3 kg of carbon dioxide when burned; thus the medical waste generation directly impacts the amount of CO_2 emissions, which contributes toward the global warming effect (Wyssusek et al. 2018).

Moreover, in Greece, the generation rates and compositions of infectious and urban medical wastes, generated from private medical microbiology laboratories, were investigated using real weight measurements, which were conducted over a 6-month period. The study found that infectious medical waste (IFMW), or the hazardous percentage of total MW, accounted for 35% of the total medical waste. The study also concluded that private microbiology laboratories in Greece generate about 580 tons of IFMW each year (Komilis et al. 2017). Furthermore, it was estimated that the laboratory units from different nursing departments in Rio University Hospital in Greece add up to almost 0.149 kg/bed/day of medical hazardous waste that is highly contagious (Zamparas et al. 2019).

5.4 Regulations Related to Medical Wastes

In 1988, the US EPA established Medical Waste Tracking Act (MWTA) which provides guidelines on medical waste management (US EPA 2011). State agencies also have their own laws and regulations under the guidelines of MWTA, and the regulations of each agency differ significantly from one to the other. Federal agencies such as Centers for Disease Control and Prevention (CDC), Occupational Safety and Health Administration (OSHA), and the Food and Drug Administration (FDA) have established safety regulations on handling medical wastes (US EPA n.d.). Several international agreements such as Basel Convention also exist to control the transport of medical wastes between the countries (UN Environment Program 2011).

One of the main goals of the MWTA is the design of a cradle-to-grave tracking system based on the waste generator and the type of regulated wastes. The act also developed the tracking system that was similar to RCRA manifests for hazardous waste. In addition, necessary waste segregation, packaging, labeling, storage, and management standards were established, as well as record-keeping requirements and fines that might be imposed for waste mishandling. From June 1989 to June 1991, these guidelines for tracking and managing medical waste were implemented in four states: New York, New Jersey, Connecticut, and Rhode Island, as well as Puerto Rico. EPA also gathered data and conducted various research projects on medical waste management (Regulated Medical Waste 2015).

Determining whether the waste is infected or not has been proven to be difficult, due to the associated uncertainty. Inconsistent treatment, storage, and disposal techniques may come from various working definitions of infectious waste. Thus, inconsistencies can impact the waste management costs, treatment technology selection, and ultimately, the possible health and environmental risks (Uzych 1990). Both CDC and US EPA as well as numerous state agencies have sought to classify infectious waste based on a variety of waste characteristics. Infectious waste, for example, is defined by the EPA as the waste that can cause an infectious disease. It necessitates the examination of at least four factors linked to the disease: dosage, resistance, portal of entry, and presence of pathogen (Uzych 1990). The CDC further issued recommendations in 1987, stating that blood and body fluids should be regarded either as human immunodeficiency virus or blood-borne infections. However, the CDC eventually limited the scope of its guidelines published in 1987 only to blood and other visible blood-containing body fluids (Uzych 1990).

Implementing EPA recommendations has been a challenge for medical waste producers. For instance, the EPA categorizes communicable disease wastes as infectious, whereas the CDC recommends managing communicable disease wastes in accordance with specific guidelines of the hospital (Uzych 1990). At present, the EPA is no longer in charge of medical waste regulation; instead, the states and other government entities have acquired that responsibility.

The existing medical waste regulatory structure in the United States is summarized as follows:

- *State Medical Waste Regulations*: To some extent, medical waste laws have been implemented in nearly all 50 states in the United States. State medical waste regulations, on the other hand, differ from state hazardous waste restrictions, which are all based on federal RCRA criteria. Some state medical waste regulations are modeled after the MWTA, while others have little or no relation. In most of the states, EPA is in charge of formulating and implementing medical waste management and disposal legislation. In other states such as Missouri and Oklahoma however, the department of health may play a significant role or even act as the primary regulating agency. In situations where both agencies are involved, the department of health is primarily in charge of on-site management, while the environmental agency is in charge of transportation and disposal of wastes. Moreover, medical waste packaging, storage, and transportation are regulated in most states. Healthcare facilities in some states are required to register and/or receive a permit. The development of emergency plans, on-site treatment of waste, training, waste tracking, record-keeping, and accident reporting may all be covered by state regulations (Regulated Medical Waste 2015).
- *OSHA Regulations*: OSHA regulates several aspects of medical waste including sharps' management, medical waste container design and requirements, medical waste bags/containers labeling, and employee training. The guidelines are intended to protect healthcare personnel against blood-borne pathogen exposure. The guidelines can however assist in the systematic management of waste, which benefits both the public and the environment. There are often overlaps between the environmental authorities, department of health, and the OSHA blood-borne pathogen standards. A set of regulations can either be generic or quite detailed. In such instances, it is recommended that the healthcare facilities adhere to the more detailed or strict rules. The OSHA standards address the significant gaps where there is a lack of comprehensive medical waste regulations (Regulated Medical Waste 2015).
- *US EPA Regulations*: EPA has active regulations governing emissions from hospitals, medical/infectious waste incinerators, as well as requirements under the Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA) for certain medical waste treatment technologies that use chemicals to treat the waste (Regulated Medical Waste 2015).
- *The Department of Transportation (DOT) Regulations*: DOT classifies regulated medical waste as hazardous. Regulated medical waste (RMW) is defined as the fraction of the waste stream that may be contaminated by blood, body fluids, or other potentially infectious materials, thus posing a significant risk of infection transmission. It is also known as "biohazardous" waste or "infectious medical" waste. Although any item that has come into contact with blood, mucus, or secretions may be infectious, it is neither practical nor a requirement to treat such waste as infectious. Guidelines and regulations, established by the federal, state, and local governments, define the types of medical wastes that are regulated, as well as the treatment and disposal standards to be followed. The degree of contamination, such as blood-soaked gauze that constitutes the discarded item, is likewise addressed by state regulations. Other specific categories of waste

generated in healthcare facilities (i.e., research laboratories that require handling precautions) are identified and categorized in the EPA's Manual for Infectious Waste Management (CDC 2003). Although understanding these standards is vital because of the liability connected with transporting to an off site, the DOT requirements largely apply to transporters rather than healthcare facilities (Regulated Medical Waste 2015).

5.5 Medical Waste Management

5.5.1 Collection, Storage, and Transportation

A proper collection and storage strategy must be devised in a waste management program. A daily collection system is needed to avoid major accumulation of wastes. Different types of wastes should be stored separately, for instance, infectious waste should never be stored in places accessible to the public. There are several criteria that should be met in order to choose a specific area of waste storage, and these criteria include the optimal temperature of the area, ease of cleaning, restriction on facility access, exposure to the sun, waterproofing of the ground, ease of access to waste transportation facilities, ventilation, amount of light, etc. The vehicles to be used for transportation of medical waste are specific. Different types of waste can, but not necessarily, use different means of transport. Moreover, on-site transportation vehicles differ from the off-site vehicles. For off-site transportation, the facility itself is responsible for packaging and labeling the waste before transporting in specifically designed vehicles. Once the waste is transported out of the storage facility, different methods are used in the sterilization and treatment of medical wastes.

5.5.2 Segregation, Labeling, and Separation

Several methods such as segregation, separation, etc. are used to minimize the volume of medical waste. Segregation is beneficial because it prevents hazardous waste from reaching and contaminating the nonhazardous ones. Thus, segregation minimizes the quantity of the hazardous wastes, and it also eases the transport of the waste to a treatment facility. The medical waste is separated into categories based on its type, amount, composition, and disposal methods. Infectious and pathological waste, as well as sharps, are stored in separate containers. For each type of medical waste, the containers are labeled as "biohazard," and they are closed and watertight and are given uniform color codes to distinguish them. Figure 5.2 shows the type of symbol used to identify medical wastes. The size of the containers is determined by the amount of waste produced, and the containers are lightweight and easy to transport (Shareefdeen 2012).

Fig. 5.2 A symbol used to describe medical wastes (Biohazard symbol n.d.)

The system for segregation, packaging, labeling, and marking of medical waste involves its separation into categories as described. Infectious medical waste, for example, is placed in yellow plastic bags and is intended to be incinerated or buried deep in a landfill. Red plastic bags or containers are used if the waste is going to be autoclaved or microwaved. Medical wastes are commonly identified by the biohazard sign, when it comes to labeling and marking. Both the packaging and the labeling are widely used around the world, and the distinction lies in the treatment method (Shareefdeen 2012). Waste containers should never be completely full; instead they should be filled till two-thirds of the capacity, as a maximum. As a precautionary measure, nonhazardous waste can be considered hazardous if the waste is placed in the wrong container (Singh et al. 2021).

5.5.3 Medical Waste Management in Different Countries: Case Studies

Iran: Medical Waste Management Practices

Kargar et al. (2020) performed a study on medical waste management practices in Iran, where a significant increase in medical centers is observed. According to the Iranian Ministry of Health and Medical Education, hospitals had a total of 120,612 active beds in 2018. In addition to 2632 rural health clinics, 2783 urban health centers provide healthcare services. In comparison to other regions of Iran, the northern part of the country has a higher population density. As a result, medical waste management in northern Iran is far more essential than in other parts of the country. Babol, a city in Mazandaran province with a population of 250,126 people, was selected as a case study. A total of 20 high-demand medical centers were considered, which consisted of 8 hospitals and 12 clinics along with 7 storage centers, 7 treatment centers, 1 transfer station, and 1 disposal center (Kargar et al. 2020). Two new treatment centers with autoclave technology as well as two storage centers were recommended for western and eastern of Babol city to manage the medical waste.

Furthermore, another study reported by Eslami et al. (2017) is based on the data gathered from Iran's 31 provinces. The study reports about 14.8% and 24.3% of private and public hospitals, respectively, lack medical waste treatment, resulting in hazardous waste being disposed without treatment which can have major impacts on public health and the environment (Eslami et al. 2017). In this study, all hospitals with access to the Ministry of Health and Medical Education network were chosen. This survey included 837 hospitals from the list. The data was obtained based on the Ministry of Health and Medical Education's instructions for the hospitals' medical waste treatment and self-reporting. Forms and questionnaires were sent to all hospitals, and the following is a list of the most crucial data that were gathered (Eslami et al. 2017):

- The number of beds in a hospital (the number of active beds in a hospital)
- The type of hospital (i.e., private, governmental, related to other organizations, etc.)
- Rate of total waste generation (kg/day)
- Rate of infectious and sharp waste generation (kg/day)
- Rate at which chemical waste is generated (in kg/day)
- Treatment procedures (i.e., autoclave)

The wastes generated were grouped into one of three categories: nonhazardous or general waste, infectious and sharp waste, and chemical waste (Eslami et al. 2017). The study pointed out that the general medical waste generation rates ranged from 0.91 to 3.27 kg/bed/day, whereas infectious and sharp waste generation rates ranged from 0.48 to 1.78 kg/bed/day. The overall waste generation rate and the infectious waste generation rate in Tehran, Iran's capital, were reported as 3.38 and 1.22 kg/bed/day, respectively. Alborz province has shown to have the highest hazardous-infectious waste generation rates, at 1.78 kg/bed/day, and Qazvin had the highest general waste generation rates, at 3.27 kg/bed/day, respectively. It was observed that the rate of medical waste generation in Iranian hospitals is significantly high.

The variation could either indicate ineffective waste segregation practices within each hospital or other factors such as external patients, higher bed occupancy, larger number of lab tests, surgeries, etc. (Eslami et al. 2017). It is obvious that the amount of infectious and sharp waste in Iran's hospitals, as well as the rate at which they are generated, is extremely high. This increase can be attributed to a variety of factors, including poor segregation, lack of waste minimization strategies, and lack of awareness on the topic. Increased generation of infectious and sharp waste eventually leads to an increase in the cost of medical waste treatment and disposal. Through this case study, the importance of implementing a precise segregation program that uses standard color-coded plastic bags or containers and educating hospital staff is emphasized (Eslami et al. 2017).

Jordan: Medical Waste Collection, Segregation, and Disposal Practices

A significant number of patients from neighboring countries travel to Jordan for medical treatment because of Jordan's rapid growth in healthcare business, which has led to the increase in the volume of medical waste generated. Jordan's hospitals have grown by 32% in the last 10 years, and the total number of hospital beds has reached 13,731 in 2017 (Al-Momani et al. 2019). Improper waste collection services and incorrect waste disposal at open dumpsites hinder Jordan's waste management methods. According to Al-Momani et al. (2019), field studies and interviews were done at some of Jordan's hospitals including educational, public, and private sectors. Public healthcare facilities are the major generators of medical waste. The northern, southern, and middle region of Jordan consist of 30 public hospitals and 1427 public medical centers which are administered by the Ministry of Health (Al-Momani et al. 2019).

The medical waste generation ranged from 0.36 to 0.87 kg per patient per day. Poor and inefficient medical waste disposal has been observed along with the large amounts of medical wastes generated in the hospitals. The case study further highlighted that there was no regulatory system in place to regulate the disposal of medical waste in Jordan. Jordan currently produces around 2,454,000 tons of wastes including municipal solid waste, hazardous industrial waste, and medical waste per year. The medical waste disposal and treatment methods being practiced include incineration and sterilization using autoclaves (Al-Momani et al. 2019). According to the study, Jordan's middle and northern areas have higher awareness on medical waste management, when compared to the country's southern regions.

The study concluded that the medical waste generation will continue to rise as Jordan's healthcare services evolve and expand; as a result, each hospital in Jordan must implement a professional medical waste management system. It has also been found that the high generation rates of waste in hospitals were due to improper segregation practices. The study proposes that healthcare workers need to be more informed of medical waste management and treatment systems (Al-Momani et al. 2019).

Myanmar: Application of Multi-Criterial Decision Analysis

The number of private and public hospitals in Myanmar is steadily increasing, which will lead to an increase in the total quantity of medical waste generated (Aung et al. 2019). In Myanmar, there are no official standards in place to ensure the treatment and processing of medical wastes. Aung et al. (2019) discusses a framework for the hospital waste management evaluation criteria using multi-criteria decision-making approaches. The multi-criteria decision analysis (MCDA) enables decision-makers to address the uncertainty that can arise while assessing the management methods and condition of medical wastes. Therefore, decision-makers have been able to compare the results and assess the performance of individual hospitals, with the help of this approach. The study revealed that open burning, incineration, and uncontrolled dumping were the common methods of waste treatment and final disposal. In public hospitals, there is also a lack of awareness and inadequate training among the healthcare staff. This study focused on the problems in Myanmar's waste management system. To enhance the waste management systems at government facilities, it is suggested that a special budget is allocated and the rate of medical waste generation is tracked in a systematic way (Aung et al. 2019).

The United States: Lean and Green Surgery Project

In a recent research study, Van Demark et al. (2018) states that the "Lean and Green" surgery project was launched in 2015 by the American Association for Hand Surgery, to reduce the amount of medical waste generated. The number of active hand surgeons in the United States is reported to be around 2000 surgeons. If each surgeon performed 100 "green" cases each year, which adds up to a total of 200,000 cases, the project would save $10.64 per case, and 5.06 pounds of medical waste per case can be reduced. This study concludes that the reusing of single-use medical devices and waste segregation are important steps to minimize the wastes from surgery rooms (Van Denmark et al. 2018).

The United States: Reuse of Anesthetic Equipment, Training, and Regulatory Requirement

Another study (Wyssusek et al. 2018) suggests reducing, recycling, reusing, rethinking, and the use of emerging technologies to achieve waste reduction. In order to reduce wastes, spreading awareness is also essential. Mandatory refresher training for employees should be conducted to keep them reminded on waste management, in conjunction with the appointment of an environmental and health and safety officer that has an impact on waste reduction. According to a survey of 413 anesthesia departments in the United States, 58% would recycle single-use anesthetic equipment only if required by law. About 83% on the other hand would participate in a recycling campaign if it was initiated by a supplier (Wyssusek et al. 2018).

Table 5.1 presents case studies that were conducted in other countries related to medical waste management (Al-Momani et al. 2019).

5.6 Medical Waste Disposal, Disinfection, and Treatment Methods

After collection and segregation of the medical wastes, medical wastes are sent to a treatment facility in securely covered and labeled containers in a highly protected vehicle (Hulley 2020). As discussed in the previous section, in many countries,

Table 5.1 Case studies of medical waste Management in different countries

Location	Aim	Method	Result and conclusion	Sources
Baghdad, Iraq	During a 4-month study, two teaching hospitals with different bed capacity were analyzed	Experimental studies, document reviews, clinical audits, and interviews	The amount of medical waste varies. The difference was due to the number of patients admitted to hospitals as a result of a variety of factors (country's current situation, explosion, and the economic situation)	Kareem Ali et al. (2018)
KwaZulu-Natal, South Africa	To determine the knowledge, attitudes, and behaviors of staff at a district hospital about healthcare waste management	Total of 241 professionals and nonprofessionals participated in this observational study. Data collection using a questionnaire was used	Healthcare waste management was not well-recognized (42.7% had poor knowledge and 53.9% had good waste management practices). Appropriate training and supervision in healthcare waste management are required to convey knowledge among personnel	Olaifa et al. (2018)
Aligarh, India	To examine management of medical waste in hospitals	Medical waste was classified according to the degree of threat	A waste management system is absent in hospitals. Most hospitals did not segregate or treat waste before disposal and lacked suitable storage facilities. There were few people in charge of waste collection and disposal, and their knowledge was insufficient	Alam et al. (2019)
Southeast Nigeria	To assess the roles and attitudes of health professionals toward medical waste management and workplace safety	A questionnaire was distributed to 54 hospital administrators	40% of medical professionals were given training on medical waste management and workplace safety. Only 1.9% followed the regular operating procedure. Standard medical waste disposal procedures and training on occupational safety measures were unavailable. Monitoring healthcare activities and proper training are required to raise awareness	Anozie et al. (2017)

treating and disposing of medical waste are a challenge. Before selecting a technology, it is critical to have a good understanding of the waste category and its volume. Selecting the disposal, disinfection, or treatment method depends on several factors including the category of the medical waste, quantity of the waste, needed budget, availability of equipment, and the laws and the regulations of the country. Medical waste can be disposed of and treated in a variety of ways including landfilling, chemical disinfection, autoclaving, microwave disinfection, incineration, plasma gasification, and pyrolysis. Nonthermal technologies release fewer pollutants and are more cost-effective, convenient, and reliable (Eslami et al. 2017); therefore, thermal technologies such as incineration which produce toxic emissions are less desirable.

5.6.1 Landfilling

Landfilling is a traditional disposal method for all types of waste; however, landfilling is unsustainable, occupies large areas, produces emissions of toxic gas, and can be accompanied with risks of spreading and transmitting diseases. Usually, a landfill site is assigned to an area which is far from the urban population and water bodies (Torkayesh et al. 2021). The factors that make a successful landfill site are proper site selection, construction, operation, and post-shutdown monitoring. Moreover, geophysical methods are used to monitor the site in all stages of operation. Geophysical surveys are used to identify any faults such as fracture zones, former mining sites, highly porous site, etc. In some cases, nonhazardous medical waste can become toxic or produce toxic by-products on-site, as an outcome of the decomposition process. This toxic waste, when mixed with the water, can form a toxic leachate that can infiltrate and pose a significant risk on the environment (Sengupta and Agrahari 2017). Thus, leachate monitoring is important to reduce negative environmental and health impacts. Landfilling, as a standalone disposal method is not adequate.

5.6.2 Chemical Disinfection

Chemical disinfection is a process that involves the use of chemical disinfectants to disinfect the wastes. This method is mostly suitable for liquid waste but can also be used to treat solids. Solid waste needs to be shredded or grinded before the chemical disinfection process, to ensure that all of the waste is exposed to the chemical agent. Chemical disinfection with prior shedding is mostly used to pretreat COVID-19-related hazardous medical waste (Ilyas et al. 2020). The shredded and crushed waste is mixed with the chemical disinfectant and is kept in a closed system in vacuum, for a certain period of time. During this period, the organic contents of the waste is decomposed, and the harmful microorganisms are destroyed. Chemical disinfection can either be chlorine based or non-chlorine based. In a chlorine-based system, sodium hypochlorite or chlorine dioxide is used as the chemical disinfectant. A non-chlorine-based system uses hydrogen peroxide (Ilyas et al. 2020). Chemical disinfection is highly effective, with a broad spectrum of sterilization possible, but it has high material and equipment cost. Moreover, the method may produce chemical leachates and it does not reduce the volume of the waste.

5.6.3 Incineration

Incineration is mostly used to treat infectious or pathological waste (Rao et al. 2017). A typical waste incineration facility includes waste storage, feed preparation, and combustion unit followed by temperature reduction with heat recovery and air pollution control; meanwhile the ash produced is sent for disposal. For medical waste specifically, the waste is stored in puncture-resistant bags in refrigerated areas preferably. The furnace should be well-maintained, the air-to-fuel ratio should be in the optimal range, and the gas mixture should have an adequate residence time (Waste incineration & public health 2000).

Medical waste treatment through incineration is fast, simple, and effective in decomposing and disinfecting the waste completely. However, incineration releases high quantities of carbon and toxic emissions which contribute to an increase in pollution. Some of the harmful pollutants released by incineration include nitrogen oxides, sulfur oxides, carbon monoxide, particulate matter, hydrogen chloride, cadmium, lead, mercury, PCBs, and arsenic (Thind et al. 2021).

5.6.4 Autoclaving

Autoclaving sterilizes the medical waste by applying steam and pressure to destroy the microorganisms prior to its disposal in landfills (Rao et al. 2017). Autoclaving is mostly used for infectious material such as sharps (i.e., syringes and scalpels) that cannot be easily combusted (Rao et al. 2017). Autoclaving ensures strong penetration of the wastes and sufficient sterilization, but it does not reduce the volume of the medical wastes. Due to the observed increase in the volume of medical wastes in recent years, there is a lot of strain put on the storage facilities. Therefore, in addition to widely used methods discussed above, other recent treatment technologies such as microwave disinfection, plasma gasification, and pyrolysis are also discussed below.

5.6.5 Microwave Disinfection

In this method, the microwave energy is used to break down chemical bonds between the structures; thus, molecules change without undergoing oxidation in a low oxygen, nitrogen-rich environment. Moreover, it is performed at low temperature range of only 150–350 °C (Environmental Waste International n.d.). In this treatment method, the waste is first shredded; then water is added. Consequently, the mixture is internally heated to destroy bacteria and other microbes. Some of the advanced systems allow for lesser restrictions on the type of waste and type of equipment used. Microwave disinfection has high efficiency, better control, and good sterilization capacity, while contributing to less pollution. However, this method has few disadvantages including high capital and operating cost and no significant reduction in the volume of the waste.

5.6.6 Plasma Gasification

Plasma gasification is a promising medical waste treatment technique that converts waste into energy, thereby reducing the volume of the waste as well as reducing negative environmental impacts, along with putting the waste into use. Plasma gasification has several stages/units which include waste handling process, the plasma gasifier, the gas cleaning process, and the waste conversion process. Plasma gasification is a thermal process that converts organic matter into a synthesis gas that consists of hydrogen and carbon monoxide, by using plasma (Erdogan and Yilmazoglu 2020). Plasma is the fourth state of matter that contains radicals, charged ions, and free electrons. When a substance is being converted to plasma, various reactions such as ionization, disassociation, and reassociation occur. Thermal plasma generators require very high temperatures up to 10,000 K (Erdogan and Yilmazoglu 2020). The residual slag produced during the gasification treatment contains recoverable heavy metals such as iron, copper, chromium, cadmium, etc.

Compared to other conventional treatment systems, plasma gasification is an environmentally friendly process that produces hydrogen syngas, reduces the volume of waste generated, and provides a good sterilization. The disadvantages of this method are (a) it produces nitrogen oxides emissions and it has (b) high capital costs, (c) high specific energy consumption, and (d) low plant life. A study by Munir et al. (2019) reports the challenges associated with utilizing plasma gasification method. The construction of a plasma gasification plant is costly, possibly because it necessitates a higher level of plant automation, special construction materials to withstand the extreme temperatures, the cost of plasma sources such as plasma torch and plasma arc, and a shortage of technical experts in the relatively new field. Plasma gasification receives a moderate community readiness level because end users are unfamiliar with the technology and are concerned about the extreme process conditions. It is important to note that the plasma gasification's commercial applicability in waste management is currently limited. Plasma gasification is currently commercially used only in five sites across the world (Munir et al. 2019).

5.6.7 *Pyrolysis*

Pyrolysis is a thermal decomposition process of material with minimal or no oxygen supply, at high temperatures. Medical waste can be converted to high-value products such as biochar and bio-oil or biofuel which can be used as an alternative to fossil fuel, whereas biochar can be used as an adsorbent due to its porous surface and high surface functionality properties (Fakayode et al. 2020). A study conducted by Jung et al. (2021) states that the treatment of disposable face masks using pyrolysis technique generated 51 wt. % bio-oil, and similarly Su et al. (2021) reported that the treatment of medical waste of plastic using pyrolysis technique generated bio-oil with a calorific value of 41.31 MJ/kg. The disadvantages of pyrolysis process are that it produces nitrogen oxide emissions, it has high capital costs and high energy consumption, and it has a short plant life. Due to the complexity of medical wastes, pyrolysis process can be affected by several factors such as heating rate, temperature and pressure range, residence time, etc.

A comparison of several treatment methods discussed above is presented in Table 5.2 (Su et al. 2021).

Table 5.2 Advantages and disadvantages of different treatment methods (Su et al. 2021)

Treatment method	Advantages	Disadvantages
Landfilling	Simple, economical	High risk of infection, large area, releases toxic gases
Chemical disinfection	Less environmental impact, high efficiency, high sterilization	High cost of chemicals and equipment, produces toxic fluids, produces residual disinfectant, does not reduce waste volume
Incineration	Simple, wide application, high volume reduction	Releases toxic gases, produces ash
Autoclaving	Good sterilization, good penetration	Produces toxic fluids, does not reduce waste volume
Microwave disinfection	Good sterilization, high efficiency, less environmental impact	High cost of operation and equipment, low waste volume reduction
Plasma gasification	High waste volume reduction, good sterilization	High cost of operation and equipment, produces nitrogen oxides
Pyrolysis	High efficiency, sustainable practice, produces high-value products, wide application	High energy consumption and pretreatment cost

5.7 Medical Waste Management and Treatment During COVID-19

Medical waste management has become a growing area of interest, due to the waste generated by the new coronavirus (SARS-CoV-2) or COVID-19 pandemic, in all fronts. Since the first case of novel coronavirus (COVID-19), the virus infection has spread rapidly to countries all over the world. COVID-19 initially emerged in Wuhan, Hubei Province, China, in late December 2019. It results in acute respiratory distress syndrome. COVID-19 was declared as a pandemic by the WHO director-general on March 11th, 2020, after 118,000 people were infected and after it spread over 114 nations. Singh et al. (2020) state that at the peak of the pandemic, the city of Wuhan generated almost 247 tons of medical waste each day, nearly six times more than the years preceding the outbreak. Prior to the COVID-19 outbreak, the city's medical waste disposal capacity was at 50 tons per day which was estimated based on an incinerator plant that operated 24/7.

The performance of the waste management systems has recently been disrupted, and serious issues have arisen in monitoring medical waste as a result of COVID-19 pandemic. An ineffective waste management system contributes to the spread of COVID-19 (Tirkolaee et al. 2021). Disposal of infectious medical wastes associated with COVID-19, as a result of the diagnosis and treatment of patients, has become a significant concern. Most of the medical waste consists of plastic which also poses a risk to the environment. The governmental authorities and healthcare professionals need to ensure that the medical waste management policies and disposal are monitored to prevent further spread of the pandemic (Tirkolaee et al. 2021).

Ilyas et al. (2020) report that South Korea generated around 2000 tons of COVID-related medical waste, since the pandemic breakout until the beginning of May 2020, and the demand for personal protective equipment (PPE) such as facemasks and surgical gloves is predicted to grow at a 20% annual growth rate till 2025. They also report an alarming rate of medical waste growth in the Unites States during the pandemic. Effective COVID waste management, including adequate disinfection and disposal strategies, is needed to restrict further spread of COVID-19 virus, as well as to reduce the medical waste generation rate and lessen the negative impacts on the heath and the environment (Ilyas et al. 2020).

The use of the personal protective equipment (PPE) became crucial to protect the frontline healthcare workers, as they treat the asymptomatic and symptomatic patients, and to allow the effective functioning of the healthcare system. According to the WHO, healthcare workers require 89 million medical masks, 76 million gloves, and 1.6 million goggles per month (Prata et al. 2020). Public concerns over this highly contagious virus have led to an increase in the usage of PPE to control the virus's transmission (Prata et al. 2020). Considering the current situation of the pandemic, the role of plastic use in the prevention of diseases has led to the vast spread of public awareness and caught the attention of regulatory authorities. Due to the persistence of plastic material, PPE residues from the COVID-19 pandemic will likely be a frequent waste item found in the environment for decades, potentially harming diverse environmental and biological systems (Prata et al. 2020).

Medical waste generated during the treatment of COVID-19-infected individuals is one route for disease transmission. This waste, if not adequately managed, will constitute a health concern to the general public as well as the medical personnel involved in the disease's treatment.

In March 2020, a study (Abu-Qudais et al. 2020) was conducted in King Abdullah University Hospital (KAUH), and it examined the transmission of coronavirus in Jordan. A descriptive statistical analysis was performed on the amounts of medical waste generated. The average generation rate was found to be 3.95 kg/bed/day, which is ten times higher than the hospital's typical daily generation rate. The increased generation rate is due to the fact that the majority of the hospital's healthcare workers are using disposable personal protective equipment (PPE). Furthermore, the constant disinfection for cleaning of equipment, floors, and hard surfaces contributes to the rise in the amount of medical waste generated. It is important to rationalize the usage of PPE and disinfectants. Healthcare workers must be given adequate training on how to reduce the hazards associated with treating COVID-19 patients, particularly on how to reduce and manage the medical waste generated (Abu-Qudais et al. 2020).

Sangkham (2020) explained a study that was done to investigate the correlation between the use of face masks and the increase in medical waste generated in Asia, during the COVID-19 pandemic. The authorities in charge should pay close attention to all elements of prevention and control, so that the spread of the virus is controlled within hospitals (Sangkham 2020). Plastics are considered widely available low-cost materials. Poor management of PPE during the COVID-19 pandemic resulted in massive environmental pollution, with an estimated monthly use of 129 billion face masks and 65 billion gloves globally (Prata et al. 2020). This is a serious health issue since used face masks or gloves are considered a vector for the spread of the SARS-CoV-2 virus. Reducing the demand for PPEs and reusing them are crucial in the minimization of medical wastes generation. The reductions of PPE use can be achieved through physical barriers, sensible use by the healthcare workers, strict quarantine practices, social distancing measures, and cancellation of non-essential activities and mass gatherings. Healthcare professionals and the public must treat PPE that has reached the end of its life as infectious medical waste. Moreover, reusing can be accomplished by producing reusable PPE, which would minimize the reliance on single-use supplies (Prata et al. 2020).

5.8 Conclusions

In this chapter, definitions, categories of medical wastes, and regulations related to medical wastes are introduced. Various medical waste management techniques such as segregation, labeling and separation, waste minimization, etc. are presented. Conventional and innovative medical waste disposal, sterilization, and treatment methods including landfilling, chemical disinfection, autoclaving, incineration, microwave disinfection, plasma gasification, and pyrolysis are discussed. The advantages and disadvantages of each method are outlined. Moreover, medical waste management during COVID-19 pandemic is presented through recent case studies. The developing countries should enforce stricter laws and regulations so that efficient medical waste disposal methods and management techniques can be enforced. Medical waste management and treatment issues should be brought to the attention of the general public through education, training, and awareness campaigns.

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