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Review

Harnessing the foundation of biomedical waste management for fostering public health: strategies and policies for a clean and safer environment

Harpreet Singh[1] · Kamal YT[2] · Arun Kumar Mishra[3] · Mhaveer Singh[3] · Sourav Mohanto[4] · Shruti Ghumra[5] · Anmol Seelan[5] · Amrita Mishra[6] · Arvind Kumar[1] · Janardhan Pallavi[7] · Mohammed Gulzar Ahmed[4] · Jeyabalan Sangeetha[8] · Devarajan Thangadurai[9]

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Abstract
The COVID-19 pandemic has led to an enormous rise in biomedical waste and plastic trash production. The sudden increase in the production of waste vehicles carrying the same for disposal presented major challenges for the current waste disposal systems, particularly in developing countries. Due to the COVID-19 health emergency, the significance of appropriate waste management has become more evident. This review aims to showcase all aspects of biomedical waste, including its management, safe disposal approaches, the risks associated with improper waste management, and other hazards from hospitals, labs, and the environment. The focus has been laid on the possible role of laboratories in hospitals, research, and academic institutions directly and indirectly involved in handling biomedical items. It is pertinent to mention that policies relating to biomedical waste management must be renewed periodically for updates and to incorporate new research and system development points. In the present review, establishing collaboration among hospitals, laboratories, and research staff is vital for proper waste management in healthcare facilities. The review demonstrates the contemporary directions in biomedical waste treatment and safe disposal methods, especially incineration, autoclaving, chemical disinfection, and land disposal. Good laboratory practices and techniques for destroying needles, shredders, encapsulation, and inertization are also covered. The significance of biomedical waste management policies in promoting environmentally responsible and safe practices and amendments to these policies has been emphasized.

Highlights

- Biomedical waste can be infectious and hazardous, and if not managed, it can cause harm to public health.
- Health hazard to waste handles and medical workers.
- Contemporary techniques for biomedical waste treatment and disposal procedure.

✉ Harpreet Singh, harpreetproctor@rediffmail.com | [1]School of Pharmaceutical Sciences, IFTM University, Moradabad 244102, Uttar Pradesh, India. [2]Department of Pharmacognosy, College of Pharmacy, King Khalid University, Abha 611441, Saudi Arabia. [3]SOS School of Pharmacy, IFTM University, Moradabad 244102, Uttar Pradesh, India. [4]Department of Pharmaceutics, Yenepoya Pharmacy College & Research Centre, Yenepoya (Deemed to be University), Mangalore 575018, Karnataka, India. [5]Department of Biological Sciences, Sunandan Divatia School of Science, Narsee Monjee Institute of Management Studies (NMIMS), Pherozeshah Mehta Rd., Mumbai 400056, India. [6]School of Pharmaceutical Sciences, Delhi Pharmaceutical Sciences and Research University, New Delhi 110017, India. [7]Department of Bio-Sciences, School of Bio-Sciences and Technology, Vellore Institute of Technology (VIT), Vellore, Tamil Nadu, India. [8]Department of Environmental Science, Central University of Kerala, Kasaragod, Periye, Kerala, India. [9]Department of Botany, Karnatak University, Dharwad, Karnataka, India.

- Revised policies amendment related to safe disposal of biomedical waste in various populated countries.

Keywords Biomedical Waste · Healthcare · Environment · Sustainability · Hazardous · Pollution

1 Introduction

The healthcare system is rapidly evolving across the globe, and it is becoming more diverse with the inclusion of both public and private healthcare providers. This diverse system offers a range of healthcare services, including preventive care, primary care, and specialized treatments. The public healthcare system offers primary and secondary healthcare services through a network of health centers, hospitals, and dispensaries. However, the potential and available healthcare services vary widely across countries and regions [1]. On the other hand, the private healthcare system is more expensive but offers better-quality services, especially in urban areas [2]. Traditional and alternative medicine utilization has augmented alongside conventional medical treatments in recent years. Besides saving lives, healthcare workouts produce 20% of infectious, traumatic, chemical, or radiation-loaded waste [3, 4]. Biomedical waste is any waste assembled during human or animal diagnosis, treatment, or immunization. Biomedical waste can be infectious, hazardous, or non-hazardous and, if not properly managed, may become an indecent hazard to the environment and public health. Biomedical waste management is an essential component of healthcare delivery systems, and its proper segregation, storage, transportation, and disposal are critical to preventing the spread of infectious illnesses and environmental degradation [5, 6]. Poor waste management can be hazardous to hospital staff, patients, family members, and neighboring communities, further leading to environmental pollution, which can result in fatalities [7, 8]. Several individuals within the structure, such as hospitals that assemble biomedical waste, those who oversee and endure it, and people outside the facility who could come into direct contact with potentially hazardous waste or by-products, are all at risk [9, 10]. The World Health Organization (WHO) briefly states that biomedical waste is "waste created while diagnosing, treating, or immunizing people or animals." [11]. Biomedical waste can also be described as "any kind of solid waste created while diagnosing, treating, immunizing, or making or testing biologicals" [12]. Heavy metal contents, pressurized containers, pharmaceutical waste, pathological waste, infectious waste, chemical waste, sharps, and radioactive waste are different or static examples of biomedical waste [13, 14]. There are considerable modes of exposure to biomedical risks, such as getting a cut or prick, reaching into intimate contact with the skin or mucous membranes, breathing, or ingesting an infectious substance [15, 16].

Pathogenic microorganisms have a limited capability to survive in the environment. The survival of each microorganism depends on the temperature, humidity, sunlight exposure, organic substrate accessibility, and disinfecting agents present in the environment, among other factors. Compared to bacteria, viruses are more resistant to infection [17, 18]. Although prions and agents of neurodegenerative diseases (i.e., Kuru, Creutzfeldt-Jakob syndrome, etc.) appear more invulnerable than viruses, comprehended their persistence [19, 20]. Microorganisms are a key part of biomedical waste management, from identifying possible infection risks during handling and disposal to validating steam sterilization machines and making waste non-infectious and non-hazardous [21, 22]. Moreover, microbes can be utilized effectively to treat dangerous waste, and it is important for lab safety to manage and control them correctly [23]. Understanding or comprehending the various types of biomedical waste and their details for effective treatment or management is essential.

Heavy metals (e.g., cadmium, mercury, arsenic, thallium, chromium, and lead) are non-toxic, dense metal-based elements [24, 25]. Heavy metals constitute essential parts of biological systems, but they can harm all living things depending on exposure retention. Unnecessary heavy metals (i.e., lead, cadmium, mercury) and metalloids (i.e., arsenic) can be poisonous and kill humans even in small concentrations [26, 27]. Furthermore, various reports suggest that the presence of heavy metals causes cancer, mutagenesis, teratogenicity, and oxidative stress, which further leads to the prognosis of various diseases and idiosyncrasies [28]. Heavy metals can impede metabolism and cause toxicity by interacting with sulfhydryl (SH) enzymes and inhibiting energy-producing enzymes [26, 29]. Pharmaceutical waste must be properly handled and disposed of, as it cannot be discarded normally and may pose risks to the environment and human health [30, 31]. Furthermore, the waste materials produced during surgical procedures are categorized as pathological waste [32]. In order to adequately dispose of human pathological waste, i.e., tissue, organs, and body parts that make up this waste, they must be incinerated. Body fluids from healthcare procedures, surgeries, and autopsies, excluding urine and fluid-soaked items, must be contained and not discarded [33]. Laboratory-based animal pathological waste is a subcategory of pathological waste that refers to tissue, organs, carcasses, and body parts derived from vertebrate animals that must be incinerated. Solid, non-sharp biomedical waste contaminated with biological material that must be autoclaved and disposed of in a landfill is known as "red bag" waste [34]. Infectious waste is characterized as waste contaminated with blood or other bodily fluids, infectious agent cultures, stocks from laboratory operations (i.e., waste from autopsy procedures and animals with infections), and waste from infected patients. Furthermore, various types of needles, syringes, gloves, masks, personal protective equipment (PPE), and animal carcasses exposed to infectious agents or utilized in research are assessed under this category [35, 36].

In addition, chemical waste can be solid, liquid, or gaseous, posing significant risks to people and the environment if not managed or disposed of properly. Chemical waste includes solvents, reagents, disinfectants, sterilant, heavy metals, paints, varnishes, acids, alkalis, bleach, and ammonia, all used in laboratory test preparations, manufacturing processes, and cleaning agents [37, 38]. Sharps are also categorized under biomedical waste, which includes any instrument or object capable of puncturing or cutting the skin, such as scalpels, razors, broken and contaminated glass, hypothermic and blunted needles, syringes, disposable blades, microscope slides, specific biomedical tubes, some plastics, dental instruments, such as burrs and files, tattoo needles, and piercing instruments [39, 40].

Proper waste treatment is crucial to eliminate all pathogenic organisms by decontaminating the generated waste. This enables the prevention of several severe health-related issues caused by infectious waste. This comprehensive manuscript delves into the basic techniques and methods utilized to prevent all environmental hazards associated with biomedical waste. The later segment of this article also emphasizes various aspects of biomedical waste, including its management, advantages and disadvantages, research gaps, related policies, and innovations. The rationale for penning this extensive literature is to furnish a comprehensive directory for all experimenters in this field and, further, serve as a reference companion for all biomedical waste collection and management individuals.

2 Consequences of improper handling and disposal of biomedical waste with special reference to human and environmental health

2.1 People who could be harmed

Individuals and professionals within the healthcare system may be at risk [35], if the originating biomedical waste is not properly handled. Diverse healthcare professionals work tirelessly to provide patients with essential care within the establishment, which comprises a team of physicians, nurses, auxiliaries, stretcher bearers, and scientific, technical, and logistic personnel. Doctors diagnose and treat patients using their medical knowledge, while nurses provide compassionate care and support. Auxiliaries assist with a variety of duties, facilitating hospital operations. Stretcher-bearers perform a vital role in the safe transportation of patients. In addition, scientific, technical, and logistical personnel contribute their specialized skills to aid in patient care [41].

However, the impact of biomedical refuse is not limited to hospital grounds. Those involved in the outside processing or disposal of biomedical refuse are also at risk. It is crucial to recognize that this waste, if improperly managed, can threaten those who labor in waste management facilities or participate in the disposal process. Although they are not directly involved in patient care, they are crucial in ensuring the safe handling and disposal of biomedical waste. Their efforts aid in protecting the environment and preventing the spread of disease or contamination to the general population. The collaborative efforts of healthcare professionals and waste management personnel are essential for maintaining a safe and healthy environment inside and outside the hospital. By collaborating, these individuals safeguard the health of patients, staff, and the broader community, ensuring that healthcare facilities operate effectively and minimize biomedical waste risks [42, 43], as summarized in the Fig. 1. The improper disposal of biomedical waste can have serious consequences, therefore it is crucial to follow safe disposal guidelines, as further discussed in Table 1.

2.2 Health risks involving trauma and infection

Trauma patients are particularly vulnerable to infections caused by biomedical waste. Biomedical waste, which includes hazardous materials like sharps, pathological waste, genotoxic waste, and pharmaceutical waste, can transmit infectious diseases like HIV, hepatitis, tetanus, and septicemia when not properly managed. Biomedical waste can also cause various infections, including gastrointestinal, respiratory, skin, eye, meningitis, AIDS, avian influenza, etc. [70]. Severe environmental and public health risks are associated with inappropriate biomedical waste management. In Allahabad,

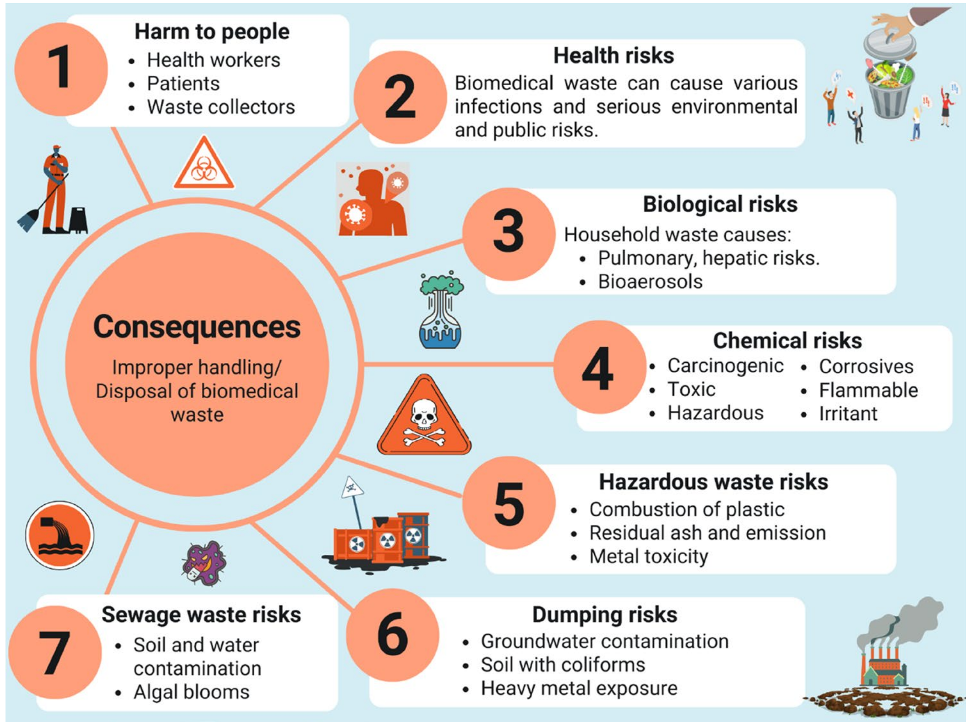

Fig. 1 General understanding of various types of biomedical wastes and its consequences in the healthy lifestyle and environment

India, an in-depth investigation revealed that sanitary staff were unaware of best practices, whereas doctors, nurses, and laboratory technicians had better knowledge of biomedical waste management. All groups of medical professionals have reported a relatively low number of injuries [71]. Similarly, a study in five major hospitals in Dakar, Senegal revealed ill-adapted sorting of biomedical waste and inadequate use of color-coding systems. Biomedical waste was often disposed of in open-air storage areas, with poor waste collection methods and inadequate protection equipment. Only 62.6% of interviewees had satisfactory knowledge of biomedical waste management [72]. A systematic review of healthcare waste management in Ethiopia found that most healthcare facilities did not practice proper waste segregation due to a lack of knowledge, with common treatment methods being low-combustion incineration, open burning, and open disposal of incinerator ash [73].

2.3 Solid Household waste associated biological risks

The operational requirements for handling household and biomedical waste are similar, making the impact on the health of workers a useful benchmark for both groups [74, 75]. Several studies conducted in high-income countries have highlighted the increased risks faced by workers in the household waste processing industry when compared to the general population. Studies conducted in high-income countries have highlighted the increased risks faced by workers in the household waste processing industry compared to the general population. These results demonstrate these workers' increased susceptibility to various health issues. The six-fold increase in the risk of infection among these individuals is a striking observation. This indicates that occupational exposure significantly increases their risk of contracting infectious diseases [76]. In addition, recent studies revealed a 2 to 6-fold increased risk of developing allergic pulmonary disease among those who process household waste. This suggests that their exposure to allergens or irritants in waste materials contributes to respiratory health problems. Moreover, the research indicates that these workers are 2.5 times more likely to develop chronic bronchitis, highlighting the effect of their occupational environment on their long-term respiratory health [77]. Moreover, the risk of contracting hepatitis is two times greater among those who work in the household waste processing industry. This emphasizes the potential exposure to pathogens in the waste materials, necessitating appropriate preventive measures and safety protocols [78].

Additionally, investigations highlight the consequences of bioaerosol exposure in specific work environments. Workers exposed to bioaerosols at landfills, storage facilities, and processing plants are likelier to develop bronchitis. This emphasizes ensuring adequate ventilation and protective measures in these environments to safeguard workers' respiratory

Table 1 Consequences of Noncompliance of Safe Disposal Guidelines of Biomedical Waste

Consequences	References
Increased risk of infection -It is important to be aware of these risk factors to take necessary precautions and reduce the chances of acquiring an infection.	[41]
Environmental pollution- By taking small steps like reducing plastic use, conserving energy, and properly disposing of waste, environmental pollution can be controlled.	[42]
Legal and financial penalties -Biomedical waste managers can be fined for not following safe disposal guidelines.	[42]
Spread of diseases-Biomedical waste can spread pathogens that can cause outbreaks and epidemics if not properly handled and disposed of.	[43]
Risk to wildlife-Biomedical waste can expose wildlife and the environment to hazardous materials, causing habitat destruction and wildlife extinction.	[44]
Health hazards to waste handlers-Lead to health hazards to waste handlers, including exposure to hazardous materials that can cause respiratory problems, skin infections, and other serious illnesses.	[45]
Risk of needle-stick injuries-Healthcare workers and waste handlers can get needle-stick injuries and blood-borne diseases from improper biomedical waste disposal.	[46]
Contamination of water sources- Improper biomedical waste disposal can contaminate water sources by allowing hazardous materials to seep into the ground and pollute nearby water bodies, posing serious health risks to humans and wildlife alike.	[47]
Spread of antibiotic-resistant bacteria- Antibiotic overuse and improper disposal can result in the growth and widespread dissemination of antibiotic-resistant bacteria, posing a serious public health risk.	[48]
Release of toxic chemicals to society- The improper handling of biomedical waste can cause the release of toxic chemicals that have the potential to harm human health. The contamination of soil, air, and water by toxic chemicals has devastating long-term effects.	[49]
Soil contamination-Biomedical waste improperly disposed of can contaminate soil and harm humans and the environment, reducing soil fertility and crop yields.	[50]
Air pollution-Incineration of biomedical waste can release toxic gases and particulate matter into the air, endangering nearby communities and degrading the environment.	[51]
Health hazards to the general public-Biomedical waste improperly disposed of can spread infectious diseases, expose communities to toxic chemicals and hazardous materials, and pose other serious health risks.	[44]
Risk of accidental exposure, and Risk of disease outbreaks-Noncompliance with biomedical waste disposal guidelines may expose unwary people to hazardous materials, resulting in chemical burns, respiratory issues, and other injuries. When not properly disposed of, infectious pathogens found in biomedical waste can pose a serious threat to public health.	[52]
Public health risks associated with hazardous waste-Such waste can expose people to harmful chemicals and infectious agents, which can cause cancer, birth defects, and other chronic diseases. Hazardous waste poses health risks.	[53]
Damage to reputation of healthcare facility-Improper biomedical waste disposal can damage a healthcare facility's reputation by damaging patient, employee, and public trust in the facility's ability to provide safe and effective healthcare.	[54]
Increased healthcare costs-Noncompliance with biomedical waste disposal guidelines can spread infectious diseases and other health hazards, requiring more medical care and treatment for affected individuals, which raises healthcare costs.	[55]
Risk of fires or explosions-Noncompliance of safe disposal guidelines of biomedical waste can lead to a risk of fires or explosions, as biomedical waste can contain flammable or combustible materials that can ignite if not handled and disposed properly, posing a serious risk to the safety of individuals and the surrounding environment.	[21]
Damage to equipment and infrastructure-Biomedical waste improperly disposed of can corrode pipes, tanks, and other equipment, causing expensive repairs and environmental damage.	[56]
Severe illness to waste management workers- Noncompliance can result in serious illness for workers who interact with biomedical waste because of the potential exposure to harmful substances and infectious agents. Waste management workers can develop respiratory issues, skin irritation, and other illnesses from improper biomedical waste disposal.	[57]
Increased risk of hospital-acquired infections-Biomedical waste improperly disposed of can spread infectious agents, increasing the risk of hospital-acquired infections for patients, healthcare workers, and visitors. This can prolong hospital stays, raise healthcare costs, and worsen patient outcomes.	[58]
Inadequate handling of chemotherapy waste-Chemotherapy waste that is improperly handled can endanger healthcare workers and the environment. Chemotherapy waste disposal can release harmful chemicals into the air and water, endangering public health and the environment.	[59]
Risk of injury to healthcare workers and to the safety of laboratory personnel-Improperly disposed needles and scalpels can cause serious injuries to healthcare workers. Healthcare costs and workday losses may rise. Biomedical waste disposal errors can expose lab workers to infectious agents and hazardous substances.	[60]
Risks to the safety of medical equipment-Hazardous biomedical waste can damage medical equipment, making it unusable or malfunctioning. This can increase healthcare costs by replacing or repairing equipment, negatively impacting patient care and outcomes.	[61]

Table 1 (continued)

Consequences	References
Damage to the environment and natural resources-Biomedical waste can contaminate soil, water, and air if not disposed of properly. This can harm wildlife and humans and degrade the environment. It can also damage the healthcare facility or organisation responsible for improper disposal and cost a lot to clean up.	[62]
Inadequate management of hazardous drugs-Drugs improperly disposed of can cause serious illness or death. It can pollute the environment and natural resources, causing long-term health and environmental issues.	[44]
Increased risk of biohazard contamination-Biomedical waste improperly disposed of can contaminate the environment and human health.	[52]
Health risks to children and vulnerable populations-Biomedical waste disposal violations can put children and vulnerable populations at risk of hazardous waste-related infections and diseases.	[63]
Loss of public trust in healthcare facilities- Public at large wants trust-based health care facility too.	[64]
Risks to the safety of waste transportation personnel-Biomedical waste improperly disposed of may expose waste transporters to hazardous materials.	[65]
Health risks to animals and pets-Biomedical waste improperly disposed of can harm animals and pets.	[66]
Risk of contamination of food and water – Hospital inmates and others may fall sick.	[44]
Spread of communicable diseases – Sometimes outbreaks become uncontrollable.	[21]
Increased risk of needle-phobia-Improperly disposed needles can cause accidental needlesticks and needle phobia.	[67]
Risk of needle reuse-Improper disposal of needles increases the risk of needle reuse, which can lead to the spread of infections and diseases.	[65]
Risk of needle recapping and inadequate disposal of expired drugs-Poor needle disposal increases the risk of needle recapping, which puts healthcare workers at risk of needlestick injuries and infection. Biomedical waste disposal violations can pollute the environment and expose people to expired drugs.	[60]
Improper disposal of radioactive materials-Radioactive biomedical waste can pollute the environment, endangering humans and animals.	[57]
Inadequate handling of chemical waste- Noncompliance with biomedical waste disposal guidelines can result in inadequate chemical waste management, posing grave risks to public health and the preservation of the environment.	[68]
Inadequate segregation and labelling of waste-Inadequate segregation and labelling of waste can lead to confusion and increase the risk of improper handling and disposal.	[69]
Risks to the safety of janitorial staff and sanitation workers-Biomedical waste disposal can expose janitorial staff to infectious materials, sharps, and hazardous materials. Sanitation workers who collect and transport biomedical waste are also at risk of improper disposal.	[65]
Health risks to waste disposal facility workers- Workers at waste disposal facilities are at risk of being exposed to transmissible and potentially hazardous substances if biomedical waste is disposed of improperly.	[22]
Risks to the safety of recycling facility workers, emergency responders and waste incineration personnel-Biomedical waste disposal violations expose recycling facility workers to hazardous materials. Biomedical waste diseases can critically ill emergency responders. Biomedical waste disposal violations may expose incineration workers to harmful chemicals and infectious agents.	[57]
Increased risk of litigation -Healthcare facilities that violate biomedical waste disposal guidelines risk lawsuits for environmental violations and public health risks.	[52]
Damage to the local ecosystem- Flora and Fauna are important component of ecosystem and improper handling may lead to loss of balance between human and environmental ecosystem.	[64]

health [79]. These results highlight workers' occupational health risks in the household waste processing industry. Implementing comprehensive safety protocols, providing appropriate training, and raising awareness about the potential dangers are crucial for ensuring the health and safety of these employees and mitigating the associated health risks [80].

2.4 Chemical associated risks

A vast array of pharmaceutical and chemical products is used in healthcare facilities. The majority of such products possess properties that make them hazardous to human health, such as being cancer-causing, mutagenic, reprotoxic, corrosive, irritating, sensitizing, explosive, flammable, and more. People can come into contact with these substances through inhalation, gas, vapor, droplets, skin contact, mucous membrane contact, or ingestion [81].

2.5 Risk of improperly processing and disposing hazardous biomedical waste

The low-temperature combustion of wastes or plastics containing polyvinyl chloride (PVC) can produce chemicals such as dioxins, hydrochloric acid, furans, and other hazardous air pollutants [82]. Emissions, residual ash, and incinerator chimney effluent gases contain toxic chemicals. Furans, dioxins, and coplanar polychlorinated biphenyls can also harm human health [83, 84]. Incineration generates persistent toxins that build up in the food chain. Most furans, dioxins, and coplanar polychlorinated biphenyls are consumed via contaminated food [85]. In cooler pockets at the start or end of high-temperature incinerators (over 800 °C), dioxins and furans can form [86]. Optimising the process by preventing combustion gas formation at 200–400 °C and incineration only above 800 °C can reduce dioxins and furans [87], further releases metals, especially lead, mercury, and cadmium [88].

2.6 Risks involved random dumping and uncontrolled dumping

Random or uncontrolled dumping can pose significant risks to both the environment and public health. According to a review of environmental studies in Brazil, dumpsites and landfills can cause contamination of groundwater, surface water, and soil with coliforms, lead, and heavy metals. Additionally, informal recycling of waste, including electronic waste, in India has been shown to cause environmental pollution and health risks for workers and residents due to exposure to substances like polychlorinated biphenyls and heavy metals. Patient dumping, or the transfer of patients for financial reasons, is also a significant issue in Taiwan's healthcare industry, leading to inadequate care and negative health outcomes. Exposure to garbage dumping sites has been found to cause oxidative stress-mediated damage to macromolecules in children, leading to serious consequences for their health. It is suggested that adequate waste management and regulations are necessary to prevent these risks and mitigate negative impacts on the well-being of humans and the natural environment [89–91].

2.7 Risks involved with raw sewage discharge

The poor quality wastewater and sewage sludge or by-products produced during industrial wastewater sewage treatment can result in pathogens or toxic chemicals contaminating water and soil [92]. Chemical and pharmaceutical waste that is flushed down the drain can cause biological sewage treatment plants and septic tanks to malfunction. These have the potential to pollute the ecosystem and water supplies [93]. Antibiotics and their byproducts are passed out of the body through urine and faeces, especially in patient rooms, and end up in the sewer system [94]. The sewage from homes contains two to ten times fewer antibiotic-resistant bacteria than hospital sewage. Antibiotic resistance is defined as a phenomenon that helps pathogens like MRSA (methicillin-resistant *Staphylococcus aureus*) to emerge and spread [95].

3 Workgroup on biomedical waste

In order to manage biomedical waste effectively, an organization needs to have strong organizational skills, sufficient funding, and active engagement from knowledgeable and trained personnel. Waste management policies encompass the conditions that must be met along the entire waste chain, from production to disposal [3]. The proper management of biomedical waste is often perceived as a menial task when, in fact, it is a crucial responsibility that every hospital staff member should be fully aware of. Therefore, all healthcare professionals must be well-informed about the associated risks and regulations [96]. The manager of the hospital is required to establish a group of employees dedicated to "waste management." The waste management working group must include the hospital's project manager, the water and habitat engineer, the local waste manager, the hospital administrator, the head nurse, the chief pharmacist, and the head of the hospital's clinical laboratory [97].

3.1 Hospital project manager

The hospital project manager oversees waste management following regulations. The waste management plan is drafted by a working group assembled by the hospital's project manager. A local waste manager is hired by the hospital's project manager to manage the plan daily. The project manager decides how to allocate financial and human resources. The hospital project manager implemented waste disposal, further responsible for updates, audits, and improves the waste management system [98].

3.2 Engineers for water and habitat

The water and habitat engineers are in charge of conducting a preliminary waste situation assessment, presenting to the working group a waste management plan, developing plans for waste storage and disposal facilities' construction and operation, evaluating the waste management's environmental impact (i.e., monitoring contamination, conducting hydrogeological assessments, etc.), conducts regular risk assessments of personnel and also supervises the area's waste manager [35].

3.3 Local waste manager

The waste manager coordinates with the working group and hospital staff to carry out the daily plan and maintain the system's longevity [99]. A local waste manager's responsibilities encompass a variety of tasks. First, they are accountable for the daily monitoring of waste collection, storage, and transportation processes. This entails closely monitoring waste disposal, ensuring the availability of suitable containers, bags, and personal safety equipment, and supervising the regular upkeep of waste management vehicles. In addition, the waste manager is responsible for communicating with the hospital administrator, who supervises the personnel responsible for waste collection and transportation [100]. Additionally, the waste manager plays a crucial role in preparing for potential accidents and keeping a detailed record of the actions required in such situations. They maintain safety precautions to prevent waste management-related incidents and accidents. The investigation of waste-related incidents and accidents that occur within their jurisdiction is an important aspect of their job. This involves conducting exhaustive investigations, analyzing the underlying causes, and implementing corrective measures to prevent future occurrences. Additionally, the waste manager is responsible for generating detailed reports, providing information on the amount of waste generated, and ensuring accurate record-keeping. Finally, the waste manager must verify the condition of the facilities where waste is stored and treated. They conduct regular inspections to ensure that these facilities meet regulatory requirements and are well maintained. By fulfilling these various responsibilities, the local waste manager is vital in promoting safe and efficient waste management practices in their community [101].

3.4 Hospital administrator

The hospital administrator assumes several crucial waste management responsibilities. First, they ensure the presence of important items like bags, containers, and personal protective equipment, ensuring that these resources are always accessible when required. In addition, the administrator is responsible for evaluating and analyzing the costs associated with waste management processes to produce informed budget allocation decisions [102]. The hospital administrator is also responsible for drafting contracts with third-party entities, such as carriers and subcontractors. This requires negotiating and establishing contracts outlining the terms and conditions of waste transportation and disposal services. In addition, the administrator provides valuable guidance on purchasing policies designed to eliminate or substitute mercury-containing equipment and polyvinyl chloride (PVC) materials with environmentally responsible practices. Moreover, the administrator plays an important part in overseeing the implementation of hospital waste management policies. By ensuring that established protocols are adhered to, they ensure that proper waste disposal procedures are consistently followed throughout the facility. This commitment to policy enforcement helps maintain a waste management system that is safe and environmentally responsible [103]. Across the board, the hospital administrator is accountable for confirming the availability of essential resources, evaluating costs, drafting contracts, advising on sustainable purchasing policies, and overseeing policy implementation. The administrator contributes to the hospital's effective and environmentally conscious waste management strategy through their diligence [103].

3.5 Head nurse

Typically, the head nurse assumes critical responsibilities and is responsible for various waste management duties. First, they play a crucial role in training the hospital care staff, particularly guiding new hires. By imparting knowledge and expertise in waste management practices, the head nurse ensures that all staff members are well-equipped to manage waste effectively [104]. In addition, the head nurse is responsible for closely monitoring the sorting, collection, storage, and movement of waste throughout the hospital's various wards. In addition, the head nurse keeps a vigilant eye to ensure proper procedures are followed, including waste management in the hospital [105]. Safety measures are of the utmost importance, and the head nurse closely monitors their implementation and carries proactive measures to enforce safety protocols, thereby promoting a safe environment for patients and healthcare professionals engaged in waste management activities [106].

In addition, the head nurse prioritizes maintaining cleanliness and preventing infections throughout the hospital. They supervise and implement measures to ensure that waste disposal practices adhere to hygiene standards, thereby minimizing the risk of contamination and spreading infections throughout the facility [107]. Nurses can further acquaint the hospital care staff, supervise waste management in various wards, oversee safety precautions, and prioritize cleanliness and infection control. The head nurse's diligent efforts contribute to a well-organized and secure waste management system, promoting a healthy and secure hospital environment [108].

3.6 Chief pharmacists or laboratory in-charge

The chief pharmacist is responsible for keeping medicine stock, limiting expired stock, and handling waste containing heavy metals. In the pharmacist's absenteeism, these jobs are done by the hospital administrator [109]. The head of the laboratory is accountable for maintaining the chemical inventory and reducing waste from chemicals [110].

4 Techniques utilized for biomedical waste treatment and disposal

Biomedical waste can be dangerous to a person's health and safety. Additionally, the different types of Biomedical waste have made people more worried about storing, treating, shipping, and getting rid of waste. In recent years, novel strategies have been developed to protect people from the harmful and infectious originating from biomedical waste. Incineration, autoclaving, chemical disinfection, land disposal, needle extraction or destruction, shredders, encapsulation, inertization, etc., are some of the most common techniques in laboratories and hospitals. According to Good Laboratory Practices (GLP), waste should be stored in suitable containers labeled in advance and kept in designated locations. When deciding on a storage location, GLP recommends choosing a well-ventilated area [111]. GLP guidelines suggest adopting microscale experiments as much as possible to minimize the generation of chemical waste. Additionally, it is recommended to perform distillation with the used solvents to enable their reuse, thereby reducing solvent waste. These practices promote sustainability and help laboratories save costs associated with waste disposal [111].

4.1 Incineration

The incineration of biomedical waste has numerous advantages, includes incineration sterilizes infectious wastes, minimizing volume and mass by up to 90%, converting harmful wastes such as carcasses of animals to non-harmful ash, allowing for the recovery of waste heat, and utilizing to discard potentially hazardous chemicals and radioactive waste of low level simultaneously [4, 112]. Infectious and toxic biomedical waste components are usually disposed of in a modern incinerator with air quality control equipment, where waste volume and weight are reduced and emissions are effectively controlled [68]. A well-designed incinerator system will have regulated feed rates, controlled air combustion, elevated temperatures, adequate burn time (long residence time), and appropriate gas mixing for combustion [113]. The air quality control apparatus collects paniculated matter, gathers trace metals and organics, and neutralizes acid gases (HCl) produced by combustion. Biomedical waste incinerators come in numerous shapes and sizes, but most modern systems have a series of combustion stages [114]. Controlled-air incinerators are the most common type of modern Biomedical waste incinerator and are preferred over other existing incinerators. In the primary chamber, waste

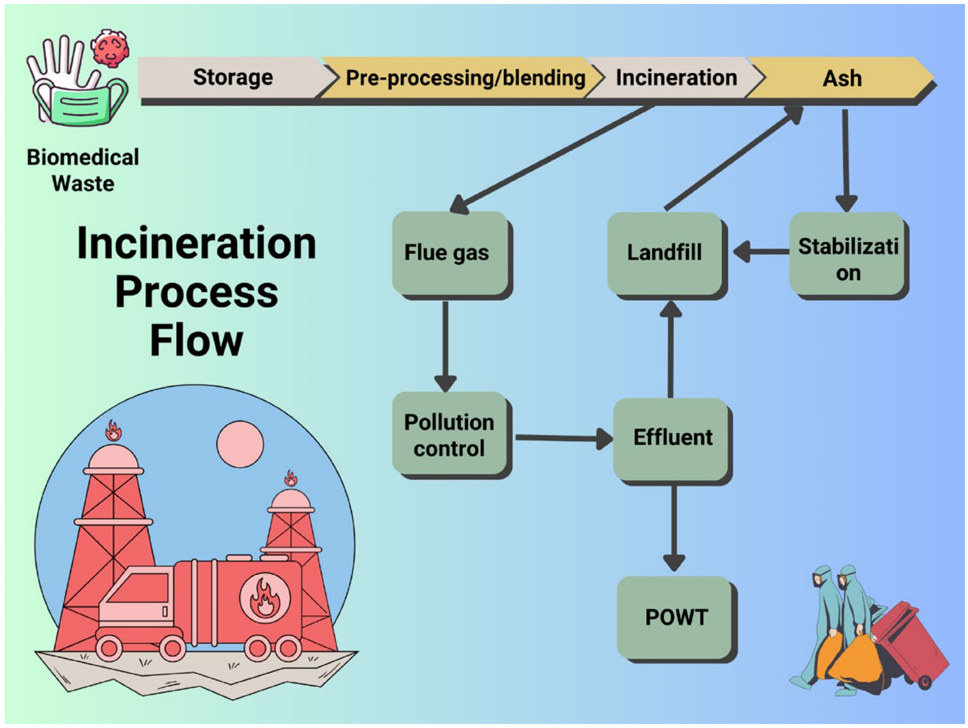

Fig. 2 Schematic representation of incineration system in biomedical waste management via various techniques or involved various stages

is burned, and gases are released. The volatilized gases are burned in the secondary chamber, resulting in carbon dioxide and water vapor emissions [115], summarized in the Fig. 2. Biomedical waste is burned under pyrolytic or reduced air conditions before being burned in stages with excess air [116]. The secondary chamber ignites the gases at an elevated temperature of around 1800 °F for a time frame of retention of up to two seconds, guaranteeing the destruction of any unburned components [117]. In order to reduce the temperature of the effluent gases and recover the energy for the production of steam, several incinerators generally utilize waste heat boilers [118].

4.2 Autoclaving

Autoclaving is a highly effective method of wet/ moist thermal disinfection [119]. Autoclaves are typically used in hospitals and laboratories to sterilize reusable biomedical equipment [120], tend to be reserved for extremely infectious waste, such as microbial cultures or sharps [121] that even hospitals with limited resources should be equipped with autoclaves. Autoclaving of the waste has the same benefits and drawbacks as the other wet thermal processes [122]. The physical necessities of sterilising biomedical supplies differ from those for steam autoclave treatment. Minimum contact times and temperatures are determined by several variables, including the waste's moisture content and the steam's ability to penetrate the waste [123]. Several research on autoclaving has determined that in order to effectively inactivate all vegetative microorganisms and most bacterial spores in a small amount of waste (about 5–8 kg), a 60 min cycle at 121 °C (minimum) and 1 bar (100 kPa) is required, allowing for full steam penetration of the waste material [21]. Autoclaves have a number of drawbacks, including moderate to high installation costs [124], need of electricity, and, in some cases, the use of a boiler with emission control [125]. Autoclaves are unsuitable for chemical or pharmaceutical waste [126]. The appearance of the waste remains constant; shredding is needed to prevent reuse; and the weight of the waste remains constant. noxious odours; having the presence of chemicals that can emit hazardous fumes; and the procedure being lengthy and time-consuming [127]. The Table 2 further summarized the various steps or methods for recycling or reusable of biomedical items from the waste.

4.3 Chemical disinfection

Biomedical devices in hospitals are frequently subjected to chemical disinfection to eliminate bacteria, which is considered under the waste category [158]. Pathogens must be killed or stopped from growing, so chemicals are used to treat the waste. However, the chemicals used for disinfection threaten the environment and the health of those who work with

Table 2 Summarize the various methods for recycling approaches for biomedical items or wastes

Recyclable Item	Methods or Steps for Recycling/Reusing	References
Glassware	Cleaning, sterilization, sorting, reprocessing, reuse	[128]
Plastics	Segregation, shredding, melting, molding, reuse	[129]
Metals	Segregation, melting, purification, casting, reuse	[130]
Paper and Cardboard	Segregation, shredding, pulping, reformation, reuse	[131]
Textiles	Segregation, cleaning, shredding, reweaving, reuse	[132]
Electronics	Segregation, dismantling, recycling of metals and plastics, disposal of hazardous materials	[133]
Needles and syringes	Incineration, autoclaving, shredding, sterilization	[128]
Gloves	Segregation, shredding, melting, molding, reuse	[134]
Gowns	Segregation, shredding, pulping, reformation, reuse	[135]
Masks	Segregation, shredding, melting, molding, reuse	[136]
Sharps containers	Segregation, cleaning, shredding, reprocessing, reuse	[137]
Plastic tubing	Segregation, shredding, melting, molding, reuse	[138]
Catheters	Segregation, shredding, melting, molding, reuse	[139]
ECG leads	Segregation, shredding, melting, molding, reuse	[140]
IV bags	Segregation, shredding, melting, molding, reuse	[141]
Glass syringes	Cleaning, sterilization, sorting, reprocessing, reuse	[142]
Plastic pipettes	Segregation, shredding, melting, molding, reuse	[143]
Centrifuge tubes	Cleaning, sterilization, sorting, reprocessing, reuse	[144]
Petri dishes	Cleaning, sterilization, sorting, reprocessing, reuse	[145]
Microscope slides	Cleaning, sterilization, sorting, reprocessing, reuse	[137]
Culture plates	Cleaning, sterilization, sorting, reprocessing, reuse	[146]
Swabs	Segregation, shredding, melting, molding, reuse	[143]
Wipes	Segregation, shredding, pulping, reformation, reuse	[147]
Lab coats	Segregation, shredding, pulping, reformation, reuse	[148]
Coveralls	Segregation, shredding, pulping, reformation, reuse	[144]
Booties	Segregation, shredding, melting, molding, reuse	[137]
Lab goggles	Segregation, shredding, melting, molding, reuse	[149]
Face shields	Segregation, shredding, melting, molding, reuse	[150]
Microplates	Cleaning, sterilization, sorting, reprocessing, reuse	[151]
Pipette tips	Segregation, shredding, melting, molding, reuse	[152]
Test tube racks	Segregation, melting, purification, casting, reuse	[143]
Cables and wires	Segregation, dismantling, recycling of metals and plastics, disposal of hazardous materials	[153]
Batteries	Segregation, dismantling, recycling of metals and plastics, disposal of hazardous materials	[154]
Lab equipment	Segregation, dismantling, recycling of metals and plastics, disposal of hazardous materials	[155]
Refrigerators	Segregation, dismantling, recycling of metals and plastics, disposal of hazardous materials	[156]
Freezers	Segregation	[157]
Microplates	Cleaning, sterilization, sorting, reprocessing, reuse	[151]
Pipette tips	Segregation, shredding, melting, molding, reuse	[152]
Test tube racks	Segregation, melting, purification, casting, reuse	[143]
Cables and wires	Segregation, dismantling, recycling of metals and plastics, disposal of hazardous materials	[153]
Batteries	Segregation, dismantling, recycling of metals and plastics, disposal of hazardous materials	[154]
Lab equipment	Segregation, dismantling, recycling of metals and plastics, disposal of hazardous materials	[155]
Refrigerators	Segregation, dismantling, recycling of metals and plastics, disposal of hazardous materials	[156]

them. This is the best way to handle infectious waste that is liquid, like blood, urine, feces, and hospital sewage. Most of the time, bleaching agents (i.e., sodium hypochlorite) solutions of 1% or active chlorine solutions of 0.5% are used [59]. Liquids with a high protein content, such as blood, require an undiluted bleach solution with a contact period of more than 12 h. It is important to remember that toxic gases (chlorine and ammonia) are produced when bleach is mixed with urine. Furthermore, chlorine-disinfected liquid waste cannot be disposed of in a septic tank [159]. Lime, ozone, ammonium salts, and peracetic acid are other disinfectants used. Due to their carcinogenic or sensitizing properties, glutaraldehyde, formaldehyde, and ethylene oxide should not be used. The skin, eyes, and respiratory system are all irritated by strong disinfectants. These agents need to be handled with care. Personal protective equipment, for instance, needs to be worn and kept properly. Before solid biomedical waste can be chemically disinfected, must be shredded [52]. This practice has numerous safety concerns, and the waste is superficially disinfected. Thermal disinfection is inevitably preferred to chemical disinfection for effectiveness and environmental reasons. Chemical disinfection is more advantageous as it is simple, relatively inexpensive, and disinfectants are widely available [160]. Chemical disinfection has some disadvantages as well, which include: the chemicals used are themselves dangerous substances [161], which should be handled with care; the suggested contact time and concentrations have to be followed for adequate disinfection; the volume of waste is not reduced; and the waste must be shredded prior to going through treatment with chemicals [162]. Table 3 summarizes the various chemicals utilized and mechanisms of disinfection for the biomedical waste.

4.4 Land disposal

Land-based waste management options include both open dumps and sanitary landfills [185]. Uncontrolled and dispersed waste deposits are known as "open dumps," and they can cause serious pollution, fires, increased risks of disease transmission, and unrestricted access for scavengers and animals [8, 186]. There is an obvious danger of disease transmission, either directly through cuts, sneezes, or swallowing or indirectly through the food chain or a pathogenic host species when infectious pathogens from hospitals come into contact with humans or animals. Sanitary landfills are the preferred option over open dumps for several reasons. These include the implementation of geological barriers to prevent waste from contaminating the environment, adherence to engineering protocols before waste is accepted, the presence of trained staff to manage operations, and the efficient organization of waste deposits and daily coverage [187]. Sanitary landfills are subject to certain rules and regulations to ensure effective waste management. One important requirement is having competent on-site personnel who can oversee and control daily operations. Additionally, vehicles are allowed to transport trash to the landfill, and designated work areas are established for this purpose. The site must be carefully divided into manageable sections before initiating landfill activities and adequately prepared [188]. To prevent any leakage of harmful substances, properly seal the bottom and sides of the landfill. This helps contain leachate, the liquid generated from waste decomposition, within the site boundaries. Furthermore, appropriate measures need to be implemented to collect leachate; if necessary, a system should be in place for its treatment [189]. A systematic approach is followed for waste disposal within the landfill. Waste is placed in a confined area in an organized manner, allowing it to be spread, compacted, and covered daily. This ensures efficient space utilization and reduces the risks associated with open waste accumulation. To manage surface water effectively, holes are excavated around the landfill to collect any runoff. As each phase of the landfill reaches completion, a final cover is constructed to minimize rainwater infiltration. This final cover acts as an additional safeguard against environmental contamination [190].

4.5 Needle extraction and destruction

Chemical disinfection is commonly utilized in hospitals to kill or inhibit microbes on biomedical equipment and management of biomedical waste [191]. The International Committee of the Red Cross (ICRC) avoids extracting or destroying needles for safety, though it is done in some cases. This is done for a couple of reasons: first, needles removed from used syringes cannot be reused, and second, the volume of sharps is reduced. Several appliances use electricity to melt the needles, making them unsuitable for use in ICRC settings, particularly in areas with limited electricity. Furthermore, these appliances need to be regularly maintained and handled with caution. Small, manually controlled devices can also be utilized in order to remove needles from syringes after injection. The needles are then discarded in a sharp container. Plastic syringes should be disinfected before being thrown into the household waste stream or recycled. Preventing syringe and needle reuse, relatively inexpensive models manufactured locally, a lowered volume of sharps, plastic from syringes that can be reused after disinfection and shredding, and ease of usage are just a few of the advantages of needle extractors [192]. The main problems with needle extractors are the risk of body fluids splashing out, the fact that some models run on electricity, the fact that needles and syringes stay dirty, the risk of the destroyer breaking, the fact that needles often fall out of the receptacle, and the fact that the safety and process have not been tested [193]. The needle destroyer requires electricity and leaves a proportion of the needle still attached to the syringe, which remains sterile [194].

Table 3 Commonly utilized chemicals for the process of chemical disinfectants

Chemicals	Mechanism of Disinfection	References
Sodium hypochlorite	Oxidizes microorganisms by releasing free chlorine, which reacts with and destroys the cell wall and cytoplasmic membrane of microorganisms.	[163]
Hydrogen peroxide	Oxidizes microorganisms by producing highly reactive hydroxyl radicals that damage their cell components.	[164]
Ethanol	Denatures proteins and dissolves lipids in cell membrane, leading to cell death.	[165]
Isopropanol	Denatures proteins and dissolves lipids in cell membrane, leading to cell death.	[166]
Quaternary ammonium compounds	Causes cell death by damaging cell membrane and denaturing proteins.	[167]
Glutaraldehyde	Causes cell death by alkylating and cross-linking proteins and nucleic acids.	[168]
Formaldehyde	Causes cell death by damaging cellular proteins and nucleic acids.	[169]
Chlorine dioxide	Oxidizes microorganisms by reacting with and disrupting their cell components.	[170]
Peracetic acid	Oxidizes microorganisms by reacting with and disrupting their cell components.	[171]
Phenol	Damages cell membrane and changes the way proteins work, which kills cells.	[172]
Iodine	Damages cell membrane and changes the way proteins work, which kills cells.	[173]
Sodium dichloroisocyanurate (NaDCC)	Releases hypochlorous acid when dissolved in water, which oxidizes and destroys microorganisms.	[174]
Calcium hypochlorite	Releases hypochlorous acid when dissolved in water, which oxidizes and destroys microorganisms.	[175]
Benzalkonium chloride	Damages cell membrane and changes the way proteins work, which kills cells.	[176]
Cetylpyridinium chloride	Causes cell death by damaging cell membrane and denaturing proteins.	[177]
Triclosan	Inhibits bacterial fatty acid synthesis, leading to death of cell.	[178]
Octenidine dihydrochloride	Causes cell death by damaging cell membrane and denaturing proteins.	[179]
Polyhexamethylene biguanide (PHMB)	Causes cell death by damaging cell membrane and denaturing proteins.	[180]
Chlorhexidine	Causes cell death by damaging cell membrane and denaturing proteins.	[181]
Ethylene oxide	Causes cell death by alkylating and cross-linking proteins and nucleic acids	[182]
Sodium percarbonate	Releases hydrogen peroxide when dissolved in water, which oxidizes and destroys microorganisms.	[183]
Citric acid	Causes cell death by damaging cell membrane and denaturing proteins.	[184]

4.6 Shredders

Shredders shred waste into small fragments. A few of these rotary devices are industrial models, and the method necessitates using qualified personnel to operate and maintain the device. They are commonly found in closed chemical or thermal disinfection systems. However, grain mills can be retrofitted to function as simple shredders; however, waste that has been disinfected should be processed in such machines [195]. When large quantities of needles and syringes are available, shredding should be considered, which provides a method for recycling plastics and needles in certain situations. This entails a centralized system for gathering and transferring the waste from different facilities [194]. Shredders can make waste unrecognizable, stop needles and syringes from being reused, reduce volume, make it easier to recycle plastic and make chemical or thermal treatment work better in closed and integrated systems [196].

While shredders offer many advantages, there are also a few downsides. For one, they require electricity and must be connected to a power source, which can limit mobility. Additionally, the initial investment in shredding equipment can be substantial, especially for smaller organizations. Another issue is that larger pieces of metal can compromise the shredder's mechanisms, leading to damage or breakdown. Eventually, it is worth noting that shredding does not inherently clean up waste but rather breaks it down into smaller pieces, which may require additional cleaning or sorting [197]. One major concern is the release of pathogens into the air when untreated trash is shredded. This poses a health risk to individuals near the shredding operation, as the pathogens can become airborne and potentially cause infections or illnesses. Therefore, proper precautions and protective measures are essential to mitigate these risks, demanding skilled personnel and constant vigilance [198].

4.7 Encapsulation

Encapsulation is the process of encasing (or solidifying) a small number of potentially dangerous substances in a mass of inert materials. The treatment aims to prevent contact between humans and the environment. Encapsulation involves placing waste in containers, adding an immobilizing substance, and sealing them up. Sharps, chemical or pharmaceutical residues, or incinerator ash are encapsulated using high-density polyethylene cubes or metallic drums filled to three-quarters capacity. The containers or boxes are then filled with a medium like plastic foam, bituminous sand, lime, cement mortar, or clay. Once the medium has dried, the containers are sealed and disposed of in a sanitary landfill or waste burial pit. For instance, the following ratios are recommended: 65% pharmaceutical waste, 15% lime, 15% cement, and 5% water (Encapsulation and Immobilisation of Medical Waste). The primary advantage of the process is that it effectively reduces the likelihood of scavengers gaining access to hazardous waste. In general, sharps encapsulation is regarded as a short-term solution. In temporary settings such as camps or vaccination campaigns, the encapsulation of sharps or unused vaccines could be considered. Encapsulation is simple, inexpensive, and safe; it can be used for sharps and pharmaceutical wastes and minimizes scavenging risk [194]. Encapsulation has several problems, i.e., being seen as a temporary solution, only being able to handle small amounts of waste, and making waste heavier and bigger [199].

4.8 Inertization

Inertization is the technique of combining waste with cement and other substances prior to disposal to minimize the risk of toxic waste substances leaching into the surface or groundwater. Inertization is particularly beneficial for pharmaceuticals, and incineration ash with a high metal content is known as stabilization [200]. In inertization, pharmaceutical waste is mixed with lime, water, and cement to form a homogeneous mass [201]. Afterwards, the cubes or pellets are manufactured on site before being transported to a suitable storage location. On the other hand, the homogeneous mixture can be taken to a landfill and poured into trash as a liquid [202]. The process is quite affordable and can be executed with relatively straightforward tools. The primary requirements are a grinder or road roller for crushing the pharmaceuticals, a concrete mixer, and supplies of cement, lime, and water, as well as human resources [200]. The Table 4 further explains the various unrecyclable items from the biomedical waste and the possible reasons thereof.

Table 4 List of items or unrecyclable items from biomedical waste and possible reasons

Unrecyclable Item	Reason for non-recyclability	References
Animal carcasses, Human tissues, Infectious waste, Sharps with attached tubing or IV bags, Gloves, Gowns, Masks, Textiles, Paper and Cardboard	Potential biohazard contamination	[33, 203]– [210]
Chemotherapy waste	Potential biohazard contamination, presence of hazardous drugs	[211]
Radioactive waste, Sharps containers containing trace chemotherapy or hazardous drugs	Potential health hazard, risk of contamination	[212, 213]
Amalgam, Mercury thermometers	Presence of toxic mercury	[214, 215]
Batteries	Presence of toxic chemicals and heavy metals	[216]
Lab chemicals	Presence of hazardous substances and chemicals	[217]
Formalin	Presence of hazardous chemicals	[218]
Expired medications	Potential health hazard, risk of misuse	[219]
Broken glassware	Potential hazard, risk of contamination	[220]
Plastics, Metals	Potential biohazard contamination, presence of hazardous chemicals	[221, 222]
Electronics items	Presence of hazardous substances and chemicals	[223]
Needles and syringes, Tubing, Catheters, ECG Leads, IV bags, Glass, Syringes, Plastic, Pipettes, Centrifuge tubes	Potential biohazard contamination	[33, 166, 205, 207, 221, 224]–[231]
Petri dishes, Microscope slides, Culture plates, swabs, wipes, lab coats, coveralls, booties, lab goggles		
Face shields, Microplates, Pipette tips	Potential biohazard contamination	[157, 163, 173]
Test tube racks	Presence of hazardous chemicals	[206]
Cables and wires, Lab equipment, Refrigerators	Presence of hazardous substances and chemicals	[174, 232]

5 Policies related to safe disposal of biomedical waste in various populated countries

5.1 Policies related to India

The recent Bio-Medical Waste Management Rules, 2016, have replaced the previous regulations of 1998 regarding the disposal of biomedical waste in India. These rules specify how biomedical waste must be collected, sorted, stored, transported, and dispose. Hospitals, clinics, laboratories, blood banks, veterinary institutions, and research facilities are all included in the recent Bio-Medical Waste Management Rules scope [233]. On the basis of the level of risk associated with the waste, the regulations classify biomedical waste into four categories:

Category 1: This category includes highly infectious waste and poses a high risk of infection to humans and animals. Human and animal tissues, organs, bodily fluids, and waste from microbiology, biotechnology, and infectious disease research all fall under this category [234].

Category 2: This category includes moderately infectious waste and poses a moderate risk of infection to humans and animals. This includes waste such as disposable needles, syringes, and other sharp objects, waste generated during surgery or autopsy, and from patients with infectious diseases [234].

Category 3: This category includes less infectious waste and poses a low risk of infection to humans and animals. This includes waste such as gloves, gowns, other protective gear and waste generated during routine medical procedures [234].

Category 4: Food scraps, paper, and plastic wrap all fall into the category of general waste that isn't biomedical waste [234].

A permit from the State Pollution Control Board or Committee is required for any business that creates biomedical waste as of the Biomedical Waste Management Rules, 2016. The license must be renewed every 5 years after considering the capacity of waste treatment and disposal facilities and the quantity and nature of biomedical waste assembled [233]. In addition, the regulations require establishments to classify biomedical waste at the generation stage and store it in bags or containers with color-coded labels. For example, waste from Category 1 must be kept in red bags; waste from Category 2 must be kept in yellow bags. Categories 3 and 4 of waste must be kept in blue or white bags, while categories 1 and 2 can be stored in black bags. In addition, the rules stipulate the duration and temperature for storing various types of biomedical waste. Category 1 waste must be refrigerated between 4 and 8 °C for a maximum of twenty-four hours. Category 2 waste must be secured and kept dry for 7 days. Category 3 waste can be maintained for up to 30 days in a covered container. Category 4 waste can be stored in the same container as general waste but must be covered [235].

The rules also require that biomedical waste be transported in a specially designed vehicle with a closed, leak-proof container. The vehicle must be outfitted with a GPS tracking system, and the driver and attendant must be trained in biomedical waste disposal. The Biomedical Waste Management Rules 2016 also specify the treatment and disposal of biomedical waste. Autoclaving, microwaving, chemical treatment, and incineration are among the treatment methods. The method of treatment selected depends on the type and amount of waste generated. The rules also state that treated waste must be disposed of in a scientifically designed landfill or incinerator that meets the prescribed standards. The rules also outline the responsibilities of biomedical waste generators, such as providing staff training on biomedical waste handling, keeping records of waste generated and disposed of, and reporting any accidents or incidents involving biomedical waste to authorities [236].

5.2 Policies related to China

Biomedical waste is a form of hazardous waste generated by medical centers, hospitals, and laboratories. Due to the rapid growth of the healthcare industry and the resulting increase in waste production, biomedical waste disposal has become a significant issue in China. Biomedical waste that is improperly handled and discarded poses a grave threat to the environment and public health. The Chinese government has enacted various policies to ensure biomedical waste vehicles' safe and proper disposal. This article aims to provide an in-depth examination of China's policies concerning the safe disposal of biomedical waste vehicles and further examine the current state of biomedical waste disposal in China, government initiatives, and remaining obstacles [237].

The amount of biomedical waste produced in China rapidly increases as the healthcare industry expands. According to a report by China's Ministry of Environmental Protection, the country generated approximately 17.38 million tonnes of hazardous waste in 2017, with biomedical waste accounting for a significant portion of this waste. Toxic chemicals may be released into the atmosphere due to improper biomedical waste disposal, which poses risks to public health. In the past, uncontrolled dumping of biomedical waste was a major issue in China, particularly in rural areas. This has resulted in soil, water, and air contamination and the spread of infectious diseases. The Chinese government recognizes the significance of proper biomedical waste disposal and has implemented several policies to govern its handling and disposal [238].

5.2.1 Law on the prevention and control of environmental pollution by solid waste (2005)

The Law on the Prevention and Control of Environmental Pollution by Solid Waste, also called the "Solid Waste Law," was enacted in 2005. The law establishes guidelines for managing solid waste, including biomedical waste. It necessitates establishing a classification system for waste, which must be sorted and managed according to its nature, characteristics, and potential dangers. The Solid Waste Law also mandates establishing a legal framework for the collection, transportation, storage, and disposal of hazardous waste, including biomedical waste. It requires biomedical waste to be collected, stored, and transported separately from other waste and disposed of in a safe and environmentally responsible manner [239].

5.2.2 Measures for the administration of medical wastes (2003)

The "Measures for the Administration of Medical Wastes" were implemented by the Ministry of Health in 2003. The policy aims to control the production process, transport, storage, and disposal of medical waste in China. It mandates that medical institutions establish a waste management system and develop procedures for safely disposing of biomedical waste. In addition, the policy requires medical institutions to classify and separate medical waste at the source, store it in designated areas, and dispose of it in an environmentally safe manner. In addition, the policy mandates that medical institutions develop emergency response plans for incidents involving the production, storage, transportation, and disposal of medical waste [240].

5.2.3 National hazardous waste list (2016)

In 2016, the "National Hazardous Waste List" was created by the Ministry of Environmental Protection. The characteristics and dangers of each type of waste are used to classify it into one of several categories on the list. Biomedical waste is now considered hazardous waste. The National Hazardous Waste List mandates that government officials establish a regulatory framework for managing hazardous waste, including biomedical waste, throughout its life cycle, from collection to disposal. It also requires hospitals to properly identify and segregate their hazardous waste, store it in enclosed areas, and dispose of it to minimize its impact on the environment. The disposal of biomedical waste has become a major issue in Japan as the number of healthcare-related activities and the corresponding increase in waste have increased. Therefore, the Japanese government has established several regulations for the environmentally responsible disposal of biomedical waste. This article analyses Japan's laws and regulations pertaining to the proper disposal of biomedical waste vehicles [241].

5.3 Policies related to Japan

The Japanese Ministry of the Environment estimated that 525,000 metric tonnes of medical waste were produced in Japan in 2018, with a sizable portion coming from biomedical waste. Biomedical waste threatens public health because its improper disposal can lead to the emission of hazardous chemicals into the atmosphere. Unregulated biomedical waste dumping was a major problem in Japan, especially in the outlying regions. This has led to soil, water, and air contamination and the spread of infectious diseases. The Japanese government recognizes the significance of biomedical waste disposal and has enacted several regulations to govern its handling and disposal [242].

5.3.1 Waste disposal and public cleansing law (1970)

The "Waste Law," also called the Waste Disposal and Public Cleansing Law, was introduced in 1970. The law lays out standards for waste management, including biomedical waste. It necessitates the creation of a waste classification system, with waste sorted and handled by its nature, traits, and potential dangers. In accordance with the Waste Law, the government must establish a regulatory framework for handling hazardous waste, including biomedical waste. Biomedical waste must be collected, segregated from other trash, transported, and disposed of according to these rules [243].

5.3.2 Guidelines for medical waste management (1999)

In 1999, "Guidelines for Medical Waste Management" were published by the Ministry of Health, Labour, and Welfare. The government of Japan has enacted this policy to control the flow of medical waste throughout the country. It mandates that medical institutions establish a waste management system and develop procedures for safe disposal. Additionally, the policy mandates that healthcare facilities sort medical waste at the point of generation, store it in designated areas, and dispose of it environmentally soundly. Furthermore, the policy requires hospitals and other healthcare facilities to create emergency response plans for situations involving the generation, transport, storage, and disposal of medical waste [244].

5.3.3 Industrial waste management law (1970)

In 1970, the Industrial Waste Management Law, also known as the "Industrial Waste Law," was enacted. The law establishes guidelines for managing industrial waste, including biomedical waste. It necessitates establishing a classification system for waste, which must be sorted and managed according to its nature, characteristics, and potential dangers. Furthermore, the Industrial Waste Law requires a regulatory framework for the collection, transportation, storage, and disposal of hazardous waste, including biomedical waste. Biomedical waste must be gathered, stored, and shipped to safeguard the environment and human health without combining with other types of waste [245].

5.3.4 Chemical substances control law (1973)

The Chemical Substances Control Law is a Japanese statute enacted in 1973 to regulate the manufacture, importation, use, and disposal of chemical substances to prevent harm to humans and the environment. The Ministry of Health, Labour, and Welfare (MHLW) and the Ministry of the Environment (MOE) enforce this law, which applies to all new and existing chemical substances [246]. Under the law, manufacturers and importers of chemical substances must provide the government with pre-manufacture or pre-importation notifications detailing the substances' properties, potential hazards, and intended uses. If it is determined that the substances are hazardous to human health or the environment, the government may request additional information or restrict their production or importation. Also regulated by the law are the use and disposal of chemical substances. Companies that use chemical substances must implement safety management systems and employ appropriate measures to safeguard workers and the environment. The disposal of chemical substances must be safe and environmentally responsible [247]. In order to better protect human health and the environment, the "Chemical Substances Control Law" has been amended several times since it was first enacted. In 2020, the law was updated to promote the use of safer chemicals and make information about chemicals more accessible.

5.4 Policies related to United States of America (USA)

The USA has a comprehensive system of policies and regulations governing biomedical waste management, enacted at the federal level in the United States by the Environmental Protection Agency (EPA), the Department of Transportation (DOT), and the Occupational Safety and Health Administration (OSHA). Biomedical wastes are subject to these regulations, which outline their treatment at each stage of their life cycle. Each state in the United States has its biomedical waste management regulations and federal laws [30]. These regulations can differ greatly between states, with some having more stringent requirements than others.

5.4.1 EPA

The protection of human and environmental health is a top priority for the US Congress, which has established the Environmental Protection Agency (EPA) to ensure that we live in a safe and sustainable world. To further these goals, the EPA has implemented important regulations to dispose of biomedical waste properly. These regulations include the Clean

Air Act, which oversees the release of air pollutants from medical waste incinerators, and the Clean Water Act, which governs the release of wastewater from biomedical waste treatment facilities [248].

5.4.2 DOT

The DOT is the federal agency in charge of regulating the transport of hazardous materials. To ensure the safe transportation of biomedical waste, the DOT has established packaging, labeling, and transport regulations [248].

5.4.3 OSHA

To ensure that all workplaces are safe and healthy, the federal government established an agency called OSHA. OSHA regulations were established to protect workers from exposure to hazardous substances and must be followed during biomedical waste collection, storage, and disposal. Two of the most crucial OSHA regulations concerning biomedical waste management are the Bloodborne Pathogens and Hazard Communication Standards. The former mandates that employers provide adequate protection for employees who may be exposed to blood or other potentially infectious materials, while the latter requires that employees be informed about and trained in the safe handling of hazardous chemicals in the workplace [249].

5.4.4 State regulations

As previously stated, each state in the United States has its biomedical waste management regulations. Some states have stricter regulations than others. California, for instance, has some of the nation's strictest biomedical waste management regulations. California mandates the treatment of all biomedical waste before disposal and has stringent requirements for transportation, storage, and management. Florida, on the other hand, has less stringent biomedical waste management requirements. Florida has less stringent requirements for the transportation, storage, and handling of biomedical waste and does not mandate the treatment of all biomedical waste prior to disposal [250].

There are numerous reasons why policies regarding managing biomedical waste are essential for minimizing its impact. The primary purpose of these policies is to protect the environment by ensuring the proper handling and disposal of biomedical waste to prevent potential harm. The implementation of regulations can mitigate the risks posed by biomedical waste, thereby protecting ecosystems and preserving environmental health. Biomedical waste poses a significant risk to public health as well. These wastes may contain infectious agents that, if not managed properly, can contribute to the spread of disease. By minimizing the potential transmission of infectious diseases and ensuring the safe disposal of hazardous materials, policies can protect the public's health and well-being by minimizing the transmission of infectious diseases and ensuring the safe disposal of hazardous materials [251]. Moreover, biomedical waste management policies contribute to resource conservation. By promoting sustainable practices, these policies encourage the reduction of waste generation, recycling, and reuse of materials. This strategy helps conserve valuable assets such as water and energy, resulting in a more sustainable and effective use of these assets. In addition, biomedical waste management policies must be legally compliant. Healthcare facilities and organizations must adhere to many jurisdictions' specific biomedical waste disposal regulations. Noncompliance can result in legal penalties, such as fines and legal action, and harm a company's reputation. Last but not least, the policies in this domain prioritize the occupational health and safety of healthcare workers and others involved in biomedical waste management. These policies ensure that workers receive the proper training and safety precautions to protect them from the potential dangers posed by hazardous materials. By addressing these concerns, policies improve workplace safety and safeguard the health of waste management employees, which are summarized in Table 5 [252]. The highlights of various policies in populated countries associated with biomedical waste have been picturized or highlighted in Fig. 3.

6 Recent advancements in biomedical waste disposal

Biomedical waste disposal has garnered considerable attention due to the potential hazards to the safety of humans and the environment. In recent times, several trends have emerged in biomedical waste management. Firstly, an increasing understanding of the hazards linked to rash disposal has led to stricter regulations and guidelines. Governments, hospitals, medical centers, and companies handling waste acknowledge the importance of proper waste disposal [105].

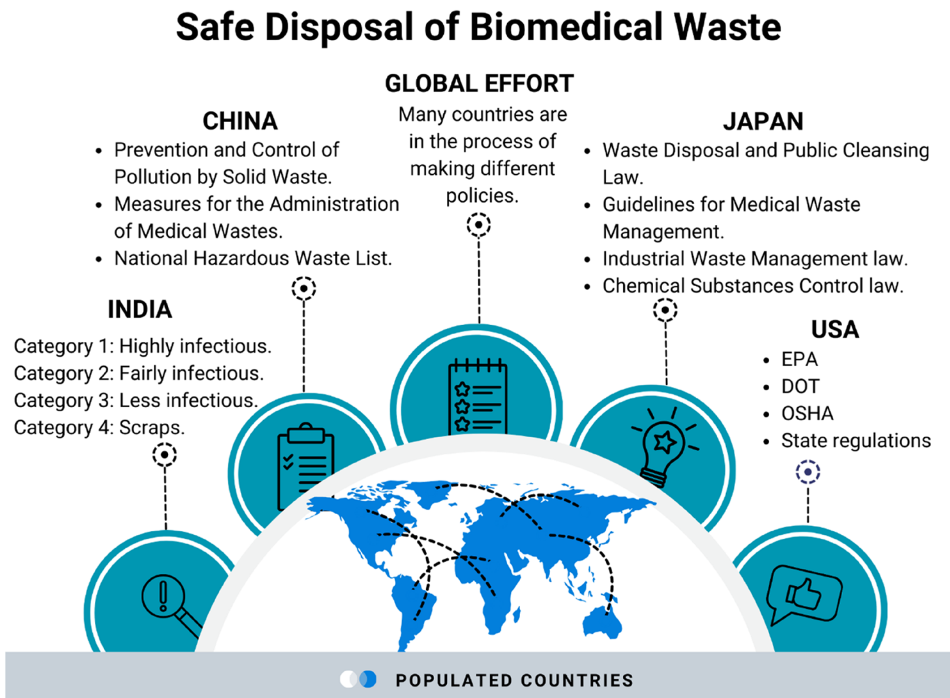

Fig. 3 Various policies of Safe disposal of biomedical waste at a glance in populated countries across the globe

Secondly, biomedical waste is being increasingly segregated at the point of generation. This guarantees that hazardous and non-hazardous materials are kept separate during the waste sorting and treatment. Thirdly, technology is increasingly being utilized to improve waste management procedures. Automated waste collection systems, tracking software, and intelligent waste bins are utilized for more effective and secure waste sorting, collection, transportation, and treatment. In addition, there is a trend toward adopting eco-friendly biomedical waste management practices [260]. Waste disposal's negative environmental effects can be mitigated through recycling, composting, and energy recovery techniques. In addition, collaboration and partnerships between healthcare institutions, waste management companies, and government agencies are on the rise. These partnerships ensure effective coordination among stakeholders, resulting in waste management systems that are safer and more efficient. In addition, governments and regulatory bodies are enforcing stringent regulations to ensure compliance and reduce health risks. These regulations specify proper disposal methods, frequency of disposal, and waste classification [261]. Another significant trend is public participation, emphasizing education and awareness campaigns to promote responsible waste disposal practices. The public is educated on proper waste disposal techniques, the dangers of improper disposal, and the significance of waste segregation. Biomedical waste management and public health initiatives are increasingly recognized as interconnected, as shown in Fig. 4. Waste management is being incorporated as a vital component of public health programmes. Lastly, biomedical waste management is characterized by an emphasis on continuous improvement. Continuous evaluations of waste management procedures are conducted, and enhancements are implemented to increase safety and effectiveness [262]. Furthermore, Table 6 displays several important findings related to the management of biomedical waste.

7 Conclusion

Keeping in view the large infrastructural setup employed for hospitals, laboratories, research organizations, and other health care industries, emphasis is necessarily to be given on proper biomedical waste and the effective methodologies adopted to minimize health and environmental risk. In the present review, an attempt has been made to showcase all sources of biomedical waste, hazards originating from human health and the environment due to

Table 5 Significance of Policies for Safe Disposal of Biomedical Waste

Policy	Significance	References
Proper Segregation of Waste	Segregation of biomedical waste at the source aids in proper waste identification and categorization, resulting in safer and more efficient disposal.	[253]
Use of Color-Coded Containers	Color-coding of biomedical waste containers makes it easier to identify the type of waste contained and reduces the risk of accidental exposure and infection.	[254]
Mandatory Training for Personnel	Training and education of healthcare personnel handling biomedical waste is crucial to ensure safe disposal practices and reduce the risk of exposure and infection.	[71]
Implementation of Standard Operating Procedures (SOPs)	SOPs provide clear guidelines for safely handling, storing, transporting, and disposing of biomedical waste, and they aid in ensuring consistency and compliance with regulations.	[255]
Use of Personal Protective Equipment (PPE)	Use of appropriate PPE by personnel handling biomedical waste can prevent accidental exposure and infection, as well as minimize the possibility of cross-contamination.	[256]
Proper Transportation and Disposal	Biomedical waste is handled and thrown away in a way that is safe for the environment and follows local and national rules when it is transported and disposed of properly.	[257]
Regular Monitoring and Auditing	Auditing and monitoring biomedical waste management procedures on a regular basis can help pinpoint problem areas and guarantee adherence to rules and regulations.	[258]
Penalties for Non-Compliance	Strict penalties for non-compliance with regulations and policies for biomedical waste management can act as a deterrent and ensure adherence to safe disposal practices.	[259]

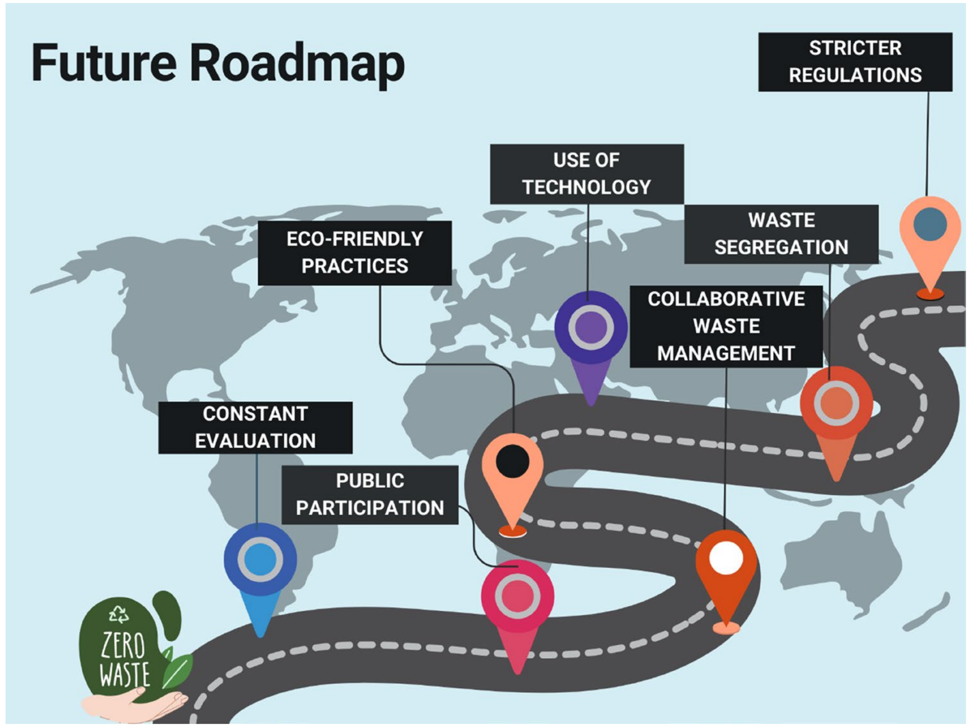

Fig. 4 Understanding the future roadmap of the safe disposal of biomedical waste for health and sustainable environment

improper handling, ultramodern facilities and their utilities to safely dispose of biomedical waste, etc. From country to country, policies pertaining to biomedical waste management differ. In the present article, literature from 40 years of previous research was reviewed, and it was concluded that in every biomedical waste generator setup, one manual must be there that depicts all safety parameters while handling biomedical waste, its pretreatment before safe disposal, and regulatory guidelines. The biomedical waste-related affairs must be handled with caution. If solid and non-sharp biomedical waste is present, it must be autoclaved and disposed of in a landfill as red bag waste. In the same way, animal-derived waste must be incinerated. Furthermore, it was concluded that in contemporary times, there is a need to work with the aim of reducing the risk of infection, avoiding soil contamination, and also preventing the spread of antibiotic-resistant bacteria.

The Sustainable Development Goals (SDGs) have been created to prevent health complications and promote the overall well-being of the population. This makes it essential to prioritize the improvement of the country's healthcare system. A smart strategy for managing biomedical waste would be crucial in achieving these SDGs laid out by the United Nations [274]. It is urgent to develop policies prioritizing international partnerships for exchanging experience, investment in medical waste disposal capacity, recycling and recovery, information dissemination, and international cooperation to achieve the United Nations Sustainable Development Goals. The development of an effective biomedical waste management strategy is only part of all the necessary measures that should be considered. Also, this is the time to invest in recycling infrastructure, research and development of new product designs and business models, and smart manufacturing. All of this may result in the creation of niches that will boost health and protect the environment and economy [275].

At present, government and non-government organizations are working to develop methods so that severe illness for waste management workers can be avoided. The present review may serve as a very good source of up-to-date information in the biomedical field for future policymakers, researchers, clinicians, doctors, and other biomedical waste handlers. The findings of this review will be advantageous in terms of environmental protection and health protection, and overall, they will serve as a ready reckoner for all the stakeholders in this area.

Table 6 Some applied key findings related with biomedical waste management

Sl. No.	Authors and Year	Key Findings	References
1	Abdelkareem et al., 2023	The present work covers the importance of thermal method of sterilization of some biogenic waste. Nevertheless, there is a dearth of research on the impact of sustainable development goals, thus requiring additional investigation. The paper covers the imperative of global collaboration in tackling issues pertaining to the management of medical waste, particularly in times of crisis. It is concluded that gaining insight into the correlation between medical waste management and sustainable development goals is imperative for devising sustainable solutions.	[263]
2	Sahoo et al., 2023	Keeping in view the plastic waste generated due to COVID-19 pandemic, environmentally friendly methods for biomedical waste management was discussed and advocated.	[264]
3	Jacob et al., 2021	Emphasis has been laid on the process of systematic incineration, The COVID-19 pandemic has led to a rise in biomedical waste in hospitals, requiring the implementation of efficient disposal techniques such as incineration and autoclaving. Inadequate administration can result in health complications and contribute to an annual mortality rate of 5.2 million. India and Wuhan, China, encounter difficulties in effectively handling and treating the increasing amount of biomedical waste.	[265]
4	Rajan et al., 2019	The paper discusses the management of biomedical waste in Ayurvedic hospitals, highlighting the need for further research in this area. Current disposal methods include sewage drains, incineration, and land fill, but each method has its advantages and disadvantages.	[266]
5	Joshi et al., 2015	A qualitative study on hospital waste management in an Indian rural tertiary care teaching hospital revealed two main themes: challenges in integrating healthcare waste management and interventions to improve it. The study found a gap between knowledge and actual practice, suggesting organizational changes, training, and monitoring to address this issue.	[107]
6	Basu et al., 2012	The present work embarks on significance of making aware to the doctors of hospitals. The study concluded that out of all the workers, most of male staff and hostilities has adequate knowledge of biomedical waste rules and symbols. However, only 55.9% could remember biomedical waste categories, and 29.5% knew disposal methods. The study recommends intensive training and regular monitoring for all staff, especially junior doctors.	[267]
7	Johnson, 1999	The present work is based on data from reproductive outcomes surveillance systems in New York, California, and five European countries, which suggest the increased risk of congenital malformations among infants whose parents lived near hazardous waste sites. This concludes the necessity of proper waste management.	[268]
8	Ronen et al., 1998	A bench-scale biological treatment process for contaminated wastes was demonstrated using factory wastewater. This process involved a two-stage reactor system, with anoxic stage aiming to remove nitrate through denitrification using carbon sources in the waste mixture. Acetone was added for nitrate removal. It was concluded that the aerobic stage can be achieved residual organic removal and total mineralization of RDX. The treatment scheme may be a cost-effective alternative to physico-chemical treatments commonly used for explosives-contaminated wastes.	[269]
9	Johnson and DeRosa, 1995	An attempt has been made to evaluate the chemical mixtures released into environmental media near hazardous waste sites and the potential health effects. The process of evaluating the risk related with improper waste management is described.	[270]
10	Wilson, 1993	During the process of gamma radiation, emphasis is given on regulatory requirements, site and technology approvals, waste separation, transportation, irradiation utilization, economies of scale, and end-product disposal as these factors can impact the financial feasibility of irradiation in specific situations especially in hospitals.	[271]
11	Schaefer, 1991	Dental clinics must comply with federal, state, and local ordinances for biomedical waste management. It is recommended that clinics must identify biomedical waste and disposal methods. Sharps should be stored in red containers, while solid waste should be contained in red bags. Waste should be disposed of by a qualified company with proper insurance and records. Regular training on hazardous waste recognition and handling should be included in the office manual.	[272]
12	Velzy and Trichon, 1990	In the present work, it was stated that Incineration of biomedical waste is a popular option, however small incinerators struggle to meet current air pollution limits. Moreover, Incineration reduces toxic effects of infectious materials and landfilling volume, especially due to its dense population and limited landfill space.	[273]

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Declarations

Competing interests The authors declare no competing interests.

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