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Review

Healthcare Waste Management Practices in Hospitals—A Review

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Abstract: The healthcare sector is witnessing a period of explosive growth due to technological innovations in treatments, diagnostics, and services in the healthcare industry. Although this development brings positive changes in the quality of care provided to patients, it is responsible for an exponential increase in Healthcare waste (HCW) production. Improper handling, processing, and disposal of such waste present environmental and public health risks, especially when hazardous HCW accumulates in the environment. HCW refers to infectious agents, pathological waste, sharps, pharmaceuticals, chemicals, and radioactive waste that require specific management techniques to ensure safety. In this review, various techniques employed in HCW disposal, such as incineration, chemical treatment, autoclaving, recycling, and landfill disposal, will be reviewed for their effectiveness and impacts on the environment and human health. This paper highlights major phases of waste management in hospitals, which include waste generation, waste segregation, waste collection, waste storage, waste transportation, waste treatment, and waste disposal. Segregation and proper handling have been highlighted as important practices to be employed to lower the risks and improve operations within healthcare facilities. This paper further examines different frameworks, policies, and awareness programs for effective healthcare waste management practices. Moreover, it evaluates the main challenges encountered by health care providers in managing waste effectively and sustainably, and the potential opportunities for improvement within this industry.

Keywords: Waste Disposal; Incineration; Recycling; Landfilling; Treatments; Public Health; Pharmaceuticals; Infectious

1. Introduction

In recent years, the healthcare sector has experienced rapid growth on a global scale [1]. Global health expenditure has reached unprecedented levels and exhibits a persistent upward trend on an annual basis. According to estimates, the global expenditure on healthcare in 2017 amounted to approximately USD 7.8 trillion, or almost 10% of the global gross domestic product (GDP) [2]. The rise in expenditure can be attributed to the growth in population and an increased need for healthcare services. It is anticipated that the current upward trajectory will persist, resulting in the global population reaching 9.8 billion by 2050 and 8.6 billion by 2030 [3]. As a result of an ageing population-driven increase in the demand for healthcare interventions and treatments, healthcare waste (HCW) will become more prevalent than in the past [3].

As a result of the ageing population, the expense of chronic diseases is increasing, and the cost of multiple morbid conditions (MMCs) is even greater. A higher frequency of utilisation is observed in relation to hospital admissions, prescriptions, and general and specialist care services when mobile medical centres are considered [4]. Having a single chronic condition increases the likelihood of experiencing multiple associated comorbidities, which in turn complicates the management of the chronic disease. The increasing prevalence of chronic diseases has led to widespread utilisation of healthcare worker disposal techniques and the expansion of the HCW disposal sector. In response to the increasing prevalence of chronic diseases, both industrialised and developing nations worldwide are implementing enhanced contagion measures to manage pandemics like Ebola and COVID-19. Consequently, there is a rise in the generation of potentially hazardous medical waste [5,6].

The prevalence of infectious diseases is on the rise worldwide, contributing to the accumulation of more waste [7]. Currently, the global annual production of solid waste is at around 1.47 billion metric tonnes, with a consistent upward trend observed over the years [8]. Out of the total of 1.47 billion tonnes, it is predicted that 5.9 million tonnes are caused by HCW [9]. However, due to the delicate nature and strict legal regulations, only a few studies have thoroughly examined the HCW streams to propose the most effective approaches for their treatment [10]. In accordance with European Union legislation, healthcare waste can be classified into seven distinct categories [11] as shown in **Figure 1**.

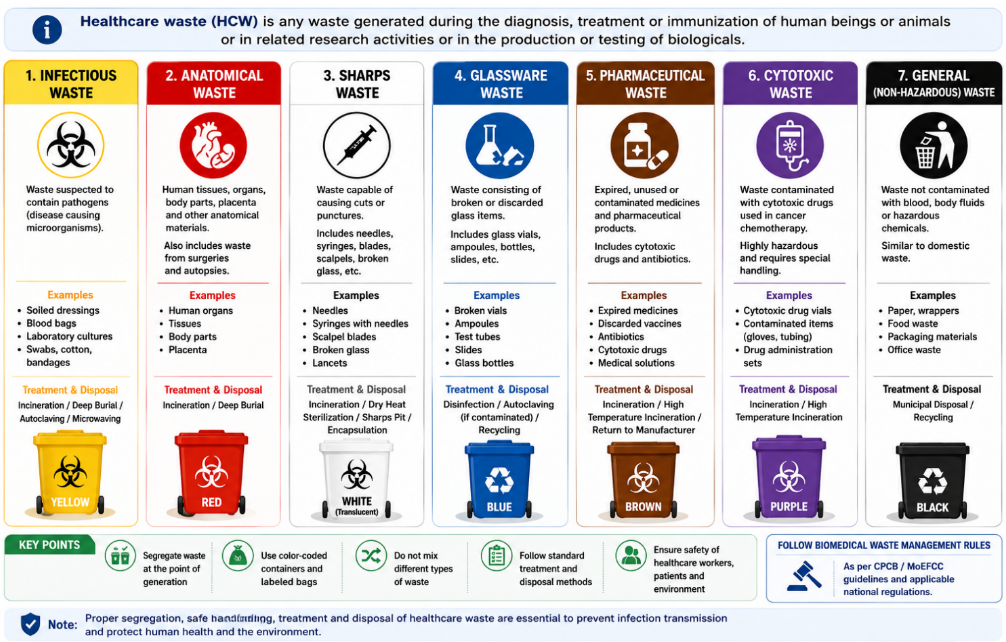

Figure 1. Classification of Healthcare Waste.

Around 75% of all garbage from healthcare centers is considered "non-hazardous waste," whereas 25% of garbage from such places can be regarded as "hazardous waste" [12]. In spite of the fact that nonhazardous waste does not sound dangerous at first glance, the process of disposing of such a waste product may cause negative consequences for both the marine and land-based ecosystems [13]. Hazardous waste may contain some toxic substances that are poisonous, infectious, and radioactive [12]; consequently, different problems arise from either disposing or not disposing of such waste. It should be noted that not all HCW is equal; some kinds of waste require specific disposal methods. The increasing amount of HCW has caused an increase in using numerous methods of getting rid of such waste products (landfills, composting, incineration, source reduction, reprocessing, and recycling) [14]. Disposal of HCW by healthcare workers has also been associated with a number of issues. Regardless of their potentially environmentally destructive nature, such problems primarily concern humans [15].

The substances that are released during proper methods of disposing HCW through incineration include sulfur, corrosive gases, nitrogen oxides, metals, and particulates [16]. The negative effects on the human body have also been experienced in terms of its respiratory system, endocrine system, the rise of cases of chronic illnesses, and even cancer caused by pollution of the environment [17]. Inefficiencies in disposing HCW could cause a bad effect on the environment and human beings. There are a number of reasons as to why there might be inefficiency in disposing of HCW [18].

Both patients and healthcare facilities like hospitals and drug stores play an important role in the management of healthcare wastes. The claim that many people dispose of their outdated medicines through dangerous means is substantiated by Bashaar et al. [19]. These acts, ultimately, lead to the discharge of pharmaceutical chemicals into the environment, thereby posing dangers to the general public [20]. Unfortunately, currently there are no options available in order to dispose of healthcare waste without causing harm to the environment and vice versa. Great strides have been made towards increasing counter-productivity in scenarios in which HCW might pose a risk to the lives of humans. The increased use of environmentally safe procedures in medical waste treatment, such as steam auguring, microwaving, and autoclaving, is due to the above efforts. In spite of the above facts, there are some possible disadvantages of the proposed environmentally friendly technologies, such as the inability to be used for bulky waste or being available to everybody [21]. Novel approaches are more likely to supplement conventional procedures than fully substitute them. Sterilization of solid medical waste by using an autoclave is possible. However, since reactivation of bacteria is possible, autoclaving cannot be considered as an alternative to incineration [22].

Additionally, they have resulted in additional training for healthcare professionals and staff about waste management and activities aimed at promoting environmentally friendly hospitals. Despite efforts to enhance the HCW disposal procedure, significant challenges and safety concerns pertaining to public health persist [23]. Better management is essential to meet the demands of a growing global population, an increasing life expectancy, and the epidemic of chronic illness that impacts everyone on the planet. Healthcare workers are in high demand. Existing methods of HCW disposal are insufficient to resolve the global HCW problem in a satisfactory manner. The present approaches employed for the disposal of healthcare waste will be the subject of this review, in an effort to ascertain their environmental and public health implications. Methods for the management of hospital waste were also discussed in the chapter. This comprises all stages of the refuse lifecycle, including generation, collection, storage, transportation, treatment, and disposal. The foundation of this study is the examination of frameworks for policies, training programmes, awareness campaigns, and waste classification, which collectively comprise hospital waste management. Management of healthcare waste is a critical concern, and this study will investigate potential obstacles and remedies for this issue.

2. Methodology of the Literature Review

This review was conducted using a structured literature search approach to identify relevant studies on healthcare waste management practices, treatment technologies, environmental impacts, and emerging sustainable healthcare waste management strategies.

2.1. Literature Search Strategy

A comprehensive search of peer-reviewed literature was performed using four major electronic databases: Scopus, Web of Science, PubMed, and Google Scholar. Also, there were more policy and report documents obtained from international bodies like the World Health Organization (WHO), United Nations Environment Programme (UNEP), and other international bodies working on healthcare wastes.

2.2. Search Keywords

The searches were carried out by the use of keyword combinations together with Boolean operators such as: ("healthcare waste" OR "medical waste" OR "hospital waste") AND ("waste management" OR "waste treatment" OR "waste disposal") AND ("incineration" OR "autoclaving" OR "microwave treatment" OR "chemical disinfection") AND ("circular economy" OR "sustainability" OR "life cycle assessment" OR "healthcare sustainability") AND ("artificial intelligence" OR "IoT" OR "smart waste monitoring" OR "RFID").

2.3. Inclusion Criteria

The studies were selected based on their relevance to:

- ➢ Healthcare waste generation, management, treatment or disposal.
- ➢ Were published in peer-reviewed journals.
- ➢ Were published in English.
- ➢ Included environmental, economic, technological, or public health aspects of healthcare waste management.
- ➢ Were published between 2005 and 2025.

2.4. Exclusion Criteria

Studies were excluded if they:

- ➢ Were conference abstracts without full text.
- ➢ Focused exclusively on municipal solid waste without healthcare applications.
- ➢ Were duplicate records.
- ➢ Lacked sufficient methodological details.
- ➢ Were not available in English.

2.5. Study Selection Process

The literature search initially identified 468 records. After removal of duplicate records (n = 92), 376 articles remained for title and abstract screening. Following relevance assessment, 152 articles were selected for full-text review. In addition, 111 papers were included for qualitative synthesis (**Figure 2**).

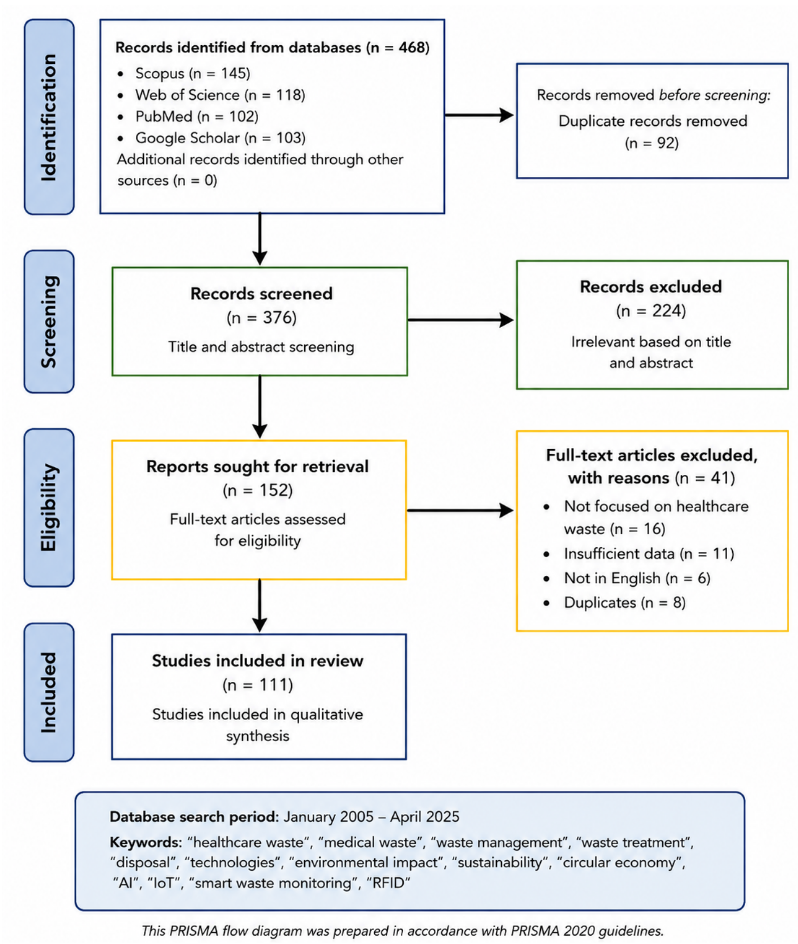

Figure 2. PRISMA flow diagram illustrating the literature selection process.

2.6. Data Extraction and Synthesis

The following data was extracted from the selected papers: publication year, geographic setting, and classification of healthcare waste, technologies used to treat such waste, effects on the environment, economic issues, sustainability, and recommendations. Findings were synthesized narratively and comparatively to identify trends, challenges, and opportunities in healthcare waste management.

3. Sources of Healthcare Waste

Healthcare waste can be found in different types, some of which have varying levels of complexity and toxicity. General waste and clinical waste can be considered two different categories. In classifying general waste as non-hazardous waste, this means that there is no risk associated with such waste and therefore does not require advanced disposal measures [24]. However, clinical waste is toxic and poses numerous risks, depending on the type of waste. As such, it requires specialist procedures to handle it. The common sources of clinical waste [25] include acute care facilities, such as but not limited to surgical operating theatres, accident and emergency departments, mortuaries, intensive care units, isolation units, pharmacies, pathology laboratories, and other research laboratories. Other facilities producing relatively less clinical waste include mental health services, immunization clinics, hospitals, community health centers, ambulatory centers, blood transfusion centers, dental surgeries, veterinarians, public health laboratories, and blood transfusion centers [26,27].

4. Healthcare Waste Management Practices

Healthcare waste management techniques (**Figure 3**) are discussed at great length below:

Figure 3. Healthcare Waste Management Approaches.

4.1. Waste Generation

It is necessary to note that the gathering of information about the amount of garbage generated is essential for efficient waste management planning. To improve the analysis of the necessary transport capacity, waste treatment methods, storage, and containers, such information forms the basis for understanding the expected refuse amount [28]. Several determinants can affect the amount of healthcare waste produced by hospitals. The above factors include the number of hospital beds, patients, hospital type, the method used to manage the waste, and departmental activity level [29]. One possible reason for underestimating medical waste in developing nations might be the practice of concealing and disposing of it by patients and their families [30]. It has been well-documented in numerous scientific papers how varied the rates of healthcare waste production can be. However, there remain differences in the research methods used by scholars in analyzing rates of healthcare waste production [29,31].

The level of waste generated by private hospitals in developing countries is higher than that of the government-run public hospitals [32]. People who belong to middle and upper economic classes prefer private hospitals rather than public hospitals because these hospitals provide medical services on minimal or free-of-cost basis [33]. However, such services have a higher cost attached to them. Therefore, the level of waste generated by private hospitals contains more hazardous components than that of the public hospitals run by the government. This is because the number of private hospitals in developing countries exceeds that of public hospitals [34].

4.2. Waste Segregation

Proper methods of separating health-care wastes are very important, considering the percentage of health care waste that does not possess any characteristics that may prove dangerous, which ranges between 75% and 90%. Specialised handling procedures are necessary for the remaining 10–25% of hazardous materials; however, these procedures frequently prove to be financially wasteful [30]. Inadequate waste segregation leads to an increase in the concentration of infectious ingredients, since any refuse that has been in contact with such components is deemed infectious [35]. As a result, waste segregation is a critical component in the efficient administration of healthcare waste [36]. Consequently, optimising waste management via recycling, decomposition, and landfilling becomes more pragmatic, secure, and economical when a greater volume of pure stream can be obtained via meticulous garbage segregation [37]. It is customary to utilise a color-coded bag for the purpose of separating [38]. This is a common occurrence in prosperous nations [27]. Placing garbage in the "three-bin system" is by far the most convenient and secure method. It commences at the generation site by classifying the collected waste into two distinct categories: nonhazardous general waste and hazardous waste, with the former typically comprising a greater quantity [39].

Once the hazardous component has been extracted, it is categorised into two parts: (i) discarded needles and (ii) potentially contagious materials. Nevertheless, the segregation of healthcare waste in developing countries is impeded by several factors, including inadequate staff attitude, insufficient data documentation, and a failure to segregate waste at its source [40,41]. The absence of sorting or segregation of healthcare refuse was documented in a prior investigation into healthcare management in developing nations [42,43]. However, more recent studies indicate that healthcare facilities in developing countries do practise waste segregation, albeit with variations in the specific methodologies utilised [29,44–48].

Tertiary healthcare facilities generate two primary types of solid refuse, according to World Health Organization [28], general garbage and sharps waste. Moreover, the waste generated from the virology laboratory is categorized into four different types of wastes: sharp, highly infectious, general, and infectious. The existing system does not conform to the recommendations of the WHO concerning the separation of different kinds of medical wastes, such as sharp, pharmaceutical, infectious, general, pathological, and radioactive waste [28]. For instance, the high rate of segregation of waste in urban centers can be explained by the existence of health monitoring authorities in those regions [46].

4.3. Training and Awareness

It is very important to make sure that health care professionals as well as other relevant stakeholders are well trained so that their healthcare waste management practices can be optimized [40]. Unfortunately, there is insufficient evidence available in the current body of literature concerning the level of awareness and training with regard to healthcare waste management by the facility waste workers as well as healthcare professionals in developing countries. This issue has been investigated at different governmental levels. Nonetheless, there have been plenty of case studies published in this area [37,47–50].

More research has been conducted on government hospitals than private hospitals [36,45]. The findings of many researchers show that healthcare workers undergo training only once after hiring, with little to no extra training conducted to improve their skillset [29,50]. There is an inadequacy of the necessary training related to workplace health and safety issues [43,50]. It is quite common for there to be no medical waste manual or signage in healthcare organizations when it comes to waste separation practices. Moreover, training of the healthcare workers in this regard is rare [30]. Employees in government hospitals have better skills and training than those working in private hospitals [37].

Possible causes of such an occurrence include heightened interest in knowledge and better availability of sources. Several countries' research shows that proper management of health care waste is still considered to be something beyond the understanding of medical staff, such as doctors, nurses, and midwives [50]. This situation gives rise to apprehensions regarding the institutions' training of healthcare workers not meeting the standards set forth by the World Health Organisation [51]. Hence, hospital refuse management in Nigeria might be inadequately utilised and undervalued [49].

4.4. Collection and Storage

To prevent waste accumulation at its source, healthcare facilities typically adhere to a consistent refuse collection schedule, which typically occurs on a daily basis [41,51]. In an effort to increase resource efficiency, standard waste management procedure dictates that collected solid refuse be stored in a designated area until it is transported to a treatment or recycling facility [52]. There are regulations governing the storage of medical refuse that must be observed [53]. A space has been allocated specifically for the disposal of medical refuse. The designated region must be enclosed in a wall or another means of seclusion, subject to limited access, safeguarded against rodents, birds, and animals, situated apart from food storage areas, and provided with adequate ventilation and illumination [41]. The inclusion of water and sewerage access is also a requirement [38]. The existing body of literature indicates that a limited number of healthcare facilities in underdeveloped nations possess healthcare waste storage facilities. Except for major urban areas, the majority of storage facilities do not adhere to specified requirements [44]. The garbage containers lack a lid, frequently exhibit overfilling, and lack leak-proof and puncture-resistant properties [47]. It is customary to establish a dedicated location within the hospital premises for the disposal of waste that is inadvertently incinerated without proper care. Certain categories of healthcare refuse, including sharps waste, infectious waste, and general waste, are each allocated dedicated storage areas. The strong government regulation and enforcement effectively elucidate it [54].

4.5. Waste Transportation

There are two alternatives available for the disposal and conveyance of healthcare waste: on-site and off-site [41,55]. On-site mobility equipment such as wheelbarrows, carts, containers on wheels, and trolleys can be utilised to transport healthcare refuse throughout the facility. The function of off-site transportation is to transport healthcare waste from the facility to a different location for disposal and treatment. All waste transporting personnel are required to wear appropriate PPE, including goggles, gloves, and water-resistant footwear. In most underdeveloped countries, wheelbarrows and trolleys were identified as the primary methods for transporting healthcare waste on-site [33,56]. On certain occasions, cleaners manually transport waste on-site using their hands or heads, without the use of personal protective equipment [44,57]. The World Health Organisation (WHO) advises the use of distinct carts for various waste types. However, this recommendation is frequently disregarded, with a single trolley being utilised for the transportation of all waste classifications. Each daily ward cleaning entails the responsibility of garbage collection and transportation to the central storage facilities. Reports indicate that the frequency of refuse collection from storage facilities to disposal centres is generally inconsistent [54,57].

5. Healthcare Waste Treatment and Disposal Techniques

Regarding the treatment and disposal of healthcare waste on a global scale, numerous methods exist. Despite being a close second to landfilling, incineration remains the most favoured option [58]. Certain forms of irradiation, including microwaving, and thermal treatments, including steam treatment and autoclaving, are considered to be less detrimental to the environment when compared to conventional methods. However, these methods are not accessible in numerous nations and are unsuitable for large-scale waste management. Although greener approaches are theoretically feasible, they are deemed unsuitable and impractical due to many factors such as their limited capacity to handle substantial quantities, their requirement to exclude volatile substances, and the substantial and costly cost associated with their implementation. Other green strategies also utilize the approach that involves pre-use steps, leading to partial waste disposal [59,60]. The need for other treatment methods should be considered when adopting green approaches such as the use of microwaves. Comparative analysis of healthcare waste treatment and disposal technologies are provided in **Table 1** below.

Table 1. Comparative Analysis of Healthcare Waste Treatment and Disposal Technologies.

Treatment Technology	Waste Type	Principle of Operation	Advantages	Limitations	Environmental Impact
Incineration	Infectious, pathological, pharmaceutical waste	High-temperature combustion (800–1,200 °C) reducing waste to ash	Significant volume reduction (>90%); effective pathogen destruction	High capital and operational costs; potential release of dioxins and furans	High if emission controls are inadequate
Autoclaving (Steam Sterilization)	Infectious waste, sharps	Sterilization using high-pressure saturated steam	Environmentally preferable; cost-effective; widely adopted	Unsuitable for pharmaceutical, chemical, and anatomical waste	Low
Microwave Treatment	Infectious waste	Internal disinfection using microwave-generated heat	Effective pathogen inactivation; lower emissions than incineration	Requires pre-shredding; relatively high energy demand	Low–Moderate
Chemical Disinfection	Liquid infectious waste, sharps	Chemical agents (e.g., chlorine compounds) deactivate pathogens	Effective for liquid waste; simple operation	Potential chemical hazards; less effective for solid waste	Moderate
Plasma Pyrolysis	Hazardous, infectious, pharmaceutical, chemical waste	Plasma arc converts waste into syngas and vitrified slag	Near-complete waste destruction; minimal toxic emissions	Very high installation and maintenance costs	Low
Sanitary Landfilling	Treated and non-hazardous waste	Disposal in engineered landfill systems	Low operational cost; widely available	Risk of leachate generation and groundwater contamination	Moderate–High
Deep Burial	Anatomical and pathological waste	Controlled burial in designated pits	Suitable for remote and rural locations; low cost	Potential soil and groundwater contamination	Moderate
Encapsulation	Sharps and pharmaceutical waste	Immobilization in sealed containers using cement or plastic	Prevents scavenging and reuse; simple implementation	Requires long-term containment; no volume reduction	Low–Moderate
Inertization	Pharmaceutical and chemical waste	Mixing waste with cement and lime to immobilize hazardous constituents	Reduces toxic leachability	Limited application; requires careful handling	Low
Shredding and Compaction	General and pre-treated healthcare waste	Mechanical size reduction and compaction	Reduces waste volume and transportation costs	Does not disinfect waste; requires prior treatment	Low
Waste-to-Energy (WtE)	Combustible healthcare waste	Conversion of waste into heat and electricity	Resource recovery; reduced landfill dependency	High capital cost; emission control requirements	Moderate

Note: Key: WtE, Waste-to-Energy.

5.1. Thermal Processes

5.1.1. Incineration

The term medical waste is also referred to as HCW and may involve burning to dispose of it. This involves the utilization of dry oxidation methods and moderate temperatures between 800 and 1,100 °C. Three main types of incinerators that may be employed when handling HCW include: Double chamber incinerators are mainly designed for HCW. The utilisation of single chamber incinerators is not as prevalent and widespread. Rotating kilns are capable of being employed for the treatment of genotoxic waste and heat-resistant compounds. Burning hazardous and nonhazardous waste has numerous applications in the context of HCW [61]. Incineration of pressurized petrol containers, reactive chemicals, silver salts, wastes with a high level of either mercury or cadmium content, halogenated plastics, sealed ampoules, and similar materials is discouraged [11]. Various forms of pathological wastes are regularly handled using this approach, whereby the wastes are converted to ashes and gases. Despite being very effective, incineration proves to be costly compared to alternative techniques, including landfilling, with the cost rate between three and five per volume unit [62]. Emissions of dioxins, which vary based on the method and equipment used during incineration, are another possible hazard resulting from this technique. A substantial number of these dioxins are listed as known carcinogenic agents to humans [63]. It is imperative to implement stringent measures in order to prevent incineration from surpassing the established dioxin standards [64]. The emissions are subjected to flue gas treatment in order to reduce the release of these detrimental contaminants. Management of such therapy is inconsistent, and in many developing countries, the failures of incineration units have led to possible emission of harmful dioxins, furans, and antineoplastic drugs [65,66].

5.1.2. Autoclaving

Autoclaving is a traditional method of sterilising healthcare workers that has been in use since the 1800s [67]. The technique employs the application of wet heat under pressure in order to eliminate germs. Although the average temperature at which autoclaves function is approximately 160 °C, the upper limit of temperature tolerance is 250 °C. Although autoclaving clinical waste is a viable alternative to burning, it can be more costly at times [68]. Autoclaving is unsuitable for specific categories of chemical waste due to its elevated cost. These include substances derived from radioactive materials, mercury, chemotherapy, volatile or semi-volatile organic compounds, hazardous chemical waste, and human body parts in large bulk [69]. Due to their specialised characteristics, autoclaves are uncommon in the majority of hospitals [70]. In order to minimise waste prior to autoclaving, an autoclave-using facility must be equipped with a dehydrating mechanism and shredder. Additionally, the process emits an offensive odour [71].

5.1.3. Steam Augur

A steam augur is employed to eliminate germs by employing both time and heat. Unlike autoclaving, this approach runs under air pressure and necessitates the shredding of trash before the process [60].

5.1.4. Combustion

Gasification is a method that uses a co-reactant and heats solid waste to temperatures up to 1,000 °C to turn it into a combustible gas. The next step is to incorporate these gaseous compounds into renewable energy sources [72]. Although combustion in pyrolysis takes place in an oxygen-depleted environment, the two processes are otherwise identical to gasification. Though they require a lot of energy to activate and certain infrastructure to work, both methods significantly reduce waste volume and are self-sustaining [73,74]. Operators of these operations must be technically and scientifically trained professionals. Most traditional healthcare facilities cannot meet the requirements to adopt these strategies [71].

5.1.5. Plasma

To generate ions within a plasma, an electric current is directed through an unreactive gas. An electric discharge, which denotes elevated temperatures of as much as 1,700 °C, is generated as a result of this ionisation procedure. In consequence, the chemicals decompose [75]. The technique is shown to be suitable for organic as well as inorganic compounds and includes highly cytotoxic drugs too. Glass, rocks, iron metal, and noble gases are examples of materials that can be converted from the waste using the technique. Though this technique has promising applications, it suffers from its high energy requirements, cost-effectiveness, the use of refractory materials, and short life of the electrodes in case of plasma torches [76].

5.2. Chemical Processes

Chemical disinfection and treatment of healthcare workers may involve the application of an extensive range of substances. Enzymes, acids, alkalis, phenols, halogens, detergents, anti-metabolites, peroxides, and heavy metal compounds are all included in this category of chemicals. In addition, a considerable quantity of these compounds generate disinfection by-products (DBPs) [77]. Pharmaceuticals and other potentially hazardous therapeutic materials are frequently chemically disinfected with chlorine and ozone [78,79]. Individuals who should not be exposed to these chemicals may develop genetic defects and suffer serious injury. DBPs have been identified as a recognised health hazard and have been associated with a range of malignancies [80], respiratory irritation, exacerbated allergies, and asthma [81].

5.3. The Processes of Irradiation

5.3.1. The Ultraviolet

Ultraviolet (UV) refers to an electromagnetic wave that spans a wavelength range of 200 nm to 400 nm. UV has cheap investment and operational expenses, but it is not widely preferred as a method due to its limited penetrative ability. Therefore, it is not practicable as a treatment method for healthcare waste. Although little known to the general public beyond the healthcare sector, this technique is among a number of methods hospitals employ to remediate wastewater [82]. The absence of protective measures for users might pose a significant risk, as exposure to some substances can lead to alterations in DNA, potentially resulting in the development of different types of cancer [83]. Consequently, the provision of suitable materials, equipment, and people training becomes necessary, a need that may not be practical for numerous healthcare facilities [84].

5.3.2. Electron Beams

As a consequence of the disintegration process of Cobalt-60, gamma rays are released, which act as an antiseptic agent. Highly energized electron rays have a highly penetrative nature, and thus they prove highly effective in getting rid of bacteria [85,86]. While the method is quite effective in disposing of the wastes, it requires the presence of certain individuals possessing specific skills owing to the health hazards posed by gamma radiation [87]. These include various types of cancer and changes in heart structure and function.

5.3.3. Microwaving

Micro-waves refer to another form of electromagnetic waves, which have frequencies from radio waves to infrared rays. If microwaving has to be successful, then the area under the process needs to contain moisture content. Some other methods use microwaves to heat up water, leading to steam production. The steam produced from microwaving is then put into the clinical waste stream. Using microwave power, thermal energy is thus transferred from inside to outside the clinical waste materials. Microwaving can help significantly minimize the amount of waste generated, making it eco-friendly [11]. However, microwaving being less applicable in its use is often more expensive than incineration or any other form of waste disposal [69]. Disposing waste through the process of microwaving leads to extra concern regarding possible issues that may arise during operation and maintenance besides the high cost [11]. Shredding machines used in microwaving make very loud noises, while the process has been found to produce bad odors. Though the use of microwave technology has become common in many countries to dispose of HCW [20], some researches have shown that microwaves may not be sterilized enough to destroy all forms of bacteria and viruses [69,88].

5.4. Other Techniques of Healthcare Waste Treatment and Disposal

5.4.1. Recycling

For ensuring human and environmental safety, it is always preferred that HCW recycling takes place only using the non-clinical and non-contaminated waste. Consequently, its impact on the overall productivity of healthcare personnel is inconsequential. This category typically encompasses paper, plastic, and medical/pharmaceutical packaging, which may consist of decontaminated glassware [89]. Despite the potential for some of its components to be recycled, hospitals, primary care centres, and private clinics are unable to recycle HCW due to various legal and logistical obstacles [89].

5.4.2. Reuse and Reprocessing

In the realm of mitigating the transmission of infections and other contagious ailments, disposable goods and consumables play a pivotal role. However, a substantial amount of waste and financial resources are expended on this approach. Several medical instruments, including reusable trays, surgical garments, scalpels, and sharps containers, and exhibit reduced environmental and economic impacts compared to their disposable counterparts after undergoing sterilization. Instead of repairing, cleansing, and sterilising reusable medical devices (SUDs), medical personnel frequently utilise consumables and SUDs. Examples of such things encompass catheter equipment, which can have a price tag of up to 4,500 euros per unit. This phenomenon has resulted in numerous healthcare providers repurposing substance use disorder after it has been returned to the supplying firm for sterilisation, reprocessing, and subsequent sale to the healthcare provider at a reduced expense, with the aim of minimising overall expenses and waste. Although controlled reuse of substance use disorders is beneficial for the environment, there are numerous instances of unregulated reuse of SUDs [90]. Patients who relapse after using SUDs may be placed at risk in the absence of adequate legislation and regulation. Nevertheless, research has shown that pathogenic microorganisms can endure reprocessing despite undergoing sterilisation [91].

5.4.3. Sanitary Landfilling

The main technique of waste disposal even for purified waste is through landfilling. The main technique for disposal of HCW is the technique that does not cost much. It is important to manage landfills because of the danger posed by landfills in contaminating water and soil, thereby leading to serious health problems. Perilous gases, such as volatile organic compounds and BTEX isomers (benzene, toluene, ethylbenzene, and xylene), are prevalent and pose a significant risk to human well-being [92]. Additionally, landfill leachate, which is a byproduct of landfilling, is another potentially hazardous consequence [93].

Their research indicates that the disposal of healthcare waste in landfills produces greenhouse gas emissions [94], as was demonstrated by Nwachukwu and Anonye [49]. According to Nock et al. [95], the carbon inefficiency of landfills is exacerbated by the mandate to purge landfill methane. Inadequate employee training, a lack of financial resources, and the mixing of hazardous and nonhazardous refuse in healthcare facilities are a few instances of the inefficiencies that diminish landfill efficiency [68]. However, it necessitates fewer specialised skills compared to the approaches discussed before and may be preferred for this reason, especially in poor nations [96]. In addition, the European Union has enforced landfill laws that consistently mandate the decrease of biodegradable garbage in landfills [61].

The ongoing need for continual reduction will result in a gradual decrease in landfill usage over time [97]. There are limitations to every method utilised by healthcare workers that endanger the environment and, by extension, global health. Due to the intrinsic complexity of this decision-making process which includes the management of multiple stakeholders and competing evaluation criteria [94], ensuring the sustainable selection of healthcare worker treatment approaches is vital. For the purpose of streamlining the intricate procedure of choosing sustainable healthcare waste treatment methods, previous studies have provided a comprehensive examination of various decision-making frameworks [98]. It is recommended that technical, environmental, economic, and socio-cultural factors be taken into consideration in choosing a healthcare waste management system [99]. The task becomes more difficult for developing countries due to the scarcity of available resources [100,101]. The contamination of groundwater in landfills due to untreated medical waste is merely one instance of how inadequate management of healthcare waste can have detrimental effects on human health and the environment [102]. A comparative evaluation of healthcare waste treatment technologies is shown in **Table 2**.

Table 2. Comparative evaluation of healthcare waste treatment technologies.

Technology	Cost	Treatment Efficiency	Environmental Impact	Carbon Footprint	Developed Countries	Developing Countries
Incineration	High	Very High	High emissions	High	Suitable	Commonly used
Autoclaving	Moderate	High	Low emissions	Low	Highly suitable	Increasing adoption
Microwave	High	High	Low–Moderate	Moderate	Suitable	Limited adoption
Chemical Disinfection	Low–Moderate	Moderate	Chemical residues	Moderate	Suitable	Suitable
Plasma Pyrolysis	Very High	Very High	Very Low	Low	Emerging	Limited
Waste-to-Energy	Very High	High	Moderate	Moderate	Growing use	Limited
Recycling	Low	Moderate	Very Low	Very Low	Widely adopted	Limited infrastructure
Landfilling	Low	Low	High contamination risk	High	Restricted	Common

6. Results and Discussion

The reviewed studies indicate that healthcare waste management remains a major environmental and public health challenge worldwide. Although significant technological advances have improved waste treatment efficiency, implementation remains uneven between developed and developing countries. The technique which has been widely used is incineration, owing to the fact that it has proven to be efficient when it comes to the reduction of the waste mass, as well as eliminating pathogen waste. However, due to the emissions of greenhouse gases, as well as dioxins, furans, and various other metallic pollutants, such procedures have not been sustainable. The COVID-19 crisis caused an increase in the production of health care waste around the globe.

The widespread use of PPEs, masks, gloves, testing kits, and vaccine-related materials resulted in increased amounts of infectious waste production. Multiple reports show that health care waste production became at least two times more in peak periods than usual. Current scientific researches increasingly tend towards the idea of using the concepts of the circular economy in managing infectious waste. There is enormous potential in employing such processes as means of lowering the reliance on landfills and enhancing resource use. According to findings from the LCA study, significant variations exist in relation to the impacts of the technology applied within the industry of healthcare waste management. Usually, the level of carbon emissions is lower for autoclaving compared to incineration, whereas waste-to-energy and recycling systems offer higher environmental gains provided the process takes place under control.

Technologies play a major role in improving the management of healthcare waste. Artificial intelligence (AI), Internet of Things (IoT), RFID, and smart waste bins allow real-time monitoring of waste, segregation, stock management, and optimization. Sustainable healthcare initiatives are currently becoming more common, as they strive to be net-zero-carbon. Hospitals around the world are starting to implement green purchasing policy, reusable medical equipment, and renewable energy sources.

7. Recent Developments in Healthcare Waste Management

7.1. Artificial Intelligence (AI) and Smart Waste Tracking

The introduction of AI technology in waste management in hospitals has enabled the formation of evidence-based approaches to waste forecasting, segregation process, waste transport, and compliance with regulations. Waste management forecasting using AI technology is done through machine learning models, which predict future waste production based on past trends, admission rates, and hospital practices [103]. Incorporating computer vision and deep learning approaches in waste segregation in hospitals has made it possible for the segregation of infectious, pathological, pharmaceutical, recyclable, and general waste to be fully automated. These approaches improve precision in segregating waste and also facilitate compliance with waste management policies in hospitals. Further, AI-enabled Geographic Information System (GIS) approaches have been applied to optimize waste transport [103].

7.2. IoT-Enabled Waste Monitoring

Internet of Things (IoT) technology has been a critical development in enhancing the monitoring process of healthcare waste. IoT uses sensors and wireless networks to collect data on waste containers. These devices monitor parameters such as fill level, temperature, humidity, weight, and contaminations of the waste bins in real time, resulting in improved collection and containment processes [104]. Smart sensors fitted in the healthcare waste bins send information continuously about fill levels to the centralized systems to help facility managers avoid overflows and plan collection times effectively. Predictive maintenance of such equipment as autoclaves and incinerators can be facilitated by means of IoT in order to make sure these machines operate well [105]. Mobile apps can be integrated with IoT to make the reporting process easier for healthcare workers.

7.3. RFID-Based Waste Management Systems

Radio Frequency Identification (RFID) technology has emerged as a crucial means of tracing and monitoring health care waste management systems. RFID tags on waste receptacles, collection bags, and transport vehicles help monitor the waste from generation to its ultimate disposition [106]. Using RFID technologies leads to greater regulatory compliance because the process is tracked. This ensures the safety of the waste during all phases of management by preventing mishandling, dumping, and other violations. Moreover, data provided by RFID technologies can help assess waste production patterns within departments and develop programs aimed at waste reduction and audits [107].

7.4. Smart Segregation Systems

Segregation of waste constitutes one of the most important elements in waste management due to the fact that inappropriate segregation results in significant cost burdens. Modern intelligent segregation technology, which utilizes smart sensing technologies and automated sorting equipment, has been adopted for segregation purposes in recent years [104]. With their advanced technological capacities, such systems are capable of segregating infectious waste, sharps, pharmaceuticals, recyclables, and general waste in an efficient manner. Automatic segregation technology helps in reducing occupational exposure and reduces the occurrence of needle sticks among healthcare professionals. Such modern waste segregation systems have limitations associated with high costs and lack of technical know-how, especially in developing countries.

8. Circular Economy Approaches in Healthcare Waste Management

A great deal of attention has been paid to the circular economy because of its potential for sustainability. It is one method of resource management which includes waste prevention, waste reuse, waste recycling, resource recovery, and production of energy from waste [108]. Some examples of circular economy implementation within the healthcare industry include reprocessing of medical devices, recycling of non-hazardous plastic and packaging waste, composting of biodegradable waste, and generating energy from waste products. This will help reduce dependence on landfill, protect natural resources, and avoid greenhouse gas emissions. A recent study has demonstrated the benefits of circular economy implementation for improving sustainability within the healthcare industry and saving money on waste management costs [103].

8.1. Sustainable Procurement and Green Hospitals

Sustainable procurement has emerged as an effective approach to curb the waste generated from health care activities right from their source. The principles of green procurement involve the selection of environment-friendly products through the entire life cycle of production, transportation, use, and disposal [105]. The focus of health care organizations has shifted towards using reusable equipment and devices, recyclable containers and wrappers, biodegradable products, and partners who believe in sustainable development. This would pave the way for the creation of 'green hospitals,' which encompass efficient waste management, energy conservation, water saving measures, sustainable construction, and environmentally sound supply chains [108].

8.2. Net-Zero Healthcare Initiatives

The healthcare industry makes a considerable contribution to worldwide greenhouse gas emissions; hence, there is increasing attention given to net-zero healthcare strategies. Net-zero healthcare involves balancing emissions caused by the healthcare industry through emission mitigation, renewable energy use, and carbon offsets [108]. Waste management in healthcare systems has a significant part to play towards achieving net-zero goals. The key approaches involve minimizing the production of waste, boosting recycling rates, substituting high emission technology with low emission technology, and utilizing renewable energy in waste treatment plants. From LCA research, it is evident that environmentally-friendly waste management technology can significantly reduce the carbon footprint of the healthcare system without affecting the measures for preventing infections [109]. Healthcare net-zero approaches including waste minimization, a circular economy approach, and sustainable procurement practices have been adopted by some countries [110].

8.3. Post-COVID-19 Healthcare Waste Management

Infection caused by the novel coronavirus led to the production of much more healthcare waste due to the widespread use of personal protection equipment (PPE), facial masks, gloves, testing material, vaccinations, and other single-use medical items [105]. The outbreak highlighted the challenges with the pre-existing waste management structures, which lacked sufficient capacity for dealing with the amount of generated waste, sufficient storage space, and were poorly prepared for any emergency situation. This resulted in post-COVID-19 healthcare waste management strategies being aimed at improving infectious waste handling procedures, developing the capacity to deal with infections, planning better emergency responses, and increasing monitoring capabilities [111]. The pandemic was also accompanied by an increase in interest in reusable PPE, biodegradable materials used in healthcare institutions, sustainable medical products, and flexible and robust waste management systems to be ready for future outbreaks [112].

9. Prospects and Challenges for Healthcare Waste Management

A considerable number of nations already have inadequate healthcare waste management systems in place, and this will only worsen due to factors such as a substantial increase in urban and total populations, particularly in developing countries. The overall performance of the waste management system has been negatively impacted by the declining economy of the nation and inadequate institutional governance. Consider the following factors when contemplating healthcare waste management:

9.1. Insufficient Financial Resources

The management of solid wastes in world cities has enormous financial ramifications because of the expensive nature of the development and management [52]. Some waste management facilities include landfills, autoclave, incinerator, and garbage trucks. Regular expenses may cover different aspects, including payments, training, equipment, power, and tools required by individuals responsible for waste handling. Availability of finances plays a vital role in determining how well a nation will be able to solve its waste problems. It is necessary to allocate sufficient funds and materials for effective healthcare waste management involving waste collection, classification, treatment, and disposal. Moreover, there is a reduction in the number of hospital-acquired infections because of this process [47].

The management of healthcare waste does not have a specific budget allocated by hospitals or governments in most countries. The management of solid waste, which involves mostly the collection and disposal of refuse, receives the bulk of municipal spending, while the management of wastes through sorting, training, and education gets nothing. In the course of time, many healthcare institutions in the country pay firms specializing in waste management for the removal of their MSW. Some hazardous materials are found in healthcare waste, but the organization is not mandated to handle such waste. This is because of their incapability in managing hazardous waste. Thus, healthcare organizations dispose of such waste through incineration or burial [52].

In developing countries, incineration is the main technique used in the disposal of hospital wastes [113]. There are various advantages associated with the incineration technique for disposing of hospital waste, such as the use of a small piece of land, which leads to a reduction of over 90% of waste. Additionally, the heat created from incineration may be effectively utilised for various reasons, such as the combustion of boilers and the creation of energy [114]. Nevertheless, if garbage incinerators are not run correctly, they can significantly contribute to air pollution [114]. Incineration processes give rise to detrimental pollutants, such as dioxins and heavy metals, which have the potential to persist in the atmosphere for extended periods, hence posing significant environmental and public health hazards [113].

9.2. Training, Sensitization and Awareness

By educating and raising awareness, it is possible to influence the optimal management of healthcare waste [56]. It is evident that there remains a deficiency in national awareness and instruction regarding the administration of healthcare waste. The inadequate training outcome can be attributed, in part, to the lack or limited accessibility of financial resources. In numerous healthcare establishments when training and awareness initiatives are implemented, there is a lack of subsequent programmes for ongoing staff retraining. Furthermore, there is evidence suggesting that the training quality in certain cases falls below the expected standard. Training has been found to be helpful in the domain of healthcare waste minimization. The concept entails the implementation of procedures and methodologies aimed at proactively mitigating waste generation. This measure is expected to contribute to the augmentation of the clean waste stream, hence leading to a subsequent decrease in disposal expenses and mitigating the negative environmental consequences. Educating hospital administrators on source reduction strategies, such as transitioning to a more streamlined supply chain that generates fewer hazardous byproducts, is one method to reduce healthcare waste [115].

9.3. Effective Legislature

The majority of countries lack a sufficient legislative framework for the handling of healthcare waste. With the exception of Lagos, a state in Nigeria, which is responsible for the establishment and enforcement of regulations pertaining to the appropriate disposal of medical refuse. Regarding healthcare waste management, no other state in the United States has enacted legislation as of yet. Despite the latest NESREA guideline on healthcare waste distribution, it is necessary to establish suitable legislation to ensure efficient implementation and enforcement. As a consequence of the lack of penalties for noncompliance, medical waste disposal in healthcare facilities has been left unregulated in the majority of nations. The provision of sufficient protective equipment and a secure working environment for waste labourers is mandated by healthcare regulations [45,116].

9.4. Data Acquisition

The implementation and strategy of waste management are dependent on precise data extraction. Limited data exists regarding the generation and collection of refuse [117,118] pertaining to waste management in Africa. In the majority of countries, policies and procedures governing healthcare waste management at the federal, state, and local levels are largely undocumented. A lack of practicable and efficient standards is the reason for the omission of data regarding healthcare waste management. Quantitative and qualitative elements comprise the comprehensive data set concerning healthcare waste management. There are several pieces of data to gather, among which: the frequency with which garbage is being collected, the total amount of garbage produced, what kind of materials make up garbage, the knowledge and skill level of people working in waste management, the number of people employed in waste management, the total amount of healthcare waste burned, the proportion of garbage that is to be put into landfills, and how many recyclables are being gathered. Proper waste data collection can be made much easier with the availability of sufficient funds, waste management committees in healthcare establishments, and proper training for healthcare waste specialists [118].

9.5. Efficient Waste Treatment Techniques

In developing countries, the high initial and ongoing costs of capital, maintenance, and operations are a major barrier to the widespread use of cutting-edge waste treatment technology like incinerators and biochemical waste conversion equipment [119]. But there are practical technical solutions for medical waste management that could work in countries with low or medium incomes. To pre-treat garbage before disposal or landfilling, one example is a mechanical-biological treatment system suggested by Ezeudu et al. [120], that is both cost-effective and environmentally friendly. This technology was tailored to cater to the requirements of nations that either have low or medium levels of income. Stabilization of organic wastes and the generation of fuels from such wastes are the secondary benefits generated by this fuel conversion technology [52]. Generation of energy, handling of solid wastes, and delivering an array of socio-economic as well as environmental benefits constitute the circular economy, which is promoted through this technology. Reduction of landfill gases, prevention of contamination from leachates, and removal of unpleasant odors are among these benefits. Such technologies can be developed in-house through effective cooperation between hospitals and indigenous research institutions in most of the developing nations. This objective requires a thorough analysis of the contextual issues and the formulation of a sustainable management approach, which takes into consideration the unique characteristics of each locale [52].

10. Conclusions

The management of healthcare waste has remained one of the significant elements concerning the environment, occupational safety, and public health worldwide. The findings from the conducted literature review indicate that even though the conventional technologies for waste treatment, for example, incineration, remain predominant in the management of healthcare wastes, problems associated with environmental pollution, environmental sustainability, and economics have led to increased focus on other technologies such as autoclaving, microwaves, plasma pyrolysis, and waste-to-energy technology. Technology innovations such as artificial intelligence, internet-of-things, RFID, and waste segregation technology have played a critical role in ensuring effectiveness. Moreover, the application of concepts such as circular economy approach, lifecycle assessment approach, sustainable procurement policies, and net-zero healthcare approach is expected to change healthcare waste management for the better. However, there are some challenges, especially in the third-world countries due to issues such as poor infrastructures, lack of financing, and training among others.

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Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this manuscript.

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