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Review

Modernizing Medical Waste Management: Unleashing the Power of the Internet of Things (IoT)

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Abstract: The rapid technological advancements of modern times have brought about the need for an innovative and contemporary approach to medical waste management procedures. This arises from the inadequacy of conventional manual techniques in ensuring the safety of employees and the environment from infections. The increasing amount of waste produced each day can exacerbate the situation if no action is taken to address the current issue. This article presents a systematic review of the use of the Internet of Things (IoT) in medical waste management, utilizing the PRISMA approach. The adoption of the IoT in waste and medical waste monitoring is analyzed for its potential to enhance the overall waste monitoring procedure and contribute to achieving net-zero goals. Empirical evidence from studies conducted in the last five years has revealed the benefits of employing waste bin sensors as a digital surveillance tool for real-time waste status monitoring. While a few researchers have proposed the use of the IoT in medical waste monitoring, the application is currently limited to either monitoring storage facilities, waste transportation, or disposal processes, specifically. These limitations are discussed to understand the barriers that hinder further development. Among the selected analyzed studies are published articles and conference papers that offer solutions for addressing waste management issues and facilitating further development. This paper also aims to identify IoT technologies for monitoring waste and medical waste management. The digitalization of medical waste can ensure that the entire monitoring procedure is conducted directly and in real time. The collected data can be easily shared, and the condition of the waste can be updated periodically.

Keywords: medical waste management; IoT in waste management; contemporary waste monitoring; real-time waste status; net-zero goals; digitalization in waste management; IoT technologies in medical waste management

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1. Introduction

The generation of waste is a pervasive problem caused by human activities, animals, and various other living organisms. It is a consequence of the technologies employed by industries across different sectors. With the combined effects of population growth, industrialization, urbanization, and economic development, the global production of waste has experienced a substantial surge. If appropriate monitoring and control measures are not implemented, it is projected to increase by a staggering 70% by the year 2050 [1]. This claim is reinforced by Azyze et al. [2], who found evidence supporting the notion that social events like parades and concerts contribute significantly to the accumulation of waste in urban areas.

According to the Malaysian National Environment Health Action Plan (NEHAP), approximately 4 million tons of waste were generated in the country in 2019 alone. The issue of waste has become a pressing concern in numerous countries worldwide, primarily due to the rapid growth of the global population. It is crucial to address the challenges faced in waste management, particularly in African countries, as highlighted by Wawale et al. [3].

Urgent attention and action are required to effectively resolve this issue and mitigate its adverse impact on the environment and public health.

In 2014, European countries were reported to produce 72 million tons of hazardous waste, and this amount increased to 74 million tons in 2016 and 82 million tons in 2018 [4]. The United Kingdom itself had a total medical waste amounting to 150,852 tons in 2019/2020, which increased to 161,449 tons in 2020/2021 and to 176,883 tons in 2021/2022 [5].

The appropriate management of medical waste is critical to prevent potential risks to human health and the environment. Mishandling and the mismanagement of medical waste can result in numerous negative consequences, such as the loss of human lives, environmental damage, and financial burden [3]. In India, an alarming amount of medical waste, 18,000 tons, was reported between June and September 2019, highlighting the severity of the issue [6]. In 2009, a failure in the management system caused an outbreak of disease in Gujarat, infecting around 240 people [2]. The coronavirus pandemic has made medical waste more infectious, and this waste has the potential to claim lives [7]. According to the Ministry of Environment in South Korea, 295 tons of medical waste related to COVID-19 was generated in February 2020 [6,8]. Given the highly contagious nature of the pandemic, proper medical waste management is of utmost importance. Therefore, alongside general waste management, medical waste management must receive equal attention to ensure the safety and well-being of individuals and the environment.

Several nations have implemented diverse systems for managing medical waste, with some systems being more dependable than others. In certain countries, the manual handling of medical waste is still prevalent. The management of medical waste comprises four crucial stages: segregation, storage, transportation, and disposal. Although digitalization in waste management has become a prevalent practice, it is mostly implemented in municipal waste management rather than medical waste management.

Recently, the Republic of Korea has introduced radio frequency identification (RFID) bags to track waste, enabling waste to be traced as a product from the hospital to the disposal location [8]. By scanning the bag tags, waste contractors can conveniently exchange information about waste. This system is applied to both municipal and medical waste. However, in most other countries, medical waste is still managed manually with the assistance of portal website technology. The adoption of digitalization in medical waste management has been slow, but there is an increasing interest in this service, and more proposals are necessary to enhance the current systems.

This paper critically analyzed existing approaches and proposals to identify future research possibilities. Hence, the following research questions were formulated:

- RQ1: What is the current status of digitalization in waste management?
- RQ2: What are the existing challenges and barriers to the adoption of digitalization and IoT technologies in medical waste management?
- RQ3: How can IoT technologies contribute to achieving net-zero waste goals?

1.1. Challenges

If a system can resolve issues autonomously, it can effectively monitor the entire waste management process. These solutions would be particularly useful for scheduling waste maintenance, and their implementation could effectively reduce the need for manual human labor, instances of fraud in documentation, and communication gaps. Some notable system diagnostic challenges that have persisted over the past few decades include the following:

- The implementation of advisable procedures in waste management;
- Violation in the segregation of waste;
- The effect of improper waste management on humans and the environment;
- Minimizing manual labor in monitoring waste management;
- The digitalization of the entire process of waste management.

1.2. Contribution

This article aims to provide a structure and broad overview of digitalization used in monitoring medical waste management. Existing papers on the topic either focus on the application of digitalization proposed for medical waste or general municipal waste. This paper lists the proposed application techniques and the interest in waste management issues. However, many reviewed articles still need to provide discussions or information on the real-time data collected and the actual impact on waste management. The authors have noted that most of the digitalization implementations in this field are focused on weight measurement and bin status. Therefore, a key goal for future waste monitoring systems is to create a system that monitors entire waste management procedures. There is also a need for the development of digital solutions and appropriate benchmarking for the solution framework. Since these techniques often involve many parameters, it is sometimes unclear which architecture will work better for a particular application. Finally, it is helpful to outline the critical contribution of the paper:

- This paper provides a systematic literature review of waste management procedures recommended by the World Health Organization under the surveillance of the United Nations.
- This paper provides an overview of challenges in waste management and the frameworks in the proposed projects associated with successful implementation.
- This paper aims to facilitate a deeper understanding of application complexity and provide insights into suitable benchmarking practices. Additionally, it will present an evaluation of the implementation costs associated with the proposed architecture.

This article is organized as follows. Section 2 provides the research methodology used for the study, and Section 3 provides a theoretical background for the review. Section 4 presents the findings from the bibliometric analysis, and Section 5 discusses the results. The conclusion is drawn in Section 6.

2. Research Methodology

To achieve the objectives of this study, a comprehensive review of the existing literature on waste management systems was conducted. In this review, PRISMA techniques have been adopted. PRISMA, which stands for Preferred Reporting Items for Systematic Review and Meta-Analyses, has been widely adopted to enhance methodological transparency and facilitate research findings [9]. This technique enables the synthesis of existing knowledge in a field, enabling future research to identify its own priorities and evaluate past research theories [10]. Based on the guidelines, this review aims to gather insights into the current state of research, including major trends, significant works, and future directions in the field. The literature review focused on journal articles and conference papers related to waste management systems. A systematic search was performed using electronic databases, including Scopus, IEEE Xplorer, and Science Direct, covering the period from 2017 to 2022. The search terms used included “waste management,” “medical waste management,” and “monitoring waste.” Synonyms such as “clinical” or “healthcare” were also included to ensure comprehensive coverage. In addition to academic sources, relevant information from authoritative web pages was considered. The inclusion criteria for selecting articles are outlined in Table 1. It is worth noting that there is limited literature specifically addressing digitalization in medical waste management. Therefore, general waste management papers were included as references to understand the monitoring process. The paper filtration process is depicted in Figure 1.

In total, 38 published journal papers dedicated to general and medical waste management were identified and analyzed. Additionally, 7 conference papers were included to supplement the study of medical waste management systems. The review process also incorporated three books and 20 web pages. Among the selected articles, more than 85% focused on the segregation stage, while approximately 50% emphasized digitalization aspects such as waste weight and bin level monitoring.

Table 1. Inclusion and exclusion criteria of the review.

Inclusion	Exclusion
Published between 2017 and 2022.	Published in a language other than English.
Included a review of waste issues and monitoring management.	Published only as an abstract.
Included some proposed methods of digitalization of waste monitoring and management via the Internet of Things.	Published as editorials, commentary, or reports.
Included a proposal of either a framework, a demonstration, or a prototype approach for monitoring waste management.	

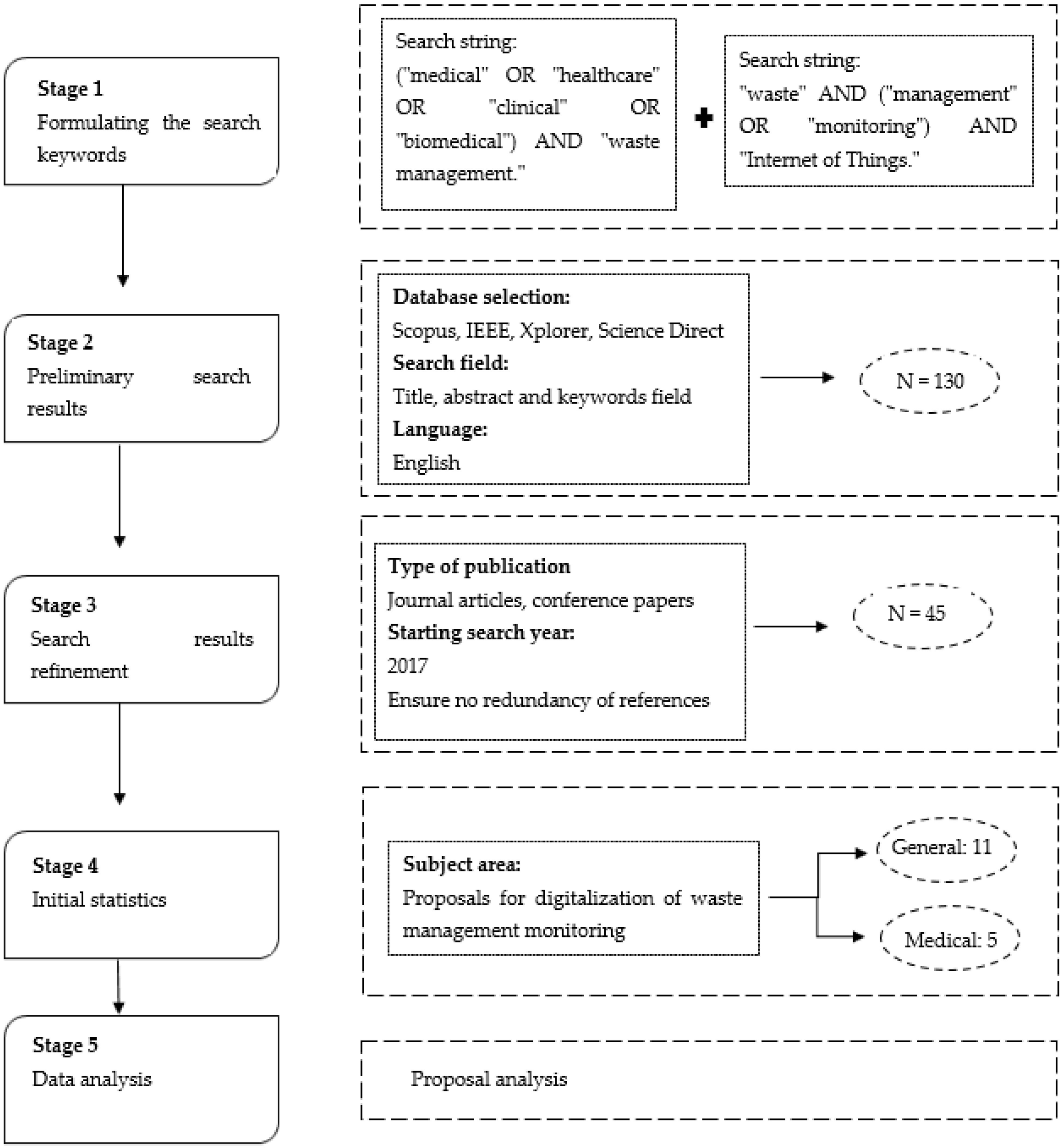

Figure 1. Review process.

This article provides readers with a comprehensive perspective on medical waste management practices over a span of seven years. The compilation of 38 journal papers, 7 conference papers, 3 books, and 20 web pages offers valuable insights into medical waste management systems. The focus of the literature predominantly centers around the segregation stage, with a significant emphasis on digitalization for monitoring waste weight and bin status.

3. Monitoring Medical Waste Management

Medical waste management monitoring involves more than just waste disposal; it encompasses various processes such as segregation, collection, transportation, storage, handling, and documentation. The ultimate goal of waste management is to ensure the safe handling and disposal of infectious or hazardous materials, protecting both humans and the environment. Despite advancements in waste management technologies, many systems still rely on manual labor. For instance, in medical waste management, collection workers empty waste bins every four hours, and the status of waste collection is recorded on bin documents shared with management at the end of the day. However, this manual approach is prone to disorganization and inefficiency and has even led to injuries among waste collectors. Furthermore, challenges persist in correctly segregating waste, highlighting the need for more sophisticated and automated waste management systems.

Typically, waste is only weighed at storage facilities before generating a consignment note for the transportation company. Monitoring storage conditions is often manual or neglected altogether. Waste is transported along designated routes, but the location of lorries is not consistently tracked, although RFID tags are used in some countries to facilitate access to disposal stations. Throughout the entire medical waste collection process, six copies of documents are exchanged among hospitals, storage facilities, transportation contractors, and disposal stations for each waste consignment [11,12].

In waste management, landfill dumping and open burning have been widely used worldwide as common, cost-effective methods of waste disposal, as highlighted by Nuzaimah [13]. However, the improper handling of waste can result in land, water, and air pollution, posing risks to animals, plants, and the entire food chain. The management of medical waste has faced significant challenges, and these challenges are worsened during global health crises such as the COVID-19 pandemic. The inadequate treatment and disposal of medical waste can contribute to the spread of infectious diseases and pose serious risks to medical and sanitation workers [14].

To ensure effective medical waste management, various stages must be followed, including waste segregation, collection, transportation, storage, handling, and documentation [6]. Different countries have developed their own strategies and processes for managing medical waste based on their priorities. The World Health Organization (WHO) has introduced basic techniques and good practices to guide waste disposal, emphasizing the importance of conducting assessments to determine the most suitable approach [15].

The Republic of Korea has long been concerned with the issue of medical waste and passed the Waste Management Act in 1999 [16]. From 2010 to 2018, medical waste in South Korea consistently increased, reaching 238,272 tons annually [17]. In 2020, during the pandemic, South Korea implemented stringent measures to treat all waste generated by patients with confirmed cases of COVID-19 as medical waste. These included disinfection, sealed discharge, and daily incineration. Yoon et al. [18] demonstrated that this treatment approach was applied to patients in hospitals as well as those in self-quarantine. Self-quarantined patients were required to seal all waste, including food waste, in dedicated medical bags and to contact health centers for proper disposal.

In Malaysia, waste management has been a significant focus, and guidelines have been in place since 1998. The Malaysian Ministry of Health collaborates with the Ministry of Environment to continually revise procedures and policies for better waste management. During the pandemic outbreaks, Malaysia implemented movement control orders (MCO) to control the spread of the virus, with varying case numbers reported [18,19]. Estonia has introduced the e-Estonia system to achieve its goal of recycling 55% of waste by 2025. The country has started by implementing a garbage bag tracking system and monitoring residents' recycling habits. In terms of medical waste management, Estonia has established two fully equipped centers in Kothla-Jarve and Slantsy Interregional Hospital, focusing on proper waste segregation, collection, intermediate storage, and transportation [20–22]. The government has invested in an autoclave ECODAS T100 for the safe disposal of hazardous medical waste [23].

India has experienced a significant annual increase in medical waste generation, with disposal being the predominant method of waste management [2,24]. Collection and transportation pose ongoing challenges in managing medical waste in the country. Programs aimed at enhancing healthcare workers' skills in waste management have been implemented, including the introduction of the analytical hierarchy process (AHP) technique [15]. Pakistan, as the fifth most populated country, produces approximately 48.5 tons of solid waste annually, with an increasing trend. In 2009, Pakistan produced 54,000 tons of trash daily, which was often dumped in low-level areas or burned [25]. The increasing volume of medical waste is a global concern, highlighting the importance of digitalization in monitoring and managing medical waste without posing new risks to disease spread.

Overall, addressing the challenges of waste management, especially medical waste, requires the adoption of efficient and sustainable approaches to protect public health and the environment.

3.1. Segregation

Waste segregation is widely recognized as the crucial initial step in improving waste management practices. It is the responsibility of all healthcare facilities to implement appropriate segregation procedures for all medical waste. Segregation should occur immediately at the point of waste generation, such as operation theaters, wards, laboratories, or retreatment centers, and can be performed by various medical staff, including doctors, nurses, scientists, and technicians. The World Health Organization (WHO) has classified medical waste into seven categories to facilitate effective segregation, storage, transportation, and processing. Mishandling medical waste can lead to the spread of infectious diseases like HIV, Hepatitis B and C, and bacterial infections that pose a threat to human life [26]. In Ethiopia, many healthcare facilities have hazardous waste proportions ranging from 21% to 70% and still face challenges in proper segregation. Similar issues of inadequate and improper segregation have been reported in Jordan [3]. The COVID-19 pandemic in 2019 has further increased the volume of waste and its infectious nature [7]. Table 2 provides guidance on the classification of medical waste for segregation purposes.

To support segregation efforts, color coding and labeling standards have been proposed by the WHO. These standards assist staff in quickly identifying and placing waste in the appropriate categories. Table 2 also references the recommended color codes and labels for waste bins. Sharps, infectious, and pathological waste are labeled with a biohazard symbol. These approaches not only facilitate waste segregation but also aid in waste's transport, storage, treatment, and, ultimately, disposal [24,27] However, frequently checking waste can be time consuming and may cause delays in transportation from hospitals.

The location of waste bins can also contribute to delays in waste management. The absence of collection status and bin location data hinders transport vehicles' ability to plan efficient routes for waste collection from nearby bins [28,29] Routing waste collection can be a strategy to minimize fuel consumption in waste management [28]. Failure to sort waste during collection can lead to resegregation, resulting in delays and the generation of leachate and gaseous emissions that contaminate the surrounding environment [30].

Table 2. Segregation categories of medical waste [27].

Waste	Definition	Color Code	Label
Sharp	Items that could cause cuts or puncture wounds, including needles, hypodermic needles, scalpels, other blades, knives, infusion sets, saws, broken glass, and pipettes.	Yellow	Marked “SHARP” with a biohazard symbol
Infectious	Material suspected to contain pathogens, including bacteria, viruses, parasites, or fungi.	Yellow	Biohazard symbol
Pathological	Human or animal tissues, organs, body parts, blood, and bodily fluids.	Yellow	Biohazard symbol
Pharmaceutical and Genotoxic	1. Expired, unused, split, and contaminated pharmaceutical products; prescribed and proprietary drugs or vaccines; and sera that are no longer required. 2. Hazardous, mutagenic, teratogenic, or carcinogenic medicine or drugs.	Brown	Hazard symbol
Chemical	Discarded solid, liquid, and gaseous chemicals.	Brown	Hazard symbol
Radioactive	Materials contaminated with radionuclides.	-	Radioactive symbol
General	Waste from hospitals without contact with infectious agents, hazardous chemicals, or radioactive substances and that does not constitute a sharp hazard.	Black	General waste

3.2. Storage

The WHO advises all healthcare facilities to collect medical waste daily and to consistently record information on waste bags and containers. This information is essential for the proper storage of waste before it is sent to processing facilities. A medical center may have both interim and central storage areas. Temporary storage could be a utility room used to store hazardous waste generated in medical areas. However, this waste must be transferred to primary storage by the end of the day. There are four distinct types of waste storage areas: (i) hazardous waste, (ii) infectious and sharp waste, (iii) chemical and pharmaceutical waste, and (iv) radioactive waste. Central storage should be separate from supply rooms and food preparation areas and have sealed or tiled floors and walls for easy disinfection.

According to WHO guidelines, infectious waste should not be stored for more than 72 h during winter and 48 h during summer. In warm climate countries, infectious waste should not be stored for more than 48 h in good conditions and 24 h during the hot season. Refrigeration is necessary for the extended storage of infectious waste, with temperatures maintained between 3 °C to 8 °C to prevent pathogen growth and gas formation [15]. Regular general waste is known to emit a toxic odor that can harm human respiration [31], which becomes a significant concern when the waste is infectious.

Pharmaceutical waste requires specific storage based on its characteristics and disposal requirements. Chemicals used in hospitals, such as iodine and hydrochloric acid, possess various properties such as flammability, corrosiveness, and explosiveness, which determine their storage and disposal methods. Similarly, genotoxic drugs, being highly toxic, require storage in designated locations equipped with liquid-proof or chemical-proof sumps. Radioactive waste poses a significant challenge in waste management due to its radioactive decay. According to Chartier et al. [16], it is recommended to store waste containing radioisotopes with a half-life of less than 90 days for a minimum duration of 10 times the half-life. Hospitals are responsible for decontaminating all infectious and radioactive waste before transferring it to designated storage facilities. To ensure proper waste management, it is crucial to maintain records of waste information, including intake and outtake dates; material safety data sheets; the types of waste stored; and the treatment methods employed. Regular weekly inspections are also recommended to ensure appropriate waste storage and management.

3.3. Transportation

Transporting waste is typically employed to transfer waste from storage facilities to the designated transportation company. Consignment notes should contain information about the waste transportation, including details about the transport vehicles, waste classes and sources, pick-up date, and destination [30]. When transporting waste offsite, it is important for the vehicles to follow precise protocols, choose suitable routes, and avoid populated areas, water catchment areas, and other environmentally sensitive locations.

In Korea, waste transport vehicles are equipped with closed loaded boxes maintained at 4 °C during transportation [8,17]. The Korean government imposes a maximum distance of 350 km or a four-hour journey for waste transportation from storage to processing facilities [17]. In Malaysia, only seven registered companies are licensed to transport waste [18]

3.4. Disposal Process and Treatment

Laboratory processes and treatment are crucial in reducing the potential hazards of medical waste and protecting the environment. The proper separation and collection of waste from the producers are essential to ensure effective disposal processes [2]. There are five main processes commonly used in medical waste disposal:

- Thermal treatment is a popular method for waste disposal. Low-heat thermal processes, such as microwave treatment, are sufficient to eliminate all pathogens, even those that cannot be combusted. This process can be carried out at temperatures ranging from 100 °C to 180 °C [15].
- Incineration is considered the most efficient method as it can handle large quantities of waste at once. It is recommended to be conducted under controlled operational conditions at temperatures between 1100 °C and 1600 °C [18]. All medical waste incinerators should adhere to air emission standards to minimize the potential for air pollution. However, incineration requires high maintenance costs and proper ash disposal, and the gas emissions resulting from the combustion of medical waste can have harmful effects on human health and the environment [25]. Consequently, some countries resort to backyard burning without proper monitoring.
- Chemical processes are often employed to disinfect or sterilize medical waste. Dissolving items in chlorine dioxide, sodium hypochlorite, peracetic acid, lime solution, ozone gas, or calcium oxide powder is a common practice to eliminate infectious bacteria from medical tools and equipment before disposal [24].
- Steam heat generated by autoclaves is commonly used for sterilization. Autoclaves can ethically and legally treat waste when sufficient time and temperature are applied. The Ethiopian government has acquired two high-technology autoclaves (T100) capable of treating up to 10–15 kg (100 L) of waste at a time, with a steam pressure of 3.8 bar and a temperature of 138 °C, followed by cooling. These machines were procured for the purpose of establishing centers for disposing hazardous medical waste in Kohtla-Jarve [32]. Malaysian health centers are advised to autoclave all clinical human waste and non-reusable general waste before incineration.
- Biological processes utilize enzymes to accelerate the degradation of organic waste containing pathogens, while mechanical techniques are employed to reduce waste volume. Mechanical methods include shredding, grinding, mixing, and compacting. Both processes contribute to enhancing the heat rate during incineration or any heat treatment. Some wastes are shredded prior to being placed in the autoclave machine to maximize space utilization [16].

The WHO does not specify the type of treatment recommended for medical waste. Each country is free to choose a suitable method. However, landfilling is not advised for medical waste disposal due to its potential harm to the environment. In Korea, the government permits only incineration as the final destination for medical waste, and the resulting ash residue is then landfilled. Chemical treatment, steam sterilization, and microwave treatment are also utilized for medical waste management in Korea [17]. Wawale et al. [3], in their article in Open Access, observed an increase in fertility problems due to medical waste. A case study conducted in Malaysia detected the occurrence of pharmaceutical waste in river water samples [33]. Monitoring the disposal process is necessary to ensure the proper handling of medical waste.

All countries have invested billions in managing medical waste, and the cost has been increasing over the years. The United Kingdom invested as much as GBP 58 377 267 in the 2018/2019 financial calendar, and this amount increased by 17% in the next term [5]. From this cost, over GBP 28 million is actually used to support the incineration process of medical waste, and this does not include the amount the UK government spends on maintenance, wages, and injury wages.

4. Digitalization of Waste Management Monitoring

Most developed and developing countries have already implemented medical waste management systems. Traditionally, before the advent of digitalization, Korea and Malaysia relied on documentation copies for consignment communication among waste generators, transportation contractors, and process occupiers. Hospitals would contact storage facilities and transportation contractors separately to manage the waste. In medical waste management, at least four stakeholders are involved: hospitals as waste producers, storage facilities, transportation contractors, and process occupiers. However, manual control fails to address the seamless communication among these stakeholders. Currently, all waste management stakeholders fill out six copies of documents, which are then submitted to one another. Improved stakeholder communication can help verify the waste status and prevent waste from proceeding to the next step if any issues arise at the current stage. Digitalization allows for efficient real-time data monitoring and may utilize rewards and penalties to enhance communication and reduce the risk of tampering and falsification [27].

In Korea, waste generation calculation using RFID has become more accurate compared to the past [17]. RFID waste bags are used for both general and medical waste, enabling the measurement and tracking of waste disposal. The vehicles transporting waste are white and labeled with a biohazard logo. Waste is scanned for generator information and then transported to process occupiers. Process occupiers can track the location of waste producers using RFID technology. Prior to any disposal process, CCTV cameras equipped with WiFi technology are used to detect any violations in waste segregation [34]. If a violation is captured, the process occupier will not proceed, and the waste will be returned to the generator.

In Malaysia, the digital waste management system called Electronic Schedule Waste Information (eSWIS) was adopted in early 2007. Waste generators can easily check the list of scheduled waste facilities along with license number information using the website. Kualiti Alam Sdn Bhd, located in Ladang Tanah Merah, is a landfill specifically used for medical waste disposal, and eleven storage facilities are licensed to store medical waste [35]. Using the website, waste generators can easily consign storage, transport, and treatment centers based on availability [36]. The system administers data regarding the date of each process, but real-time data monitoring is not currently tracked.

The Estonian government aspires to achieve total digital waste management and has prioritized waste reduction to prevent waste generation [37]. The government has started tracking waste similarly to how it tracks postage parcels, but this tracking system currently applies only to general municipal waste. Various digital platforms have been introduced to minimize waste generation, including those facilitating food donations. In terms of medical waste, the Estonian government has taken a step forward by building two high-technology medical waste disposal facilities, but these projects have not yet included any digital monitoring systems.

In India, a color-coded management system is employed for waste segregation, and vans are used to transport the waste to common biomedical waste treatment facilities (CBMWTF). These CBMWTFs, which receive the waste, are responsible for quantifying waste, determining the appropriate treatment for the waste, and record keeping. The facilities are authorized by a governing body for daily activities and are required to provide annual reports.

The main parameters that need to be monitored include waste classification, storage records and facilities, and the type and condition of the treatment process. Table 3 illustrates the comprehensive focus of each monitoring parameter.

Table 3. Review of the whole waste management procedure.

Type of Waste	Segregation and Collection	Storage Facilities	Transportation	Process and Treatment	Study
General	Waste level, status, and collection status	-	-	-	[2]
Medical	Waste level and status and bin location	Storage record	Route and Location	Facility location	[3]
Medical	Waste classification via image processing and robotic arm	-	-	-	[7]
Medical	Waste status, level, weight, and collection status.	-	-	-	[30]
General	Waste classification via waste moisture	-	-	-	[25]
General	Waste level	-	-	Process emissions	[26]
Medical	Waste classification via QR codes and waste weight	Waste weight	Waste weight	-	[28]
General	Bin location and waste collection status	-	-	-	[1]
General	Collection status	-	-	-	[29]
Radioactive	-	Storage record, amenities, and waste weight	-	-	[31]
General	Waste classification via waste moisture	-	-	-	[38]
General	Waste level	-	-	-	[39]
General	Waste status, waste level, and bin location.	-	-	-	[40]
General	Waste status, level, classification via moisture, and collection status	-	Route and Location	Facility location	[41]
General	Waste level	-	-	-	[42]
Solid waste	Waste level and status and collection status	-	-	-	[43]

4.1. Internet of Things in Waste Management Monitoring

The journal articles and conference papers were selected for reviewing the proposal to upgrade digitalization in waste management. Digitalization, using the Internet of Things, has been employed as a monitoring system with different focuses and benefits. Table 4 presents the advantages and limitations of the main references in monitoring waste management.

The digitalization of waste collection can benefit transportation companies by allowing them to track which bins are full and ready for collection or the status of emptied waste bins. This information can assist clinical workers and transportation companies in planning their collection routes. Waste status refers to an ultrasonic sensor connected to an intelligent bin that detects the presence of waste in the container. Waste status works in conjunction with the bin waste level function, in which the bin is programmed to display the amount of garbage inside. The percentage of waste visible from outside the bin helps workers plan and communicate with subsequent stages. These three parameters enable waste management via digitalization and reduce human involvement, but they do not directly assist in monitoring waste management. Central waste monitoring during the segregation and collection stage ensures that the same groups and categories segregate the waste.

Table 4. Review of techniques in digitalization of waste management.

Technique	Strengths	Limitations
Segregation		
Collection of waste	These systems may be able to facilitate the vehicle route planning, reduce collection time, and optimize fuel costs for the vehicles.	No information on waste violations is provided.
Waste status	These systems allow smart bins to detect the presence of waste.	
Bin location	Designated systems will allow transportation companies to detect the location of the bin and arrange collection routes.	
Waste level	Administration can be notified to arrange contracts for storage and transportation.	
Waste classification	Waste is classified according to humidity and odor.	No classification of waste according to the advised group of segregation. No notification is given if a violation of segregation happens.
Waste weight	Storage facilities and transportation are notified about the weight that the vehicle will transfer.	No information on waste violations is provided.
Storage requirement		
Storage record	Data of waste moving in and out of storage are being recorded.	-
Amenities	The temperature of the storage room is recorded and monitored according to the product's suitability.	-
Waste weight	Details information to avoid fraud and misuse of waste.	-
Transportation details		
Vehicle registration	Details information to avoid fraud and misuse of waste.	-
Route and location	Route taken by the vehicles and real-time waste location are monitored.	-
Waste weight	Details information to avoid fraud and misuse of waste.	-
Disposal treatment and process		
Type of process		No tracking of the type and condition of the process or treatment given to the waste.
Location	Details information to avoid fraud and misuse of waste.	
Process emission	The effect of the process on the environment is documented.	

Seven project reviews propose monitoring waste categories, although they only touch on segregation based on the humidity of the waste. A humidity sensor such as DHT11, DHT22, or FC-28 is integrated into a smart bin to validate the type of waste inserted [1,30,38]. None of these projects propose segregating waste into groups. Even reviews [2,6,27] that focus on medical waste are applicable only to municipal waste segregation. Mixing medical waste can be hazardous to humans and the environment, requiring human effort to resegregate in case of violations.

Monitoring the route and location of waste is crucial as it allows tracking the correct and suitable path taken by vehicles and the location of the disposal center. Recording data in and out is essential for the surveillance of the duration that waste spends in the facilities. The same method should be applied to transportation registration data. Additionally, the condition of storage facilities must be suitable to avoid chemical or microbial reactions.

Following the onset of the COVID-19 pandemic, digitalization may become an ideal option as it can minimize the chances of human intervention. Most of the procedures are maintained and monitored remotely. The amount of medical waste increased during the pandemic, and digitalization can help with the more efficient use of time. Malaysia has remotely monitored residents' movement by using a QR code mobile application, MySejahtera, and this seems very useful for tracking and tracing if there are any cluster outbreaks happening in the country [44]. All users will be required to check in and check out of each place they visit on a daily basis. In the event of an outbreak, individuals who are potentially infectious can be traced and will be requested to undergo checkups and quarantine, if necessary. The utilization of digitalized remote monitoring can also enhance the management of medical waste, providing an additional service that can be improved.

Disposal and treatment processes result in the emission of harmful gases and leachate. Monitoring the emission of these processes could be a foundation for further environmental preservation plans. Few reviews focus on the weight of waste. From the studies, none of them focus on the type and condition of processes and treatments advised by the WHO. The weight of the waste can be valuable as a record for monitoring the entire waste management process. This parameter is also relevant for communication when transferring waste from one stakeholder to another.

All the parameters focused on in the reviews are digitally integrated for their respective purposes. However, the studies only cover some of the procedures that stakeholders should monitor throughout waste management. Wawale et al. [3] focus on each of the four stages of the procedure using fuzzy classified integrated techniques, which can be used to assess the parameters of risk, environmental impact, biodegradability, and process cost.

Apart from that, the majority of the references suggest approaches to comprehend and address only specific aspects rather than the entire waste management procedure. In most instances, researchers focus on bin status and condition. While these two parameters are very important in maintaining proper waste collection from the bins, they do not encompass the monitoring of the complete waste management process. However, the World Health Organization (WHO) has emphasized the significance of information pertaining to waste segregation prior to collection, storage time, transportation routes, and procedures, considering each as a main factor in waste monitoring.

4.2. Internet of Things Systems

The Internet of Things can be easily understood as a means of intelligent communication with non-digital objects. It involves sensing, networking, and information processing, enabling cooperation between humans, objects, and services within three-layered networks without the need for human intervention [25,31]. Internet of Things services are reliable due to their integration with cloud data systems. Automation is advantageous for waste management monitoring systems as it reduces manual labor and streamlines operations. The Internet of Things empowers stakeholders to track real-time data and gain insights into the current status of waste.

Using smart bins, the IoT can significantly improve the accuracy of garbage collection compared to traditional methods [25]. This approach has a profound impact on our daily lives as it enhances our awareness of the environment via modernization. The three-layered networks of the Internet of Things comprise the perception, network, and application layers.

The application of machine learning and artificial intelligence could improve the stability of IoT systems. Deep learning ascended as one of the fastest developing regions of machine learning, which centers on attempting to imitate all the undertakings that an ordinary human brain can perform. In modeling a smart city's waste management, Mohammed Aarif et al. [45] discovered how to utilize deep learning on the proposed smart bin. The bin will be used to segregate the waste as biodegradable and non-biodegradable.

4.2.1. Sensors, Network, and Application

The perception layer of the Internet of Things comprises devices that directly communicate with objects. In most applications, systems utilize sensors and actuators. Research studies have identified various types of sensors and networks proposed for building such systems. The sensors and networks proposed in the reviewed works are listed in Table 5. In the context of waste monitoring, sensors are installed on the lid of the bins [1,25,28–31,38,40]. These sensors are connected to WiFi or Bluetooth, allowing for the transmission and processing of data collected by the sensors or actuators. The collected data is stored in the cloud and can be easily accessed to provide the necessary services.

Table 5. Devices and networks in reviewed work.

Sensor	Sensing	Transporter	Communication	Gateway	Service Platform	Study
GPS	Waste bin location	-	Not specified	Arduino	Not specified	[28]
DHT22	Waste moisture	-	WiFi	Arduino	ThingSpeak	[1]
GPS	Waste bin and lorry location	RFID	Not specified	Not specified	Not specified	[2]
Not specified		-	Not specified	Raspberry Pi	Not specified	[6]
Not specified		RFID	Not specified	Raspberry Pi	Not specified	[26]
HC-SR04	Ultrasonic sensor	MQTT publisher	WiFi/LoRa	MQTT802.11	Not specified	[29]
HC-SR04	Ultrasonic sensor	-	WiFi	Arduino	Not specified	[30]
FC-28	Moisture of waste					
HC-SR04	Ultrasonic sensor	RFID	LoRa	Not specified	Firebase	[25]
HX711	Weight					
TGS2600	Odor and gas emissions					
Not specified		QR code	Not specified	Not specified	Not specified	[31]
HC-SR04	Ultrasonic sensor	-	WiFi	Raspberry Pi	Not specified	[38]
DHT11	Waste moisture					
Not specified	Ultrasonic sensor	RFID	Not specified	MSP430	Not specified	[39]
Not specified		-	Zigbee	XBee	Not specified	[40]
GPS	Lorry location	-	Not specified	Not specified	Not specified	[41]
Not specified		-	WiFi	Adruino	ThingSpeak	[43]
HCRS-04	Ultrasonic sensor	-	WiFi	Adruino	Ubidots	[42]

Geospatial

Geospatial technology is a technology used to describe and analyze the geographic mapping of the Earth. It enables us to determine the precise location of humans, transportation, and other connected items. In modern waste management, geospatial technology is utilized for tracking transportation routes, vehicles, and waste bins. Remote sensing, geographic information systems (GIS), and Global Positioning Systems (GPS) are technologies employed for geospatial identification [41]. Remote sensing involves using imagery and data collected from space or airborne cameras and sensor platforms. It can provide detailed images up to one meter or smaller [46]. A GIS is an application system used for mapping and analyzing georeferenced data, while GPSs utilize a network to provide precise location information. Both GISs and GPSs allow for detailed geographic location analysis based on patterns or coordinates [46].

Based on the studies, GPS is commonly chosen for geospatial detection. It aids in tracking vehicles and waste bins by utilizing their longitude and latitude coordinates. Waste management systems can accurately monitor the exact location of vehicles and the routes taken for waste transportation. Drivers can easily locate waste bins during collection. The GPS is also found to support landfill and site selections in some other reviewed studies. Detailed functions of the GPS in waste management are provided in Table 6.

Moisture

The moisture content of waste is a crucial parameter in waste degradation. High moisture levels in waste can facilitate landfill bioreactors, where water is added to the waste to produce leachate [47]. In some reviewed studies, moisture detection is employed as part of waste segregation. This allows for informed decision-making regarding the final waste processing and opens up possibilities for recycling. A moisture sensor is installed in the waste bin to provide data to the smart bin, enabling the separation of waste into different categories. Typically, the categories are limited to dry and wet waste. Table 6 presents some studies that utilized moisture sensors.

The studies used different types of sensors, namely, DHT22, FC-28, and DHT11. Each sensor type has its own characteristics. Both DHT11 and DHT22 are low-cost sensors that operate at a power range of 3.5–5.5 V with 0.3 mA. However, DHT22 is more sensitive, capable of detecting moisture from 0% to 100%, while DHT11 detects moisture in the range of 20% to 90% [48]. FC-28 is typically used to detect soil moisture and can also collect moisture readings ranging from 0% to 100% [49]. DHT22 measures temperature too, and its measurement precision is higher than that of DHT11.

FC-28 is a moisture sensor commonly used in plant gardens by gardeners to measure soil humidity. This device collects data in both analog and digital formats. DHT11 and DHT22, on the other hand, are low-cost sensors that can easily connect to the Internet. Given that their humidity reading ranges are similar, FC-28 may be more suitable for leachate detection in landfills. DHT11 and DHT22 can be options for measuring waste humidity when placed in waste bins.

Measuring the humidity of waste aids the smart bin in categorizing it appropriately. In municipal waste, this method can be useful as the bins can segregate waste based on its humidity status, easily separating wet waste from dry waste. However, when it comes to medical waste, which is categorized into seven distinct categories, relying solely on humidity may not be sufficient for effective waste segregation.

Presence of Waste

In some areas, waste disposal may not be very active. To conserve power and enable the connectivity of the smart bin to the Internet, an ultrasonic sensor can be employed to detect the presence of waste. Ultrasonic waves travel faster than audible sound waves and can be reflected, making them useful for measuring the distance to an object. In some reviewed studies, ultrasonic sensors are used to gather data on waste levels in the bin. This information can assist management in planning waste collection and transportation. Table 6 provides an overview of studies that utilized moisture sensors. Among the reviewed proposals, the HC-SR04 ultrasonic sensor is commonly used. This sensor is cost-effective and operates on a 5 V direct current circuit. It requires a minimum current of 15 mA and can detect objects within a range of 2 to 400 cm with a measuring angle of 15° [50].

Weight

In most cases, the weight of waste has an impact on its size. Therefore, knowing the weight can be beneficial for storage, transportation, and disposal facilities. Storage facilities can allocate space accordingly, transportation can identify and prepare suitable vehicles for collection, and disposal facilities can use this information to approximate disposal efficiency. In their review, Hussain et al. [26] utilized the HX711 weight sensor to create a blockchain in medical waste management. The HX711 sensor operates within a voltage range of 2.6 V to 5 V and is capable of reading data within a temperature range of −40 to +85 °C. The data rate output falls within the range of 10–80 Samples Per Second (SPS) [51].

Air Contaminant

In monitoring the environmental impact of waste, it is beneficial to consider proposals for sensing waste odor and gas emissions. By collecting this data, researchers and governments can plan measures to control odors and manage environmental effects. For instance, in Korea, the collection of leachates and recording the odor of municipal waste are utilized in methane production for landfill power supply [52]. In one study, the TGS2600 gas sensor is suggested for this purpose [25]. The TGS2600 sensor operates with a voltage of 5 V and requires a minimum current of 42 mA. It can detect gas within the range of 1–30 ppm [53].

Table 6. A review of GPS in waste management.

Application	Sensor	Function	Limitation of Study	Study
Waste bin tracking	GPS	Tracking the exact location of waste bins during collection.	No real-time data sharing to any storage or processing facilities.	[1]
Waste bin and vehicle tracking	GPS	Communicate the precise location of the waste bins and activities of the vehicles.	No real-time data sharing to any storage or processing facilities.	[3]
Vehicle tracking	GPS	Communicate the precise activities of the vehicles.	No real-time data sharing to any storage or processing facilities.	[41]
Drive tracking	GPS	Communicate the activities of the drivers.	No real-time communication is presented.	[54]
Landfill selection	GPS	Integrating feasible locations for disposal.	No direct and real-time communication with the landfill management.	[46]
Bin status	DHT22	Monitoring the humidity inside the garbage bin to determine the released toxic odor.	No data sharing to storage, transportation, and disposal management.	[2]
Waste segregation	FC-28	Separate waste to dry and wet waste for disposal.	No data sharing to storage, transportation, and disposal management.	[25]
Waste segregation	DHT11	Separate waste to dry and wet waste for disposal.	No data sharing to storage, transportation, and disposal management.	[38]
Waste detection	HC-SR04	To detect the waste presence and connect to smart waste segregation.	Data on waste level and status are still presented manually.	[25]
Waste level detection	HC-SR04	To measure the waste level in the bin.	Data on waste status are still presented manually.	[26]
Waste level detection	HC-SR04	To measure the waste level in the bin and connect the data to the waste collector.		[29]
Waste and level detection	HC-SR04	To detect the waste presence and measure waste level.		[38]
Waste level detection	HC-SR04	To measure the waste level in the bin and connect to clouds and apps.		[42]

4.2.2. Technology Used in Monitoring Waste Proposals

In order to provide optimal service in waste monitoring using the Internet of Things, researchers have proposed several approaches. Data collected by sensors are typically connected to microcontrollers like Arduino Uno. Simple technologies such as RFID and QR codes are highly feasible and can be easily integrated with microcontrollers, RFID readers, and Raspberry Pis. Wawale et al. [3] suggested using RFID connected to the IoT via the fuzzy method to monitor waste management. Four questions are posed to the waste before any decision is made. The fuzzy method will ask these four questions to the scanned items before deciding to categorize them into any bins.

Wang et al. [28] proposed utilizing blockchain technology and the QR method to establish a robust contractual framework among stakeholders, with a focus on weighing the waste. This method can be highly beneficial as it enables stakeholders to track the waste throughout its entire journey.

Suvetha et al. [7] proposed image processing techniques to segregate medical waste. This advanced technology employs imaging to identify the type of waste and categorize it accordingly. It serves as an excellent method to prevent violations in waste segregation.

For radioactive waste management and the assessment of radioisotope activity, Park et al. [31] suggested deploying an IoT device on the radioactive container to collect humidity and temperature data. This device gathers real-time information on radioisotope activity and communicates with monitors using digital twin technology.

4.2.3. Data Transporting Device

Transporters are devices used to represent items and provide data. In monitoring the condition of radioactive materials in storage, each can is tagged with QR codes [31]. These QR codes help storekeepers easily identify radioactive materials for transportation and removal or in the case of any high-pressure issues. Another smart device proposed for use in smart waste studies is RFID. RFID is chosen to be mounted on the waste bin as a representative of waste data, including data regarding bin location, waste level, collection status, and waste weight.

4.2.4. Software Application Technology

A gateway device sits between the network and the application. Raspberry Pi, Arduino, and MQTT are well-known gateway tools used to transfer all collected data to the Internet. The size of the communication range in systems is determined by networking signals. According to our review of the literature, most projects choose to use WiFi for internet connectivity. Long-range communication (LorA) works faster and provides reliable real-time data. Zigbee, a short-range communication technology, is only proposed by Joshi et al. [40], who used it to transmit waste data from the bin to the collector. To enable data transfer and provide services to the user, a service platform is used. Table 7 highlights the differences between LorA, WiFi, and Zigbee.

Table 7. Difference between LoRa, WiFi, and Zigbee [55,56].

	LoRa	**WiFi**	**Zigbee**
Wireless network	Low-power wide area network (LPWAN)	Local area network (LAN)	Personal area network (PAN)
Operating band	433, 869, and 915 MHz	2.4 and 5 GHz	815 and 915 MHz
Data rate	50 kbps	11–54 Mbps	20, 40, 100, and 200 kbps
Bandwidth	<500 kHz	22 MHz	2 MHz
Transmission range	5 km (urban) and 10 km (rural)	100 m	100 m

The platform serves as a data store for storing all collected data from every sensor using transporter devices. On this platform, the data can be aggregated, visualized, and analyzed. ThingSpeak and Firebase are examples of platforms used to access data in waste monitoring. Table 8 provides the specifications of both platforms used in waste monitoring.

Table 8. Specification of ThingSpeak and Firebase platform [57].

ThingSpeak	Firebase
IoT developers store, visualize, and analyze live data streams on the cloud.	Mobile app developers design and execute their applications.
Collect the data privately on demand from third-party sources.	Data monitoring and troubleshooting using mobile apps.
Data can be transferred easily to MATLAB.	Data can be easily analyzed using Google Analytics.
Develop IoT systems without setting up servers or developing web software.	Locally synched with the database when the device is established.
Communicate data using third-party services and social media platforms.	Customers can easily sign in to check data using secure platforms like Google, Twitter, and Facebook.

5. Critique and Further Development

Medical waste has become a global issue, particularly with the rise of the COVID-19 pandemic. The increased use of personal protective equipment (PPE) has led to a surge in medical waste production, making traditional manual waste management methods inefficient. Delays and inefficiencies occur at various stages of waste management, and the initial step of waste segregation is time consuming. Digital technology has the potential to expedite waste management procedures and address these challenges.

However, the utilization of digital technology in waste management monitoring is currently limited. Existing solutions, such as website portals and RFID tags, may only cover certain aspects of waste tracking and lack standardized platforms for comprehensive waste management monitoring. The absence of a standardized platform results in the use of multiple websites and platforms throughout the waste management process.

This critique highlights several issues in medical waste management that need to be addressed:

1. Inadequate waste segregation: Insufficient attention to and the improper segregation of medical waste pose significant risks to the public and waste management workers. Manual segregation processes are time consuming and prone to errors. Research projects have focused on waste segregation, but it remains a pressing issue, with healthcare centers sometimes violating waste separation regulations.
2. The partial digitalization of waste management: While digitalization efforts have been made in some countries using QR codes and RFID, the current practice still relies on manual processes for waste separation and quantification. Real-time tracking, particularly for surveillance purposes, is lacking. Proper storage facilities, including monitoring humidity and duration, are crucial to prevent the environmental impact. Monitoring heat treatment procedures is also essential to ensure safe disposal.
3. The lack of a unified platform: Hospitals and medical facilities use different platforms for purchasing, administration, and waste monitoring. There is a need for a communication platform that connects manufacturing companies, hospital purchasing and inventory departments, waste generators, storage facilities, transportation contractors, and disposal process occupiers. Such a platform would facilitate accountability for waste generation and management.

Addressing these issues requires comprehensive digital solutions that encompass waste segregation, real-time tracking, proper storage monitoring, and a unified platform for communication and accountability among stakeholders in medical waste management.

6. Conclusions

The process of waste management monitoring is currently conducted manually, which presents challenges and consumes a significant amount of time, especially with the increasing daily waste production. In the case of medical waste, manual management exposes employees to infectious diseases, bacteria, and viruses. Although the digitalization of waste management is not a new concept, it has not been fully utilized to monitor the entire waste management process and provide accurate insights into the waste situation. For instance, while information about the manufacturing and usage of a box of facial masks is readily available, understanding the disposal process and how to properly dispose of masks is crucial. Digitalizing waste management monitoring procedures can ensure compliance with regulatory requirements.

Over the years, digitalization approaches with a focus on the Internet of Things (IoT) have been proposed to understand the characteristics of medical waste and establish communication channels with the waste to track its status and location. While these approaches are practical, digitalization can offer even more benefits by minimizing manual work, mitigating data fraud, and preventing the misuse of waste. As digitalization advances, it is essential for all stakeholders to actively participate in monitoring waste management procedures, including important measurements at every stage.

In the pursuit of achieving the goal of net-zero emissions by 2050, waste management can play a crucial role in transforming global emissions. Reuse and recycling, which are not new concepts, present significant opportunities for resource recovery. However, in industries such as the medical sector, the potential for waste to be integrated into the circular economy is limited due to the lack of specific data and information to unlock these opportunities. For example, medical equipment used in healthcare facilities could be reused and recycled if proper sterilization is ensured. Accurate data and information on sterilization treatments for medical needles can open avenues for manufacturers seeking stainless steel sources. Digitalization holds promise in waste monitoring, and with the exponential growth of technology, medical waste can benefit from advanced waste monitoring systems, contributing to a cleaner planet.

While the installation cost of RFID technology can be relatively high, it offers cost advantages in municipal waste management as it does not require specialized collection and categorization. In terms of operational costs, RFID tags and readers depend on the operation, while handling costs can be more efficient when waste is properly segregated into different groups. Implementing effective waste segregation not only prevents environmental damage but also streamlines certain processes, such as incineration, by sorting waste according to its composition. Comparatively, waste categories like electrical and electronic equipment waste (WEEE) may contain a higher proportion of hazardous materials that require proper disclosure.

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