REVIEW

Risk Management for Whole-Process Safe Disposal of Medical Waste: Progress and Challenges

Ting Yang[1,2], Yanan Du[1], Mingzhen Sun[1], Jingjing Meng[1], Yiyi Li[1]

[1]School of Health Services Management, Anhui Medical University, Hefei, Anhui, 230032, People's Republic of China; [2]Intelligent Interconnected Systems Laboratory of Anhui Province (Hefei University of Technology), Hefei, Anhui, 230009, People's Republic of China

Correspondence: Ting Yang, Email yangting@ahmu.edu.cn

Abstract: Over the past decade, the global outbreaks of SARS, influenza A (H1N1), COVID-19, and other major infectious diseases have exposed the insufficient capacity for emergency disposal of medical waste in numerous countries and regions. Particularly during epidemics of major infectious diseases, medical waste exhibits new characteristics such as accelerated growth rate, heightened risk level, and more stringent disposal requirements. Consequently, there is an urgent need for advanced theoretical approaches that can perceive, predict, evaluate, and control risks associated with safe disposal throughout the entire process in a timely, accurate, efficient, and comprehensive manner. This article provides a systematic review of relevant research on collection, storage, transportation, and disposal of medical waste throughout its entirety to illustrate the current state of safe disposal practices. Building upon this foundation and leveraging emerging information technologies like Internet of Things (IoT), cloud computing, big data analytics, and artificial intelligence (AI), we deeply contemplate future research directions with an aim to minimize risks across all stages of medical waste disposal while offering valuable references and decision support to further advance safe disposal practices.

Keywords: medical waste, safe disposal, major infectious diseases, progress and challenges

Introduction

Medical waste refers to the infectious, toxic, and hazardous waste generated by medical and healthcare institutions during activities such as treatment, prevention, and healthcare.[1] This type of waste poses significant risks to human health and the environment. Therefore, the recycling and disposal of medical waste must adhere to strict regulations and specific requirements. Inadequate disposal can not only jeopardize people's lives but also lead to pollution of soil, water, air, etc.[2,3] As economies grow rapidly and healthcare services expand globally, there is a continuous increase in the volume of various types of medical waste generated.[4] Currently, global production of medical waste is growing at an annual rate between 2% to 3%.[5] Medical waste has been identified as a major contributor to environmental pollution. Thus, effective management and proper disposal are crucial for achieving sustainable development goals.[6,7] Consequently ensuring safe handling and management practices for medical waste has become increasingly vital.

In recent times, the occurrence of severe acute respiratory syndrome (SARS), influenza A (H1N1), novel coronavirus infection, and other emerging infectious diseases has led to significant public health incidents. This has placed immense strain on the existing healthcare system and health management framework. One of the major challenges in dealing with a widespread outbreak of infectious diseases is ensuring the safe disposal of medical waste throughout the entire process. It is crucial to properly handle and manage the large volume of infectious medical waste generated during such epidemics to prevent secondary infections and control further spread.[8] Consequently, there has been an increasing focus from academic circles, medical institutions, and relevant regulatory bodies on emergency disposal and management strategies for medical waste. Scholars from various disciplines have conducted extensive research from different perspectives including studying the characteristics and factors influencing recycling and disposal methods for medical waste,

controlling and evaluating processes involved in its recycling and disposal, as well as assessing risks associated with disposing infectious disease-related medical waste. Substantial progress has been made through these research endeavors.

Based on an overview of the characteristics of medical waste and relevant laws and regulations governing its safe disposal, this paper provides a comprehensive review of existing research on the entire process system encompassing collection, storage, transportation, and disposal of medical waste. The objective is to present the current state of safe medical waste disposal while contemplating future research directions. This study aims to minimize risks throughout the entire process of medical waste disposal and offer valuable references and decision support for further advancements in ensuring its safe management.

Background
Definition of Medical Wastes

The World Health Organization defines medical waste as the byproducts generated during diagnostic, therapeutic, or immunization processes in humans or animals.[9] The United States Medical Waste Tracking Act of 1988 defines medical waste as a subset of waste generated in healthcare facilities such as hospitals, physician offices, dental clinics, blood banks, and veterinary hospitals/clinics, medical research facilities, as well as laboratories.[10] The US Environmental Protection Agency (EPA) defines healthcare waste as any solid waste generated in diagnosis, treatment (eg, provision of medical services), human or animal immunization, research related to these activities, or production/testing of biological products (EPA, 24 March 1989, pp. 12,373–12,374).[11,12] According to the Waste Control Act of South Korea, medical waste refers to the waste produced by healthcare facilities, animal hospitals, laboratories, inspection institutions and other organizations that may pose a risk of human infection or other hazards. Additionally, it includes waste that requires special management for health and environmental protection purposes such as extracts from human tissues and laboratory animal carcasses. Medical waste is categorized into three types: isolated medical waste, hazardous medical waste and general medical waste.

According to the Regulations on the Management of Medical Waste issued by China, medical waste refers to wastes generated by medical and health institutions during activities such as medical treatment, prevention, and healthcare that possess direct or indirect infectious, toxic, or other hazardous properties.[11,12] In accordance with the Classification Catalogue of Medical Waste revised in 2021 by the National Health Commission and the Ministry of Ecology and Environment, medical waste is categorized into five groups: infectious waste, damaging waste, pharmaceutical waste, pathological waste, and chemical waste.[13] By referencing the study conducted by Zhao et al, we have comprehensively summarized the origins, characteristics, and collection methodologies of diverse medical wastes,[14] as illustrated in Figure 1.

Related Policies on Medical Wastes Disposal

Due to the potential hazards posed by medical waste to both human health and the environment, the management and disposal of such waste have garnered increasing attention. In order to enhance control and regulation over medical waste, numerous countries have devised and implemented a series of laws and regulations pertaining to its proper disposal.

US and EU

Congress enacted the Health Care Waste Management Act in 1988, and subsequently, the Environmental Protection Agency (EPA) implemented health care waste regulations. However, since 1991, state governments in the United States have assumed responsibility for medical waste management. To guide states in this endeavor, the Council of State Governments has developed the Model Guidelines for State Medical Waste Management. As a result, nearly all states in the United States have issued their own comprehensive health care waste management regulations. In response to managing potentially infectious medical waste effectively, various departments including the National Safety Council of the United States collaborated with entities like Centers for Disease Control and Prevention (CDC), Environmental Protection Agency (EPA), and Department of Transportation to jointly compile two essential documents: "Management Guide for Class A Infectious Solid Waste" and "Planning Guide for Treatment of Solid Waste Contaminated by Class A Infectious Substances". These guides serve as valuable references to aid departments in formulating plans pertaining to
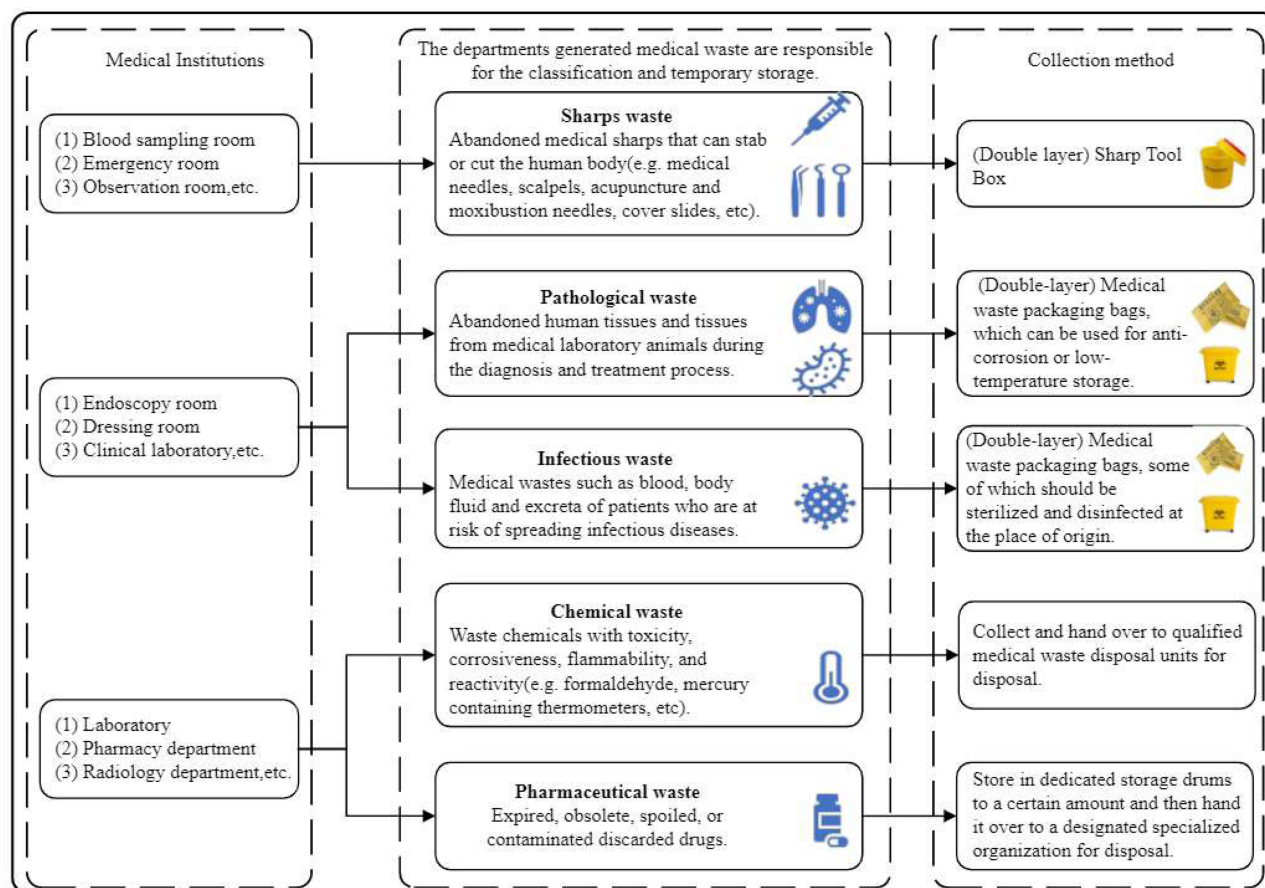
Figure 1 Classification and collection methods of medical waste.

collection, transportation, and disposal of medical waste.[15] The disposal of medical waste is strictly regulated within the United States; notable examples include promulgation of "Environmental Pollution Control by Incineration of Medical Waste" acts in both 1996 and 2000.

There are no separate laws and regulations on medical waste in the European Union, and medical waste management is mainly based on the European Waste Framework Directive and the European Waste Landfill Directive. Based on the concept of circular economy and environmental protection, EU member states have established their own relatively independent policy systems to supervise and manage the whole process of medical waste from generation to disposal.[16]

Japan and South Korea

The legal framework for medical waste management in Japan is highly comprehensive. The Bureau of Environmental Regeneration and Resource Recycling, which operates under the direct jurisdiction of the Ministry of Environment, compiles policies, regulations, standards, and technical guidelines to effectively guide and regulate nationwide treatment and disposal practices for medical waste. In November 1989, Japan issued the "Medical Waste Disposal Guidelines", followed by the revised implementation of the "Waste Disposal Law" in July 1992. This designation officially classified medical waste as special management waste requiring adherence to infectious waste management regulations. Simultaneously, Japan developed an Infectious Waste Disposal Manual outlining specific treatment protocols for infectious waste. Recognizing that proper classification, collection, storage, transportation, and treatment should be implemented at the source of generation; Japan has also enacted legislation such as the Law on Transporting Hazardous Substances and Technical Specifications for Medical Waste Treatment to ensure safe transport and disposal practices.

In terms of medical waste management, South Korea has established a comprehensive system encompassing waste classification, discharge, storage, transportation, and treatment. This system is primarily based on the Waste Management

Law, Guidelines for the Classification and Management of Medical Waste, and Guidelines for the Classification and Discharge of Medical Waste. To ensure effective monitoring and management throughout the entire lifecycle of medical waste from generation to disposal, South Korea has implemented an advanced intelligent waste network management system known as Allbaro electronic computing system.[17] Furthermore, in response to infectious diseases such as COVID-19 pandemic, South Korea has developed its own crisis early warning system along with specialized measures for managing COVID-19 medical waste.[18]

China

To date, China has implemented numerous policies, regulations, and standards as depicted in Table 1. The table demonstrates the initial establishment of technology and management systems for the classified collection, temporary storage, transportation, transfer, and centralized disposal of general medical waste. This development effectively supports the safe disposal of diverse medical wastes encountered in routine healthcare services. However, a unified and comprehensive set of technical standards, procedural specifications, and regulatory framework for the secure disposal of medical waste resulting from major infectious diseases—particularly emerging ones—is yet to be established in China. Consequently, the entire process encompassing collection, storage,

Table 1 Laws and Regulations on Medical Waste Disposal in China

Year	Laws and Regulations	Content
1989	Law of the People's Republic of China on Prevention and Treatment of Infectious Diseases.	It clearly stipulates the disposal, supervision and management of medical waste, and legal liability investigation.
1995	Law of the People's Republic of China on the Prevention and Control of Environmental Pollution by Solid Waste	It stipulates that medical waste shall be managed in accordance with the national list of hazardous wastes
1999	Measures for the Management of the Transfer of Hazardous Waste	Strengthen effective supervision over the transfer of hazardous wastes
2003	Clinical Waste Management Ordinance	We will strengthen safety management of medical waste
2003	Clinical Waste Classification Catalogue	Medical waste has been uniformly classified
2003	Technical Specification for Centralized Disposal of Medical Waste	The regulations set technical requirements for temporary storage, transportation and disposal of medical waste during centralized disposal, as well as training and safety protection requirements for relevant personnel, prevention and emergency measures for emergencies, and special requirements for medical waste management during major epidemics.
2003	Measures for the Management of Medical Waste in Medical Institutions	To standardize the management of medical waste by medical and health institutions
2004	Administrative Penalties for Medical Waste Management	To provide for administrative penalties for violations of regulations on medical waste management
2004	Measures for the Administration of Hazardous Waste Operation Permit	The supervision and administration of the collection, storage and disposal of hazardous wastes shall be strengthened
2014	Environmental Protection Law (Revision)	Medical waste was added to the traditional pollution category
2017	Notice on Further regulating the Management of Medical Waste	We will attach great importance to the management of medical waste, fully implement the responsibility of medical waste management, and standardize the whole-process management of medical waste classified collection, storage, transport and disposal.
2020	Management and technical guidelines for emergency disposal of medical waste during the outbreak of COVID-19 (trial)	To standardize the management and technical requirements for emergency disposal of medical waste during pneumonia epidemic
2020	Work Plan for Comprehensive waste Treatment of Medical Institutions	We will strengthen comprehensive waste management at medical institutions
2021	Notice on Issuing a Classification Catalogue of Medical Waste (2021 Edition)	Standardizing medical waste management and promoting scientific classification and disposal of medical waste

transportation, and disposal of medical waste associated with major infectious diseases poses significant safety risks.

Disposal Methods of Medical Wastes

With the rapid advancement of medical and healthcare services, coupled with the escalating demand for medical care, the quantity of various types of medical waste generated during these processes continues to escalate. However, it is crucial to acknowledge that medical waste often poses direct or indirect hazards and has been identified as a primary source of environmental pollution. Consequently, there is an urgent need for effective management and disposal methods for medical waste. Currently, numerous countries have established relatively mature centralized treatment technology systems for medical waste both domestically and internationally. These systems primarily encompass incineration treatment, high-temperature steam treatment, chemical disinfection treatment, microwave disinfection treatment, among others. The most commonly employed technology for medical waste disposal is incineration, which offers cost advantages but also generates hazardous emissions, particularly in developing countries. A comparative analysis was conducted by Bolan et al,[19] Kenny and Priyadarshini[20] to assess the merits and drawbacks of diverse technologies for medical waste disposal.

With the rapid economic development and the emergence of various sudden infectious diseases, there has been a significant increase in the volume of medical waste. Considering its potential threats to the environment, human health, energy conversion, and sustainability, it is crucial to adopt appropriate disposal methods. In response to this challenge, numerous new and advanced technologies have been proposed, including plasma gasification[21] and friction heat treatment.[22] This highlights that governments, medical institutions, relevant departments, and the academic community are fully committed to ensuring safe disposal of medical waste throughout the entire process. Scholars from diverse fields and disciplines have conducted extensive research from different perspectives encompassing three main areas: investigating the requirements for safe disposal of medical waste; managing and evaluating recycling and disposal processes; as well as assessing risks associated with infectious disease transmission during medical waste disposal.

Research Methods

The present study focused on the topic of "medical waste" and conducted a comprehensive search in the core database included in the Web of Science, resulting in a total of 52,446 relevant documents. Analysis of publication dates (as depicted in Figure 2) revealed an overall increasing trend in medical waste research, particularly since 2018 when this upward trajectory significantly accelerated, coinciding with the outbreak of the COVID-19 pandemic. Notably, there was approximately twice as many publications after the epidemic compared to before it occurred. Similar findings were obtained when searching using keywords such as "medical waste" and "risk management" (as illustrated in Figure 2).
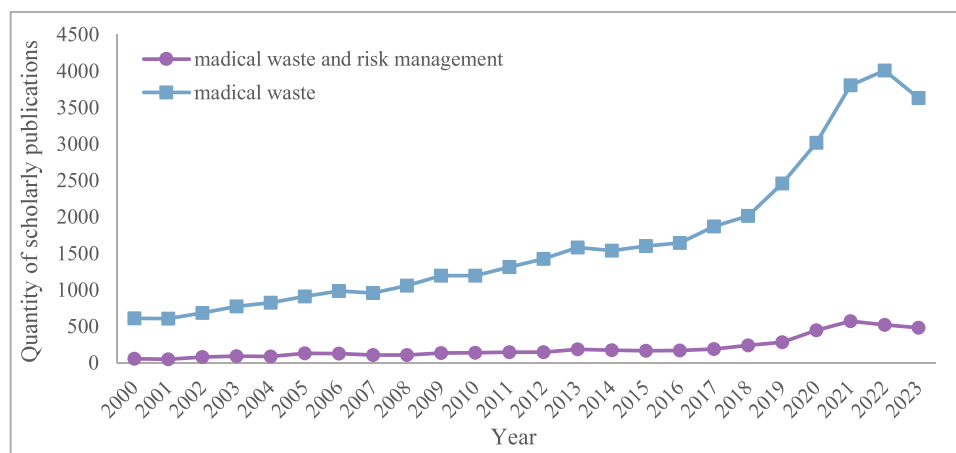

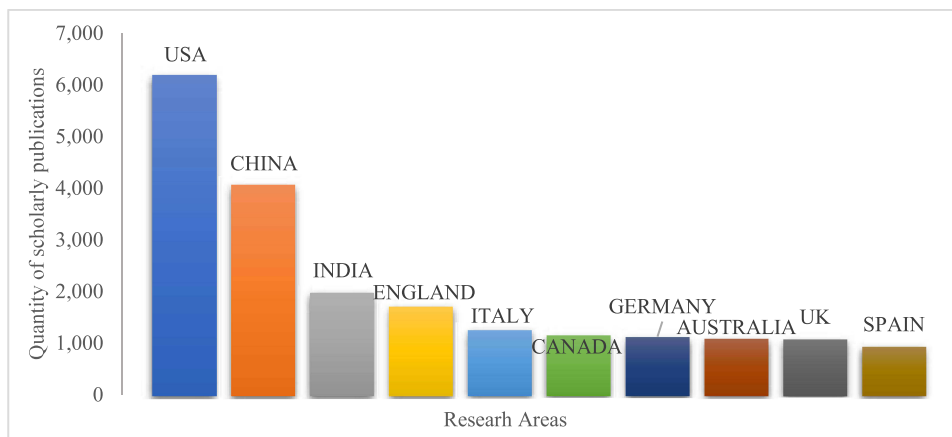**Figure 2** Trends in the publication of medical waste and risk management research from 2000 to 2023.

Figure 3 Relevant literature on medical waste from 2014 to 2023: Countries of origin.
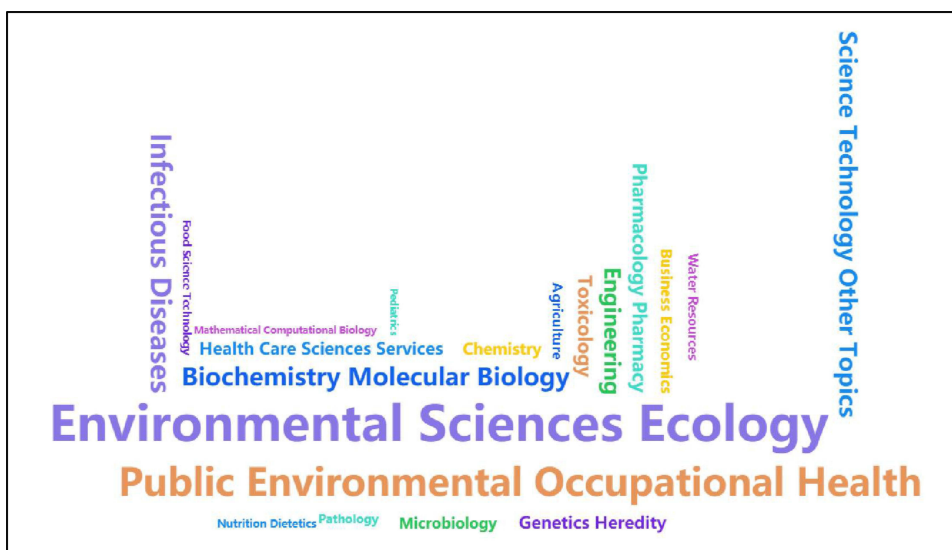

Figure 4 The primary research directions in the field of medical waste literature from 2014 to 2023.

Based on this, a total of 25,587 relevant literature were obtained using publications from the past decade (2014–2023) as search criteria. Among the countries contributing to these literature (as depicted in Figure 3), the United States, China, India, England, and Italy emerge as the top five nations publishing medical waste-related literature. Notably, the number of literature originating from the United States is approximately three times higher than that of India, highlighting its leading position in medical waste management.

From the main research directions depicted in Figure 4, foreign studies primarily focus on Environmental Sciences Ecology, Public Environmental Occupational Health, Infectious Diseases, Biochemistry Molecular Biology, Science Technology Other Topics, among others. Simultaneously, both domestic and international research emphasize the challenges and risks encountered within the medical waste field.

Characteristics and Influencing Factors of Medical Waste Recycling and Disposal

Distinguished from general wastes in other sectors, medical waste exhibits numerous distinctive features during its recycling and disposal process. Conducting an in-depth analysis of these characteristics and influencing factors can facilitate a comprehensive understanding and grasp of the specific requirements and constraints encountered throughout

the entire safe disposal process for medical waste, thereby establishing a more precise, objective, and effective index system for evaluating the safety of the entire process. This will support a more efficient comprehensive risk assessment for safe disposal. Currently, both domestic and international scholars primarily concentrate on studying the risk characteristics, environmental impact, as well as cost-effectiveness associated with medical waste recycling and disposal.

Risk Characteristics of Medical Waste Recycling and Disposal

Safety risk is the primary concern of medical waste recycling and disposal, and the analysis of medical waste safety risk characteristics needs to take different methods for different subjects or links.

Makajic-Nikolic et al used Fault Tree Analysis (FTA) to assess the risk associated with medical waste management in clinical centers located in Serbia.[23] Liao and Ho used the failure mode and impact analysis method to evaluate and analyze the health impact of supervisors and outsourcing risks.[24] Mastorakis et al investigated the potential health risks faced by personnel involved in medical waste transportation and disposal due to the emission of numerous hazardous gases during medical waste incineration.[25] Shareefdeen et al pointed out that medical centers will produce highly hazardous waste, which puts people at risk of fatal diseases.[26] Le et al point out that if health care waste is not properly controlled or treated, it endangers not only the safety and health of workers, but also the communities through which the waste is transported.[27] Wang et al believed that medical waste is a unique material containing infectious materials, and the risk of infection during the collection process must be considered when optimizing the collection route of medical waste.[28] They also believed that the final infected population includes individuals who were directly exposed to infectious materials due to the event and individuals who were indirectly infected during the infection process after the event. Mazzei and Specchia pointed out that approximately 15%, if not up to 35%, of health care waste is hazardous waste, and that exposure to hazardous waste can cause physical, chemical, or microbial hazards to the people and health care workers involved in waste handling, disposal, and removal.[29] However, when health care waste is properly sorted at its source, the proportion of hazardous waste can be reduced to 1–5%. Mol et al point out that segregation and safe disposal of health care waste is essential for risk management.[30] Yang et al also posit that garnering support from frontline healthcare providers for medical waste management can facilitate the implementation of sustainable practices in this domain.[31] Ajay and Prathish have conducted a comprehensive spatial and temporal analysis of dioxin emissions and associated health risks from bio-medical waste incineration.[32]

Environmental Impacts of Medical Waste Recycling and Disposal

Environmental impact is also an important factor to be considered in the whole process of medical waste disposal. The environmental impacts of medical waste recycling and disposal are also multifaceted, including impacts on soil, water, atmosphere and other ecological environments.[33,34]

Utilizing the Life Cycle Assessment (LCA) methodology, Nabavi-Pelesaraei et al developed a comprehensive evaluation framework for medical waste disposal in order to quantitatively assess the environmental impact associated with such practice.[35] Patwary et al used a series of sampling strategies and data collection techniques to study the process of healthcare waste management in Dhaka, Bangladesh, and analyzed the potential risks to the environment.[36] Chen and Liao established a regression analysis model to verify that effective management of medical waste can reduce environmental pollution, save hospital costs, facilitate resource recycling, and realize the construction of a resource-saving and environmentally friendly society.[37] Liu et al pointed out that incinerators are still the main way to treat medical waste in most transition economies, and analyzed the environmental impact of incineration without collection of pollutants such as dioxins and heavy metals.[38] Wisniewski et al have highlighted the challenge of incinerating single-use plastic products used in medical services due to their high chlorine concentration, which can significantly impact the environment. Therefore, minimizing medical waste is crucial for protecting the environment and reducing costs.[39] Zamparas et al have emphasized that proper treatment of medical waste is a critical environmental issue since improper disposal can contaminate underground aquifers and pose significant environmental risks.[40] According to Wilder-Smith and Freedman,[41] Malekahmadi and Yunesian,[42] health care waste resulting from human activities has been identified as the third largest known source of dioxin emissions, contributing to 10% of total environmental mercury emissions. Lee et al conducted a simulation of clinical scenarios involving the generation of medical waste to evaluate the impact of

Table 2 Safety Risk Characteristics of Medical Waste Recycling and Disposal

Potential Hazards of Health Care Waste	Potentially Hazardous Population	Potential Environmental Risks to Health
Infectious, genotoxic, contains toxic or dangerous chemicals or drugs, radioactive, sharp instruments	There is a potential risk to all individuals who come into contact with healthcare waste, including healthcare facility doctors, nurses, healthcare assistants, hospital maintenance personnel, patients, visitors, and workers involved in the sorting, collection, temporary storage, transportation, and centralized disposal of healthcare waste.	(1) Exposure to hazardous wastes such as mercury and expired medicines may cause respiratory and skin infections, etc. (2) Injuries caused by sharp instruments may often lead to infection of tetanus, hepatitis B and other diseases (3) Harmful gases such as methane and sulfide are released from the open storage of medical waste (4) Healthcare waste combustion releases toxic gases, such as dioxins and furans. (5) Improper disposal of healthcare wastes may contamine groundwater, surface water, and soil

medical waste bins on environmental pollution.[43] Ravindra et al quantified the emissions of various toxic and persistent air pollutants from biomedical waste incineration during the COVID-19 pandemic by assessing changes in the composition of biomedical waste generation compared to pre-pandemic levels.[44]

Between 15 and 35% of healthcare waste is hazardous waste, which can contain infectious materials, sharp objects, cytotoxic waste, etc. The potential risks associated with healthcare waste are diverse. The process from generation to disposal of medical waste can be roughly divided into five stages: generation, collection/separation, temporary storage, transport, and recycling. Each of these stages is very important and may pose a threat to human health, the environment, and sustainable development. The safety risks and environmental impacts of medical waste recycling and disposal are summarized in Table 2.

Cost-Effectiveness of Medical Waste Recycling and Disposal

In recent years, the output of medical waste is increasing rapidly in developed and developing countries. Given the exponential growth in the magnitude of medical waste and the ever-evolving disposal standards, cost constraints must be taken into account when considering the recycling and disposal of medical waste.

According to the forecast, the global cost of healthcare waste management will grow at a rate of about 6.8%, and is expected to grow from US $12.5 billion in 2022 to US $23.7 billion in 2032.[45] As the world's largest producer of healthcare waste, the United States alone generates more than 3.5 million tons of healthcare waste annually, with an average disposal cost of US $790 per ton.[46] Based on Life Cycle Cost (LCC) analysis, Martinez-Sanchez et al used a bottom-up calculation method to analyze the cost of key technologies involved in medical waste disposal.[47] Liu et al focused on assessing the cost and benefit of implementing a plastic medical waste recycling system, developed a benchmark model for evaluating the benefits of decision-making related to plastic medical waste recycling in China in 2019, and conducted a sensitivity analysis to examine the impact of relevant parameters on the efficiency of the recycling system.[48] Vaccari et al investigated the association between the trend of medical waste production and the costs associated with medical waste management in Italy. They discovered a positive correlation between the percentage of healthcare expenditure in GDP and the quantity of generated medical waste, while also observing that the amount and type of medical waste were influenced by departmental characteristics and clinical manifestations.[49] Su and Chen used an environmental Kuznets curve model to test whether there is an environmental Kuznets curve in the generation and illegal disposal of medical waste, and found that both the generation and illegal disposal of medical waste are positively affected by medical capacity, but negatively affected by medical policies.[50] Ansari et al evaluated the economic and environmental performance indicators of hospital solid waste in developing countries.[51] Sun et al conducted an analysis on the

issues and causes related to the charging policy for centralized disposal of medical waste, proposing enhancements to the charging strategy for such disposal.[52]

In summary, both domestic and international scholars have examined the safety risks, environmental impacts, and cost-effectiveness of medical waste recycling and disposal from various perspectives, emphasizing the significance of secure and efficient management of medical waste. However, their focus has primarily been on specific aspects or processes within medical waste treatment or management. The interactive effects of multiple constraints can be considered to analyze the system characteristics of medical waste recycling and disposal. To further reveal the multi-dimensional characteristics of the whole process of medical waste recycling and disposal.

Related Research on the Management and Evaluation of Medical Waste Recycling and Disposal Process

The medical waste generated by healthcare facilities is typically initially collected and temporarily stored within these institutions before being transported to specialized waste disposal facilities for safe and environmentally-friendly treatment. In the whole process of medical waste collection, storage, transportation and disposal, it is necessary to consider its multiple impacts and potential risks on people, the environment and society. Therefore, it is necessary to optimize the management and control of medical waste recycling and disposal, and comprehensively evaluate the recycling and disposal process and effect. Scholars at home and abroad have carried out relevant researches on the design of medical waste recycling reverse logistics network, recycling and disposal management system, and recycling and disposal evaluation methods.

Design of Reverse Logistics Network for Medical Waste Recycling

Reverse logistics is a process that starts from consumers or any other node and flows up the supply chain. Its main purpose is environmental protection and raw material recycling. At present, many scholars have carried out research on the design of reverse logistics network for medical waste recycling.[53,54] The reverse logistics of medical waste recycling entails a meticulously planned and designed reverse network structure that encompasses the entire process of medical waste management, from generation to disposal. This comprehensive framework primarily involves strategic planning and design of pivotal nodes including collection points, collection centers, testing centers, and disposal centers.

Liu et al proposed an intuitive fuzzy set and VIKOR method to evaluate the capacity of medical waste recycling channels during COVID-19 pandemic.[55] Based on the combination of Memetic Algorithm (MA) and Tabu Search (TS), Asgari et al proposed a multi-objective hazardous waste siting-routing problem (LRP) model considering various types of waste and several treatment technologies. In order to design a green reverse network for medical waste management.[56] Govindan et al proposed a circular economy transition model based on multi-project, multi-period, dual-objective mixed integer linear programming. Queuing theory was used to manage the waiting time of trucks transporting infectious medical waste.[57] Huo and Guo considered the uncertainty of the amount of medical waste recycling, and built a multi-objective and multi-period sustainable medical waste recycling network model in a fuzzy environment with the goals of minimizing economic cost, minimizing environmental impact, and maximizing social benefits.[58] Linfati et al proposed a mixed integer linear programming model for optimizing customer scheduling and route allocation in medical waste collection, emphasizing the importance of minimizing infection risks by optimizing the path from collection to disposal center.[59] Eren and Tuzkaya used safety scores to determine the safest and shortest transportation routes for medical waste transportation vehicles.[60] He and Liu constructed a three-layer recycling network optimization model with the goal of minimizing the total recycling cost (transit station fixed cost, receiving cost, and transit cost).[61] Gan et al used relevant theories and methods of management science to optimize the collection and transportation system and disposal system in the reverse logistics system of infectious medical waste.[62] Karimi et al developed a reverse logistics network to manage hazardous medical waste, considering the uncertainties in the supply chain network for such waste.[63]

The research on reverse logistics network design of medical waste recycling mainly aims at minimizing economic cost, minimizing environmental impact, minimizing time, and maximizing social benefits. Different algorithms such as genetic algorithm and ant colony algorithm are used to optimize the location of recycling points and path planning.

Medical Waste Recycling and Disposal Management System

The whole process of safe and efficient recycling and disposal of medical waste is a complex management project, which requires scientific and systematic management methods to support its optimized operation.

Zhu et al investigated the stochastic failure of network nodes in the transportation of infectious medical waste and proposed a robust modeling approach for transportation network resilience based on network leakage and risk assessment. The network robustness was defined from the perspective of transportation time risk, and the network connectivity rate model including risk was constructed.[64] Aiming at the sustainable siting-allocation problem of medical waste management, Joneghani et al proposed a multi-objective mixed integer linear programming model under uncertainty, encompassing medical waste storage, purification, recycling, incineration, and disposal facilities within a sustainable network.[65] Dong and Li developed a multi-objective mixed integer programming model to optimize the medical waste management system network, considering multiple time periods, diverse types of medical wastes, treatment technologies, recycling options, while simultaneously minimizing both total cost and total risk.[66] Bagheri et al proposed a planar graph-based cluster-routing approach to optimize the collection of Medical Solid Wastes, incorporating Geospatial Information System (GIS) data.[67] Aung et al analyzed the medical waste management system in Myanmar by using multi-attribute decision making method.[68] Mor et al used questionnaires and descriptive statistics to analyze the perceptions of waste management teams, doctors, nurses, laboratory technicians, and waste handlers on biomedical waste generation, legislation, and management in medical institutions in Northwest Delhi, India.[69] Akkajit et al used a stratified random sampling method to evaluate the knowledge, attitudes, and practices of healthcare workers in clinics in Phuket province, southern Thailand, and concluded that healthcare workers' knowledge and practices in healthcare waste disposal are essential to implement effective healthcare waste management.[70] From the perspective of environmental behavior theory, Nie constructed a system dynamics model for the reduction behavior of rural medical waste recycling and treatment.[71] Jerie et al emphasized the potential environmental health risks associated with inadequate solid waste management in rural hospitals and proposed a hierarchical model to achieve sustainable practices in this area.[72] Chen et al utilized the COVID-19 outbreak in Wuhan as a case study to investigate the influence of the medical waste management system on epidemic response.[73] Barua and Hossain studied the role of healthcare waste management systems in the COVID-19 outbreak in Bangladesh.[74] Wang et al analyzed the problems found in the development of medical waste disposal in China and put forward countermeasures and suggestions.[75]

Evaluation Methods of Medical Waste Recycling and Disposal

Considering the systematic nature of medical waste recycling and disposal, as well as the imperative for enhanced management and control, it becomes essential to establish a corresponding evaluation index system encompassing the entire process of medical waste recycling and disposal for comprehensive assessment.

Celik et al took Turkey as an example and used the intuitionistic fuzzy multi-criteria decision-making method to deal with the high uncertainty in the whole process evaluation of medical waste recycling and disposal.[76] Liu et al established a Pythagorean fuzzy combination compromise solution framework for the evaluation of medical waste disposal technologies.[77] Koo and Jeong used life cycle cost and Delphi method to compare four medical waste disposal methods (incineration, heat recovery incineration, steam sterilization, and microwave disinfection) in South Korea. The results showed that heat recovery incineration was the best disposal scheme.[78] Nie and Wu used questionnaire survey, interview, and comparative analysis to evaluate the current situation of rural medical waste management in China, and pointed out that rural medical waste management is weak in classification, unified recycling, disposal, relevant personnel protection measures, regulations, and policy awareness.[79] Hong et al used LCC and LCA methods to quantify the environmental and economic impacts of three medical waste disposal options (ie, pyrolysis, steam sterilization, and chemical disinfection).[80] Narayanamoorthy et al evaluated the bio-medical waste disposal based on comprehensive weighting method and hesitant fuzzy MOOSRA, and the results showed that autoclaving is the best choice for bio-medical waste treatment.[81] Korkut estimated the scale and trend of medical waste in Istanbul, Turkey, using 18 years of historical data.[82] Xu et al, using analytic hierarchy process, evaluated and screened the five medical waste disposal technologies used in China, namely rotary kiln incineration, pyrolysis, high temperature steam sterilization, chemical disinfection and

microwave disinfection. The results showed that high temperature steam sterilization had the best comprehensive benefits in four aspects of society, environment, technology and economy.[83] Santo et al conducted a comparative analysis of the merits and demerits associated with incineration, pyrolysis/gasification, autoclave, microwave treatment, and other technologies employed for managing the substantial volume of medical waste generated during the COVID-19 pandemic. Additionally, they proposed plasma technology as a viable alternative for medical waste treatment.[84] Li et al proposed a novel integrated system aimed at optimizing the process of medical waste treatment and pyrolysis sludge.[85]

Domestic and foreign scholars have made rich research progress in the management and evaluation of medical waste recycling and disposal process. The entire process of medical waste management and control, spanning from production to disposal, can be further integrated with the new generation of information technology. By leveraging data-driven comprehensive evaluation and analysis, the safety risk management and control strategy for medical waste recycling and disposal can be enhanced.

Research on Risk Assessment of Medical Waste Disposal for Infectious Diseases

Medical waste from infectious diseases has many special features compared with general medical waste. Therefore, the whole-process safe disposal and safety risk assessment of medical waste from infectious diseases are different from general medical waste. Medical wastes generated in the process of diagnosis and treatment of infectious diseases are all infectious wastes with high spatial pollution, latent and acute virus transmission. If improperly disposed, they are easy to cause the secondary transmission of infectious viruses, resulting in environmental pollution and serious harm to human health. Domestic and foreign scholars have carried out some research work on the analysis of the characteristics of medical waste disposal for infectious diseases and the evaluation indicators of medical waste disposal for infectious diseases. In view of the COVID-19 epidemic, scholars have also paid attention to the evaluation of medical waste disposal.

Analysis of Characteristics of Medical Waste Disposal for Infectious Diseases

The whole-process safe disposal of medical waste from infectious diseases requires an in-depth analysis and understanding of its main characteristics. Zhou et al pointed out that medical waste during a major epidemic has the characteristics of a large increase in a short period of time, stronger infectivity, and concentrated sources. Under normal conditions, the collection, transfer, and disposal capacity of medical waste cannot meet the demand.[86] Xu and Wei pointed out the problems of sudden onset, insufficient capacity, and difficulty in medical waste treatment under the background of COVID-19 epidemic.[87] Zhang et al analyzed the "closed-loop" collection, storage, and transportation mode of medical waste in Shanghai Public Health Clinical Center during the epidemic of infectious diseases, as well as the technological characteristics of the harmless treatment of gasification rotary kiln. They held that the "closed-loop" management of medical waste is an effective means to deal with infectious diseases and realize the safe, safe, timely, and efficient disposal of medical waste.[88] Klemeš et al evaluated the life-cycle environmental impacts of various personal protective plastic products during the COVID-19 pandemic, and discussed the main challenges of medical waste management during and after the epidemic of infectious diseases.[89] In the context of the COVID-19 pandemic in Nigeria, Oruonye and Ahmed investigated the specialized equipment and environmental prerequisites for managing healthcare waste from highly infectious diseases.[90] Bin et al conducted a study on medical waste types and management across 50 medical institutions in Chongqing, revealing that tertiary hospitals exhibited relatively standardized medical waste management practices, while primary healthcare facilities such as clinics and village clinics faced numerous challenges.[91]

Construction of Evaluation Indicators for Medical Waste Disposal of Infectious Diseases

The unique nature of medical waste disposal for infectious diseases necessitates the consideration of specific factors and indicators in constructing its evaluation index system. Li et al focused on standardizing the collection and transportation

of infectious medical waste, identifying that the total population and transfer capacity of waste transfer facilities are the two primary influencing factors for selecting a collection and transportation system in medium to high-risk areas.[92] Singh et al pointed out that the comprehensive disposal mode combining centralized disposal with on-site disposal and the automatic treatment technology based on the Internet of things are the successful experiences of Wuhan in coping with the disposal of medical waste during the COVID-19 epidemic.[93] Ilyas et al analyzed the various physical and chemical treatment steps of medical waste disposal during COVID-19 epidemic and other infectious diseases, and discussed the application of different disinfection techniques.[94] Nzediegwu and Chang focused on the rapid growth of medical waste management in developing countries in the face of COVID-19 and other infectious diseases.[95] Su et al highlighted that China has implemented a comprehensive, refined, and standardized system for the disposal of infectious medical waste in response to the COVID-19 epidemic. Moreover, they have established a treatment mechanism that integrates centralized disposal centers with mobile equipment.[96] Taking Istanbul as an example, Eren and Tuzkaya established an occupational health and safety oriented medical waste evaluation index system for infectious diseases.[97] Kalantary et al evaluated the medical waste management of five hospitals in Iran during the COVID-19 epidemic, focusing on the production, composition, and management of medical waste during the COVID-19 epidemic.[98]

Safety Assessment of Medical Waste Disposal Amidst the COVID-19 Pandemic

The COVID-19 pandemic is a sudden major public health event, which has brought a huge impact on the global medical and health system and medical and health management. The assessment of medical waste disposal during the COVID-19 pandemic has garnered attention from scholars both domestically and internationally.[99,100] Zhao et al used the life cycle assessment method to identify and analyze three mobile disposal scenarios (incineration vehicles, mobile steam, and microwave sterilization equipment) in the COVID-19 epidemic, and evaluated the key factors of their environmental impact.[101] Tang et al established an integrated framework combining Bayesian network and fully explanatory structural model for the risk assessment of medical waste transportation during the COVID-19 epidemic.[102] Li et al constructed a two-stage hybrid dynamic method to predict the amount of medical waste generated during the COVID-19 epidemic, and to support the transportation network optimization between hospitals and medical waste treatment centers.[103] Maderuelo-Sanz et al studied the feasibility of recycling and reuse surgical or medical disposable masks into new products or applications.[104] Tirkolaee et al employed a sustainable multi-trip location-path planning approach with consideration of time windows, service priority, and system budget constraints to assess the medical waste disposal situation during the COVID-19 pandemic.[105] Thind et al analyzed the emission of toxic pollutants from incineration of medical waste in India during the COVID-19 pandemic, and evaluated the impact of increased emissions on health.[106] To minimize both costs and risks, Govindan et al designed a two-objective mixed integer linear programming model to evaluate the impact of medical waste on community population health and ecological environment damage during the COVID-19 epidemic.[107] Nosrati-Abarghooee et al employed the concepts of pandemic disruption, capacity level, complete coverage, treatment technology, and demographic risk to develop a reverse logistics network for managing medical waste amidst uncertainty and pandemic interference.[108] Tushar et al proposed an effective and secure system for medical waste management by integrating the best-worst approach, explanatory structural modeling, and cross-influence matrix multiplication applied to classification.[109] Calis Boyaci and Sisman employed a geographic information systems-based Pythagorean fuzzy decision analysis to determine optimal locations for the disposal of face masks and gloves waste boxes during the COVID-19 pandemic in Samsun city, Turkey.[110] Wu et al proposed an innovative technology for collaborative disposal of medical waste in cement plants, namely a novel system integrating plasma gasification, gas turbine, and the organic Rankine cycle with cement plants.[111] Kumari et al proposed a highly efficient, straightforward, and environmentally friendly approach for the conversion of discarded medical waste, such as disposable syringes, gloves, and face masks, into fluorescent carbon dots with optimized optical and emission characteristics.[112]

The COVID-19 pandemic has led to a significant surge in the generation of medical waste across nations worldwide. Before the COVID-19 pandemic, developed countries had relatively complete laws, regulations, disposal strategies and countermeasures.[99] However, the sudden and unpredictable nature of infectious diseases, coupled with the complexity involved in their management and disposal, renders medical waste generated in developed countries susceptible to space pollution, acute infection, and latent infection. Inadequate recycling or improper disposal practices could potentially

transform it into a novel source for virus transmission (PRC, 2020). As a result, the further spread of infectious diseases has brought great challenges to countries around the world.

Especially in developing countries, due to economic development, health status, insufficient training, limited cognitive level and other factors,[113–115] medical systems in many places are on the verge of collapse. With limited resources, many patients cannot be treated in time, and medical waste cannot be disposed of in time, leading to people's fear of the COVID-19 epidemic to a certain extent.[116] In addition, there are differences in the generation patterns of medical waste between different countries and regions. However, the timely recycling and safe disposal of infectious medical waste constitute a crucial aspect in the management of infectious diseases.

Risk Management Pertaining to Recycling and Disposal of Medical Waste Associated with Major Infectious Diseases

Characteristics and Challenges

Researchers have conducted a comprehensive analysis of the safety risks, environmental impacts, cost-effectiveness, recovery pathways, and management systems associated with medical waste recycling and disposal from diverse perspectives and employing various methodologies. Additionally, pertinent research findings pertaining to the assessment of infectious disease-related medical waste disposal are also available. However, compared with general medical waste, medical waste generated by major infectious disease outbreaks has many new characteristics and faces many new challenges in its safe disposal process, mainly reflected in the following aspects:

(1) The virus infectivity of major infectious diseases is stronger, and the safety requirements of medical waste disposal are higher. Major infectious disease outbreaks are often highly contagious, and the virus can survive and spread on medical waste. For example, SARS-CoV-2 can survive on medical waste such as masks for up to 7 days in the early stage. The safety requirements for the disposal of medical waste resulting from major infectious diseases are exceptionally stringent, with disposal means, methods, and processes subject to increasingly rigorous physical, environmental, and spatiotemporal constraints.

(2) The outbreaks of major infectious diseases are usually sudden, resulting in insufficient safe disposal conditions for medical wastes. The outbreak of major infectious diseases is characterized by obvious suddenness, and the emergence and spread of the virus are highly spatio-temporal random. Public health events caused by major infectious diseases have a great impact on the normal operation of economy and society, and there is often a lack of medical waste disposal plan and related resources, conditions, and capacity preparation for major infectious disease outbreaks, especially in the early stage of an outbreak.

(3) The rapid spread of major infectious diseases and the sudden increase of medical waste in a short period lead to huge disposal pressure. The short-term sharp increase in confirmed cases of major infectious diseases will bring great pressure on the medical service system, and also lead to a sharp increase in the amount of medical waste. Compared to general medical waste, the disposal burden of medical waste resulting from major infectious diseases is significantly amplified. For instance, during the COVID-19 epidemic, Wuhan generated a peak daily volume of 247 tons of medical waste, approximately six times higher than pre-epidemic levels.

(4) The entire process of disposing medical waste from major infectious diseases necessitates integration, and intelligent management is urgently required. Due to the high safety standards involved in the disposal of medical waste caused by major infectious diseases, it is crucial to ensure that all aspects of disposal are seamlessly connected and the whole process is organically coordinated. Therefore, integrated disposal of medical waste caused by major infectious diseases demands more sophistication, and data analysis-based intelligent management and control are urgently needed.

In response to the aforementioned challenges, there is an urgent necessity for a comprehensive, scientific, precise, efficient, objective, and in-depth evaluation of the safe disposal of medical waste throughout the entire process of major infectious diseases. This evaluation aims to gain a more timely and comprehensive understanding of the safe disposal

practices associated with major infectious diseases while effectively identifying various risks involved in the overall management of medical waste during epidemic outbreaks. By formulating accurate early warning systems and risk prevention strategies that address safety concerns related to medical waste throughout its entire lifecycle within major infectious disease scenarios, we can support sustained, stable, reliable closed-loop approaches for managing medical waste generated by these diseases and minimize the risk of epidemic spread and transmission.

Research Directions

With the extensive implementation of emerging information technologies, such as the Internet of Things, cloud computing, big data, and artificial intelligence in all stages of medical waste management including collection, storage, transportation, and disposal for major infectious diseases; a vast amount of structured data can be gathered from various stakeholders (doctors, patients, managers, operators), machines (transport vehicles, disposal machines, monitoring equipment, computing devices), objects (medical waste and related devices), as well as real-time status data on internal and external environments along with data on changes in status and interactive behaviors. It also has semi-structured and unstructured data, which is multi-modal, multi-granular, high-dimensional and mixed frequency data. Through the aggregation of data, ensemble learning, knowledge discovery, and decision fusion, it can facilitate the integration, coordination, and precise comprehensive evaluation of safe disposal methods for medical waste associated with major infectious diseases. This aims to enhance the reliability, timeliness, and cost-effectiveness of the entire process involved in safely disposing medical waste from major infectious diseases. Therefore, future research should focus on multi-dimensional analysis of the entire process involved in medical waste disposal related to major infectious diseases. This includes constructing evaluation indicators and designing evaluation methods for this whole-process disposal system as well as identifying risks and developing control strategies based on evaluations. The objective is to conduct a systematic and thorough investigation into risk assessment pertaining to safe disposal processes for medical waste associated with major infectious diseases (as depicted in Figure 5).

(1) Multi-dimensional characteristics analysis of whole-process disposal of medical waste from major infectious diseases

Compared with general medical waste disposal, medical waste from major infectious diseases has many special characteristics in terms of disposal requirements, disposal methods, risk control and environmental impacts. In-depth understanding, comprehensive description and accurate measurement of these characteristics are prerequisites and basic requirements for the whole-process safe disposal evaluation of medical waste from major infectious diseases. The integration of emerging information technologies such as Internet of Things, cloud computing, big data, and artificial intelligence into the entire process of equipment, operation, and management system for medical waste disposal in major infectious diseases has facilitated the accumulation of diverse and heterogeneous big data resources to support comprehensive risk assessment. By analyzing multidimensional characteristics encompassing data collection, cleansing, and quality improvement processes, a profound understanding of risk attributes associated with safe disposal throughout the entire medical waste lifecycle in major infectious diseases is achieved. This knowledge serves as a fundamental basis for establishing an evaluation methodology and devising risk control strategies for ensuring safe disposal practices.

(2) Construction of evaluation indicators and design of evaluation methods for the whole-process disposal of medical waste for major infectious diseases

On the one hand, traditional evaluation of medical waste disposal is hampered by such factors as the accessibility and availability of evaluation data, the accuracy and effectiveness of evaluation models, the dispersion of evaluation tasks, and the inconsistency of evaluation objectives, which often lead to subjectivity and inaccuracy of evaluation results. On the other hand, despite the increasing availability of data on medical waste disposal due to the widespread use of new generation information technology, obtaining satisfactory evaluation results remains challenging due to issues such as low data aggregation, weak ensemble learning ability, poor data quality, and limited model generalization capability. To

Figure 5 Future research ideas.

address these challenges, association fusion and integrated modeling based on multi-modal data throughout the entire process of medical waste disposal can facilitate more accurate extraction, representation, and construction of evaluation indicators for major infectious disease waste management. Furthermore, it can support the development of more effective comprehensive evaluation models and methods for managing medical waste associated with major infectious diseases.

(3) Risk identification and control strategies for the whole-process disposal of medical waste from major infectious diseases based on evaluation

The comprehensive safety assessment of the entire medical waste management process for major infectious diseases is imperative due to heightened safety requirements. On the one hand, the purpose of evaluation is to have a more comprehensive and in-depth understanding of the current disposal situation, identify the weak links and risk points of the current disposal, and then deal with all kinds of risks that may occur in each link in a timely, accurate and effective way. To facilitate risk assessment, prediction and early warning, as well as to mitigate potential risks and adverse impacts during the disposal of medical waste associated with major infectious diseases. On this basis, on the other hand, based on the comprehensive evaluation results, it is also to more effectively support the continuous improvement and strategy optimization of the whole process of safe disposal of medical waste from major infectious diseases. Especially with the rapid spread of major infectious diseases and virus mutation, under the changing disposal environment, conditions and needs, The continuous improvement and dynamic optimization of disposal strategies cannot be separated from the results of scientific comprehensive evaluation.

Conclusion

As a special type of waste with great harm to human health and ecological environment, medical waste recycling and disposal has many special requirements and strict norms. Currently, numerous countries have implemented a multitude of policies, regulations, and standards to establish a comprehensive system for the classification, collection, temporary storage, transportation, and centralized disposal of medical waste. This framework serves to enhance the secure management of diverse types of medical waste generated during routine healthcare practices. However, the management of medical waste generated by major infectious diseases, particularly those caused by newly emerging pathogens, is confronted with significant safety hazards throughout the entire process encompassing collection, storage, transportation, and disposal. Future research can combine multi-module data fusion, integrated deep learning, decision feature association, classification and clustering mining, abnormal diagnosis and identification, knowledge extraction and aggregation, etc., to effectively identify the multi-granular characteristics of the whole-process disposal of medical waste caused by major infectious diseases, and accurately establish the mapping relationship of the whole-process disposal. In this manner, a more timely and comprehensive understanding of the entire process of safe disposal of medical waste resulting from major infectious diseases can be achieved, facilitating the effective identification of various risks associated with the complete medical waste disposal process caused by major infectious diseases. Consequently, the safe disposal of medical waste stemming from major infectious diseases can be sustained, stable, reliable, and fully closed-looped to minimize the spread and transmission risk of epidemics. The information discussed in this paper holds significant reference value for the sustainable management of medical waste generated during potential emergencies related to infectious diseases in future scenarios.

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