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Waste 4.0: transforming medical waste management through digitalization and automated segregation

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Abstract
Medical waste management is a crucial issue due to its potential health risks to humans and harm to the environment. The World Health Organization (WHO) advises separating medical waste into seven groups based on its type. However, despite the implementation of color-coded bin bags, cases of missegregation still occur frequently, leading to injuries and spreading diseases. Infectious waste such as sharps, human tissue, and body parts are often found mixed in waste bins, posing a severe threat to waste employees. To address this issue, this paper proposes exploring the potential of digitalization in waste segregation. The literature on current segregation methods and technology applications is analysed and compared, and a framework for utilizing barcode tagging and scanning to ensure waste is correctly categorized is presented. The barcodes and scanner will be connected through a monitoring system, which can notify waste generators and collectors of misplacing or mixed waste. This digitalization system is expected to serve as a monitoring agent for segregating waste before it is collected from any health facilities. Additionally, the exchanged data from waste generator bins can inform collectors and other waste stakeholders about the waste's condition, potentially opening up opportunities for recycling companies to purchase used plastics or metals from hospital wastes. By implementing digitalization in medical waste management, waste segregation can improve, reduce the spread of diseases and injuries, and promote the recycling of hospital waste materials.

Keywords Digitalization in waste management · Internet of things · IoT in waste management · Contemporary waste monitoring · IoT in medical waste management · Medical waste · Waste management · Waste segregation

1 Introduction

Medical waste generated by healthcare facilities, such as hospitals, clinics, and laboratories, can be infectious due to its contact with patients, viruses, bacteria, and diseases. Failure to handle it correctly can quickly spread diseases such as Hepatitis B&C, HIV, and other bacterial infections through the waste [1]. In Japan, hospitals generate an average of 0.41 kg/bed/day of medical waste annually, while high-income countries can produce up to 11 kg/bed/day [2, 3]. Sharps, human tissues, body parts, and other infectious materials from healthcare facilities pose potential health threats and environmental risks [4]. With the global population increasing annually, the amount of waste can gradually increase over time or drastically during pandemics such as the one experienced during COVID-19. Researchers have recently explored ways to reduce waste production as it aligns with achieving the goals of Sustainability 2050. The SDGs for waste management

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aim to promote sustainable waste management that protects public health and the environment. It is essential to manage medical waste properly to minimize the risk of spreading diseases and ensure environmental protection, especially in high-income countries that generate significant amounts of waste.

Medical waste management involves four strategic procedures, namely segregation and collection, temporary storage before disposal, transportation, and disposal. Learning and implementing these procedures can help healthcare facilities develop a smooth-running medical waste management system. Segregation, the first and foremost step, helps maintain the correct procedure pathway for each type of waste, minimizing large loads of hazardous waste that is potentially hazardous to the environment and requires costly treatment processes and skilled manpower [5]. However, poor monitoring of medical waste management from the early stage may lead to several difficulties in the entire procedure. Since medical waste disposal is not a profit-making business, waste companies tend to violate waste disposal procedures to save costs [6]. Typically, waste generators dispose of medical waste at their working stations, which can pose potential health risks. As a result, colour-coded bins have been introduced based on waste categories to streamline the process and treatment. A solution must be developed to distinguish waste and eliminate the difficulty of waste segregation.

1.1 Limitations of the current segregation approach

Waste segregation is critical in healthcare facilities, but missegregation can still occur, even if segregation protocols have been in place for a long time. WHO has estimated that around 16 million injections are administered worldwide each year, and if the needles and syringes are not correctly disposed of, may risk injuries of medical staff, waste handlers, and waste collectors [2]. Sharp injuries, in particular, can increase the risk of virus spread, including HIV, hepatitis B and C, TB, diphtheria, malaria, syphilis, and brucellosis [7]. To prevent injuries or misuse, needles and syringes must be destroyed before they are placed in color-coded bags or containers [5].

600000 to 80000 needle stick and sharp injuries (NSSIs) have been reported in the USA, and at least 100,000 cases are reported in the UK every year [8]. Viruses and diseases such as HIV, hepatitis B, and hepatitis C can be infected by employees while working. 30% of hepatitis B, 1–3% of hepatitis C, and 0.3% of HIV cases were caused by inappropriate waste handling [9]. In Ethiopia, waste generation is reported to be unacceptably high due to poor segregation practices [10]. Many countries still dispose of medical waste together with domestic waste, posing significant health and environmental risks [11]. Innovative medical waste management strategies in India are unaffordable and uncontrollable, while low-income countries often fail to segregate hazardous and non-hazardous waste correctly.

In some cases, up to 75% of medical waste can be non-hazardous and suitable for reuse and recycling [6]. However, mis-segregation can result in a higher amount of hazardous waste for disposal [12]. Moreover, healthcare personnel are at risk of injuries during the collection and disposal of medical waste, particularly from needles, syringes, and other sharp objects. Injuries can transmit viruses and diseases, posing a significant threat to frontline healthcare workers.

Improper disposal of pharmaceutical and chemical waste can also negatively impact human health and the environment. A study found pharmaceutical substances in river water [13], which suggests that pharmaceutical or chemical waste is not being disposed of correctly. Such waste can contain various dangerous substances; physical absorption through the skin, inhalation, or ingestion can cause poisoning. Pharmaceuticals can also enter the environment through sewage systems and be found in groundwater, surface water, and soil.

1.2 Objective of the study

This paper aims to propose a method to apply digitalization to waste segregation. The current colour-coded approach is studied to gain motivation to approach digitalization. One of the best options to classify medical waste is to implement transporter tagging, which can be represented using barcodes, QR codes, or Radio Frequency Identification (RFID). This tagging is responsible for automatically assigning waste categories, making it easy to monitor any violation of segregation. In understanding the potential of the proposal, the following research questions are investigated:

1. What is the importance of waste segregation in the healthcare industry?
2. How is the current method used to monitor waste segregation?
3. How does the potential of digitalization help for adequate waste segregation?

Effective monitoring is essential to prevent segregation violations as the amount of medical waste increases. Hospital equipment and tools are proposed to be tagged with a barcode representing the waste categories. Face masks, gloves, or even bin bags will be provided with a barcode suitable for the usage and waste categories. The barcode can connect to a simple digitalization system of smart bins to identify the waste group. Users will need to scan the barcode tagged, and this system will connect to the correct waste bin and open the lid. This system is planned to able to notify the waste generators of the segregation condition of the waste. This notification can be shared with a loop of medical waste stakeholders for complete procedure monitoring, ensuring efficient and sustainable waste management.

This article is organized by starting with the Sect. 2 on providing the research contributions on digitalization proposals and approaches. Section 3 shows the methodological approach used for the study, and Sect. 4 presents the proposal techniques in digitalization. Finally, Sect. 5 discusses the proposal's impact on the medical waste industry.

2 Literature review

2.1 Segregation of waste

The COVID-19 pandemic has increased waste production in healthcare facilities. To prevent the spread of the virus, doctors, patients, and medical staff are required to wear personal protective equipment (PPE), resulting in a significant increase in the amount of waste generated. South Korea, for example, reported producing 20 tons of COVID-19-related waste daily during the pandemic, which was segregated according to their prior experience with SARS, MERS, and Ebola [14]. Globally, over two million personnel are exposed to the virus daily, making proper disposal of PPE crucial to prevent the spread of pathogens and viruses. Segregation is a crucial first step in effective waste management, and the use of colour-coded containers can help with proper waste separation. The World Health Organization (WHO) has classified the medical waste into seven different categories [15], with each category requiring different treatment and disposal methods, as illustrated in Fig. 1. Hazardous waste categories determine how waste should be stored, treated, and disposed of, and colour-coded systems are used to identify the appropriate category, as shown in Table 1.

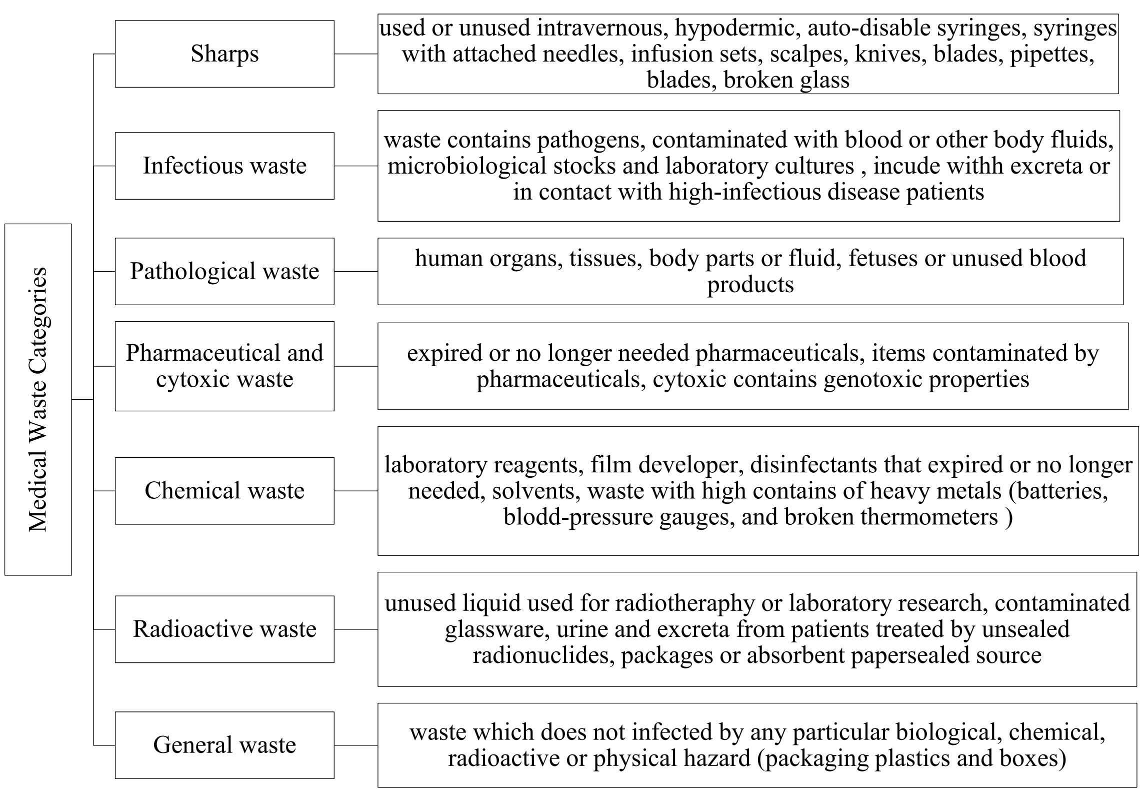

Fig. 1 Categories of medical waste according to World Health Organization (WHO) [12]

Table 1 Segregation colour coding and labels suggested by World Health Organization [12]

Category	Colour code	Label
Sharps	Yellow	marked 'SHARP' with a biohazard symbol
Infectious waste	Yellow	Biohazard symbol
Pathological	Yellow	Biohazard symbol
Pharmaceutical and genotoxic	Brown	Hazard symbol
Chemical waste	Brown	Hazard symbol
Radioactive waste	–	Radioactive symbol
General waste	Black	General waste

Waste segregation has been shown to benefit human health, the environment, the ecosystem, and resources globally. The United Kingdom updated the approaches to tackle medical waste segregation into nine groups. The new segregation aims to contribute to the net zero goals planned to be achieved by 2030 [16]. Waste categories proposed by the NHS in 2023 are shown in Table 2. This idea has been collaborated with the waste company Stericycle to come up with BioTrack tagging. This tagging function will provide transparency and accuracy of data from the point of collection through invoicing [17, 18]. This tagging is done to seven out of nine waste categories.

The tagging system proposed by the United Kingdom works to provide data on waste handling and disposal methods; however, the segregation works are still being done manually and still depend on human knowledge and ability. All categories of medical waste can be dangerous and thus require special treatment and disposal methods. High-income countries can produce up to nearly 11 kg of hazardous waste per bed per hospital daily, while low-income countries may produce up to 6 kg [2]. With this amount of waste produced daily, the missegregation of medical waste allowed the transfer of viruses and diseases to occur easily, leading to incorrect storage and disposal methods.

Incineration is a popular method for disposing of hazardous waste but can be costly. Incineration is a hygienic process where the garbage is bunted in a regulated environment, producing by-products of heat, ash, and waste gas [19]. The waste gas must be treated before being released into the environment, and the ash and heat can be used in power generation [2, 19–21]. Medical waste from healthcare facilities contains 75% non-hazardous waste, which can potentially be disposed of through other methods [22]. Separating non-hazardous waste can minimize the quantity of waste burned in incineration. Appropriate structures are available for handling each type of medical waste and monitoring the amount generated. If medical waste is disposed of in landfills without segregation and processing, harmful microorganisms, chemicals, and pharmaceuticals can contaminate soils and groundwater.

Despite guidelines for grouping and color-coded bins, missegregation issues still occur. Waste is still being segregated manually by staff without proper monitoring, and trained staff need to improve in separating waste into the correct bins. Mixed waste must be acknowledged and monitored, and waste collectors and transporters must be made aware of the correct methods for handling different types of medical waste. Waste operations are still largely manual, with bin collection occurring a few times daily and reports being made to supervisors through paper, files, and emails. Proper monitoring is needed to improve waste management and ensure the safety of healthcare staff and the public.

Table 2 Waste Colour Code and Classification in the United Kingdom [16–18]

Category	Colour-code	BioTrack Code	Minimum required treatment
Infectious A-	Yellow	HI	Incineration
Infectious B-	Orange	HT	Autoclave
Infectious sharps	Yellow	HS	Incineration
Anatomical	Red	HA	Incineration
Cytotoxic/cytostatic	Purple	HY	High-Temperature Incineration
Pharmaceutical	Blue	HP	Incineration
Offensive	Tiger (yellow & black striped)	HL	Landfill
Domestic (General)	Black		
Recycle	Clear		

2.2 The digitalization of waste segregation

Digitalization is still a relatively new concept in waste management, with many countries developing online platforms for cloud storage and communication. For example, waste generators may communicate with waste handlers for collection through online consignment [23, 24], and waste collector trucks can connect to waste bins to detect their location and plan their collection route [5]. Most digitalization efforts involve using sensors to provide information about the container, such as the status of bin collection, waste level, and weight of waste in the bin, which can help waste generators monitor bin conditions [5, 25–32]. Most digitalization ideas touch on the sentiment of communication, either to connect with the waste collector or to design the pick-up track, but not the segregation practice.

While some research has been presented on using sensors to separate waste based on moisture content, this method may not be ideal for medical waste with its diverse categories and the need for special treatment before disposal or different disposal methods [24, 33, 34]. In response, researchers have developed an autonomous land-moving robot to separate medical waste into four categories: infectious, hazardous, general, and radioactive waste [3]. Equipped with a 360-degree camera that processes images to determine waste categories, this robot is an example of how technology can automate waste segregation. Another approach involves using QR code tagging to separate medical waste [35], where all data related to the waste can be accessed by scanning the code. These ideas demonstrate how critical medical waste segregation is as the first step in managing the entire waste procedure. Automated waste sorting can be expensive, but the technology can increase accuracy and efficiency since much human error occurs when it is done manually [19]. The approach of digitalization existing in the industry or by the academical contribution is deeply arranged in Table 3.

These ideas of digitalization of waste segregation explore all the possibilities in many ways, including the usage of sensors, deep learning image processing, and mobile applications. However, these ideas are still limited. In prioritizing medical waste, which has at least seven different groups, the waste cannot be simply segregated without proper planning. A company that handles waste from the National Health Services (NHS) in the United Kingdom has come out with the idea to tag the bin with a barcode to ensure the waste procedures are arranged accordingly, but still the idea needs the waste generators to segregate the waste manually. In a simple word, some of the ideas are to digitize segregated waste, not to segregate the waste to groups. If automation approaches waste segregation, the amount of the waste and quality of the segregated waste can be improved. Imaging can be a good method for monitoring waste segregation, except this idea will need to be installed in every waste bin. Imaging before segregating will make the potential of infectious waste increase since the waste will be put together.

2.3 Waste disposal method

Waste should be treated and disposed of in the safest manner possible without posing any risk to humans or the environment. The World Health Organization (WHO) has recommended various methods for waste disposal, taking into consideration waste characteristics, technology capabilities, environmental and safety factors, and cost. Currently, landfill disposal and incineration are the most commonly used waste management strategies.

Chemical treatment processes are primarily used to disinfect waste or medical equipment and increase their exposure to chemical agents. In addition, heated stainless-steel tanks can digest tissues, pathological waste, anatomical parts, and animal carcasses [12]. Sharps, blood, or other body fluids can also be encapsulated within a solid matrix before disposal. Biological processes are done by using the enzymes to speed up the pathogens destruction of organic waste. Composting and vermiculture can help decompose placenta waste.

Mechanical processes, such as shredding, grinding, mixing, and compaction, reduce waste volume but cannot destroy pathogens. These three types of processes are not used for waste disposal directly; after the process, the waste still needs to be disposed of using landfill or incineration.

Incineration is a high-temperature combustion process that is the most preferred method of handling medical waste. It usually operates between 850 and 1600 °C. While incineration is agreed upon as the best way to dispose of waste, the process and maintenance can be expensive. Combustion through incineration, similar to open burning, will produce toxic emissions such as dioxins and furans [2], which may be carcinogenic.

Landfilling is considered the final destination for any waste. Non-hazardous waste, hazardous waste after treatment, and ashes from incineration usually end up in landfills. Many low-income countries prefer landfilling due to

Table 3 Approach and proposal of digitalization in segregating waste

Type of waste	Method	Strength	Limitation	Study
General	Segregating by humidity	Waste will automatically segregated with a humidity sensor	Limited to only two categories which are wet and dry waste Not suitable for medical waste	[33, 34, 36]
Medical	Colour-coded tag on the collection bin	The procedure of waste management can be arranged better with colour tags	Segregation on waste generation is still be done manually	[17]
Medical	Segregation using a mobile application	The lid of the bin will be connected to the mobile application and bin lid will be open once selected	The decision of selecting waste category is still be done manually	[37]
Medical	Segregating by humidity	Waste will automatically segregated with a humidity sensor	Limited to only two categories which are wet and dry waste Not suitable for medical waste	[38]
Medical	Imaging the waste for segregation	Waste will be segregated into the correct group	Mixing waste can increase the potential for contamination and infection	[3, 39, 40]
General/Medical/E-waste	Image surveillance waste bin	Mixed waste can be notified in a real-time	A camera must be installed in each of the waste bins	[41]

lower costs. However, landfilling may involve operational, administrative, and investment costs. Dumped waste may cause environmental issues, such as leachate flow and pests. Landfills need monitoring, management of ground settlement, compression of waste layers, slope monitoring, and leachate level management [42].

Alternative treatments such as recycling, reuse, and waste reduction can also be used to manage medical waste [43]. The medical industry has already started recycling various waste materials, such as placentas, which are separated and used as raw materials in some pharmaceutical products [20]. Medical waste also includes a lot of glass and plastics, which are suitable for recycling.

Waste will be disposed of based on the categories. Incineration can be the best option, but the cost of handling this disposal method will include many side costs, including emission filtration. The United Kingdom chose to treat clinical wastes by incineration to ensure the country's environmental quality. Offensive waste, the hospital equipment that is supposed to be clean from any infectious viruses, is landfilled. If there is any case of clinical waste mixed with the offensive, this can violate the landfilling process. Disposing of medical waste in landfills without proper segregation and processing will result in harmful microorganisms, chemicals, or pharmaceuticals entering soil and groundwater [2]. This will affect contamination to be happened.

2.4 Challenge of current methodology

Although the current waste segregation methodology is helpful in informing staff about the need for proper waste management, it has limitations that prevent effective waste management. Mishandling of medical waste is still occurring, leading to injuries and virus spread in some developing countries. Additionally, during the pandemic, improper disposal of PPE has contributed to the virus's spread.

To achieve sustainability goals and improve medical waste management, the current methodology must be enhanced in the following ways:

1. The current system of colour-coded bins is insufficient for monitoring waste conditions. Although the staff is informed about the need for proper waste segregation, there is no real-time monitoring of waste conditions or potential violations of segregation. As a result, an automated segregation system with proper segregation categories is needed.
2. Improper waste management contributes to the amount of hazardous waste, which requires costly and limited disposal technologies. Automating segregation can reduce the amount of hazardous waste submitted for incineration, resulting in fewer incineration cycles and lower costs [5].
3. Although digital segregation ideas such as QR tagging and image processing are sophisticated, they may not be specific enough for the seven categories of medical waste.

Enhancing waste segregation methodology will improve medical waste management, promote sustainable waste management practices, and reduce the negative impacts of improper waste disposal on humans and the environment.

2.5 Data transportation device

Transporters are devices that are used to represent items and provide data. In a case study on monitoring the radioactive condition in storage, each radioactive can was tagged with QR codes [44]. These QR codes help storekeepers track the radioactive waste for transporting, removing, or any high-pressure issues. QR codes are conventionally used in healthcare to share links in any exhibition or posters. During the pandemic in 2019–2022, QR codes were also widely used for movement monitoring of citizens [45].

Besides QR codes, the Radio Frequency Identification Device (RFID) is another smart device proposed for brilliant waste studies. RFID can be attached to the bin to represent waste data, including the bin location, level, collection status, and weight. RFID works as electromagnetic tracking and can be attached to any object. In the medical industry, RFID has been introduced through iMedBox to help monitor patients' medicine intake [46]. RFID is also popularly proposed for glucose concentration monitoring and patients in ward activities [47, 48].

In South Korea's municipal waste management, all citizens are required to use RFID waste bags sold in convenience stores to dispose of their waste [49]. The waste service charge is accounted for by the weight of the RFID bags, which the bin measures. This approach has been effective in encouraging citizens to segregate their waste and reduce the amount of waste that needs to be sent for disposal.

Barcodes, QR codes and RFID are typically transporters for conveying massive amounts of data into a small format. They offer cost-effective, speed, and labour savings among other benefits. Table 4 shows the similarities and differences of these three devices.

Each transporter type has its uses depending on the business and unique application. Choosing suitable transporters can depend on the factors essential to understanding the differences and unique features.

2.6 Internet of things in monitoring systems

The Internet of Things (IoT) has numerous benefits, particularly in monitoring and managing systems. In today's urbanisation, IoT has been applied in many areas, including smart homes. The IoT is a digitalization system consisting of three layers: perception, network, and application layers. The perception layer involves the use of sensors and actuators to collect data. The data is then stored in cloud storage, which can be filtered and analysed automatically. The network layer automatically transfers the data collected to the cloud using various networks such as Wi-Fi, Bluetooth, and Zigbee. Finally, the application layer provides a service to users based on the analysed data.

IoT is an efficient way of digitalizing as it provides real-time data accessible from any device, including smartphones and computers. With IoT, waste management can be improved by monitoring and managing waste in real-time, which can help reduce waste disposal costs, carbon emissions, and sustainable waste management practices.

No proper automation or digitalization is approached in medical waste management, especially in managing the waste. The entire procedure is still being managed manually until today. Developing countries such as Malaysia now use digitalization as a documentation system to send reports and waste status to the government authorities [52]. Tanzania started to have systems for applying KAIZEN in medical waste management [11]. However, they do not have applied any digitalization till now. Developed countries such as Korea use tracking and tracing of waste with RFID bags to manage solid waste [49]. The collected waste will be transported to the landfill, and other disposal treatment centres, and a CCTV camera will be checked before the process takes place on the waste.

3 Research methodology

The study adopted a qualitative review of the digitalization approach toward waste segregation. The waste categories, treatment, and disposal methods are studied to get a clear picture of the importance of waste segregation. To structure the diversity of the use in terms of literature, method, and materials are presented in the following the pattern of a search string *""medical" OR "healthcare" OR "clinical" AND "waste") AND "waste management" AND ("Management" OR "monitoring") AND "internet of Things""* is used.

Resources published in the range of seven years are selected to be the focus references of the digitalization approach for this study. Ten out of 85 references are related to the digitalization of medical waste segregation. The strengths and limitations of the idea are analysed as a guideline for designing the digitalization framework. Thirteen project reviews propose monitoring waste categories, and most of them only approach to focus on segregation based on the humidity of the waste [38]. None of these projects propose segregating waste into groups. Mixing medical waste can be hazardous to humans and the environment, requiring human effort to redo the segregation in case of violations. From the study, a proposal for waste tagging is presented to enable automatic waste segregation.

4 Proposed methodology

Currently, waste management authorities require a daily update on waste weight online to monitor waste generation. However, this process still requires manual input and does not help with waste segregation according to categories. Monitoring the waste can begin at the beginning of the product or equipment being used at the hospital. Transporter devices such as barcode tagging will be used for each medical equipment and tool with a unique category to represent the medical waste group, as shown in Fig. 2. Medical facilities can create standard codes to tag the waste, which can be used for group partitioning.

The bins can be equipped with a scanner that responds to the barcode. The scanner will collect waste of only one type and confirm that all the same tags in the bin belong to the respective group. The waste generators will need to scan the barcodes before being thrown away. The scanner will connect the information to the correct waste bin and open the lid.

Table 4 Similarity and difference of transporter devices [50, 51]

Device	Scanning range	Scanner technology	Lifespan	Power dependance	Similarity	Difference
Barcode	Short	Laser	No expiration	No electricity required	Same approach of data collecting, where data is stored and usually retrieved via either fixed or handheld devices Effective to be used in tracking inventory and workflows	Work on the light and sensor to read the information encoded The scanner is only able to process tags individually at every scan
QR code	Long	Optical	No expiration	No electricity required		
RFID	Long	Radio wave	A few years	Electricity		Work using the radio waves so able to obtain data without the need for line sight RFID scanners able to process dozens of RFID cards within a second

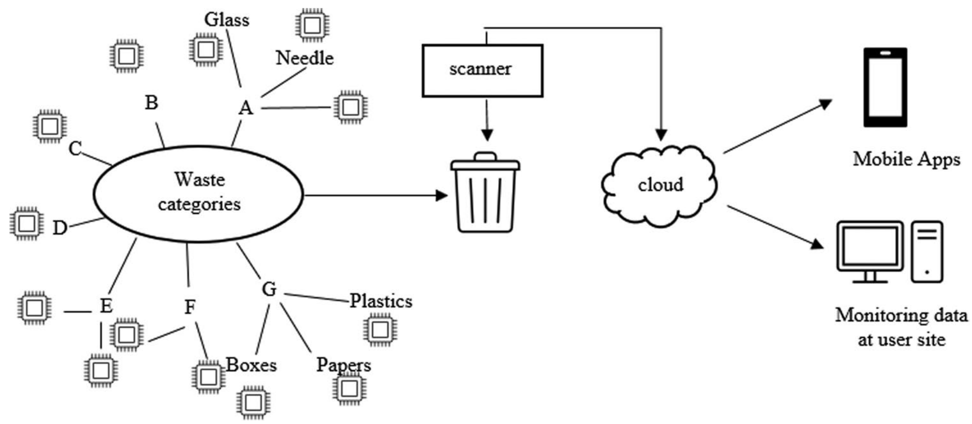

Fig. 2 Communal segregation monitoring systems overview

Scanning and opening the bin lid will allow the waste to be segregated according to their categories and avoid waste violation. This information will be shared to update the segregation condition of the waste for collection. The scanner will notify the waste generator to take corrective action if mixed waste is detected. Tagging any device directly into any human body part or blood cannot be essential. For pathological waste, since it can lead to exposure to infection during tagging, waste is planned to be put in a packaging bag and will be tagged with a barcode on it.

This system is a straightforward IoT system. The barcode scanner and the bins are likely connected to a central system or network, allowing them to communicate with each other. The barcode scanner collects data, which is processed to trigger the opening of the bin lid. This system automatically segregates the waste according to its categories based on the scanned barcode, which also reduces the need for manual intervention. The waste classification status, which will be available to waste handlers during waste collection, storage, transportation, and disposal, is a valuable service that can improve waste segregation monitoring, as illustrated in Fig. 3.

This system can be directed to a mobile application, and any device for the user site's monitoring management will process all collected data and make it accessible in real-time. The system's architectural idea is shown in Fig. 4. In this way, waste generators can receive information about the condition of waste segregation and the level of waste in the bin. The bin can be linked to another scanner to detect any violation of waste that has happened in the bin. This scanner functions to communicate with the waste manager to notify about the situation. The activity diagram of the digitalization system is presented in Fig. 5. Using this technology, waste segregation can be monitored continuously to prevent mis-segregation from happening or significantly reduce its occurrence.

5 Discussion

The United Kingdom set a goal to become the first major economy to commit to net zero emissions by 2050. The National Health Service (NHS) has set out a structural plan to support this ambition and come out with the Net Zero Carbon Delivery Plan [53]. The ultimate idea is basically to outline the NHS Clinical Strategy by eliminating avoidable waste. The UK NHS aims to reduce the number of clinical wastes by increasing the percentage of offensive waste. Thus, segregation must be the first step in having a clean and smooth strategy. The current idea of waste category tagging works to group the waste according to the waste disposal method done by Stericycle, making sense to ensure that waste will be treated

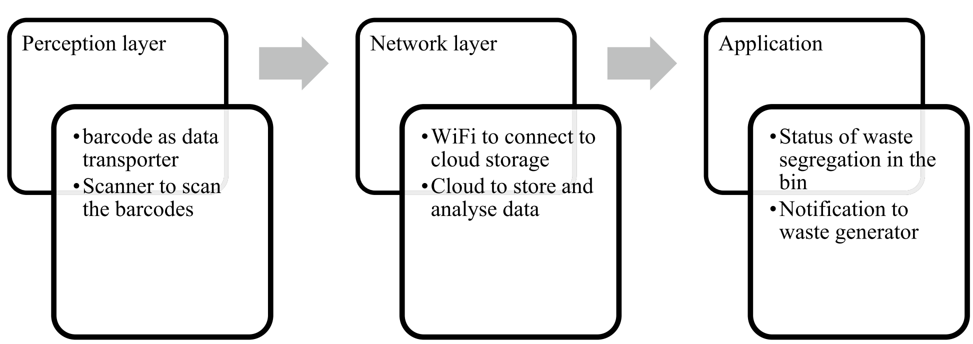

Fig. 3 Internet of Things layer in waste segregation monitoring

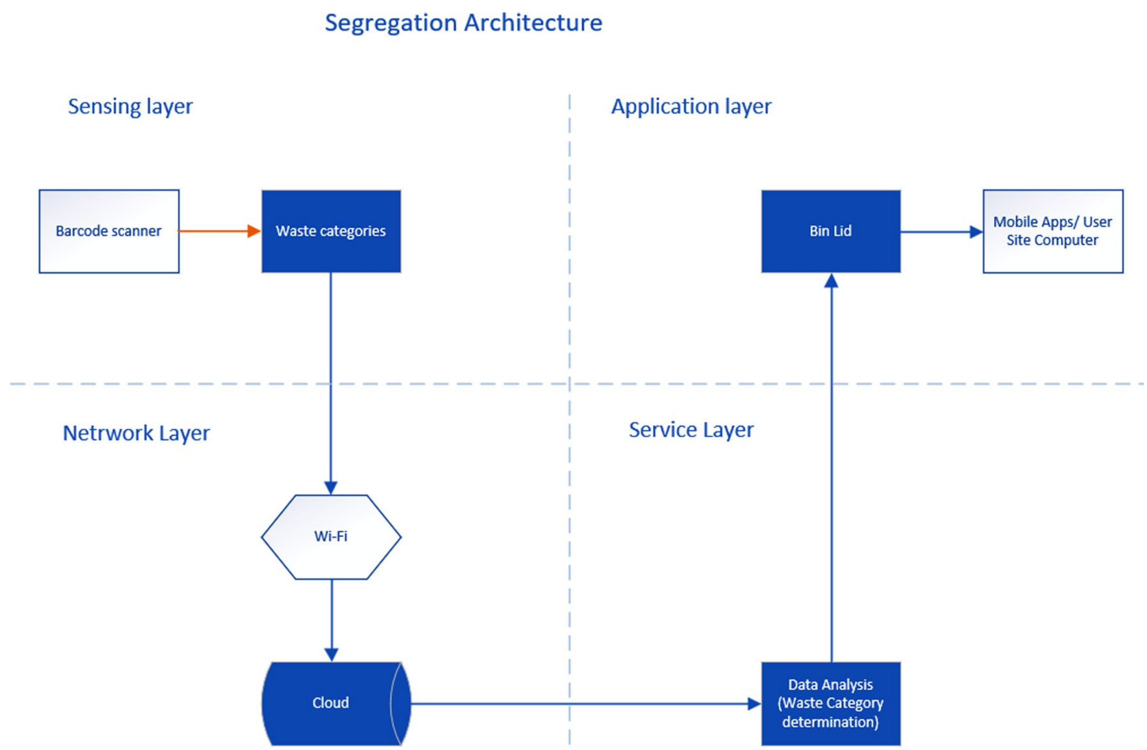

Fig. 4 Data architecture of proposed digitalization of waste segregation

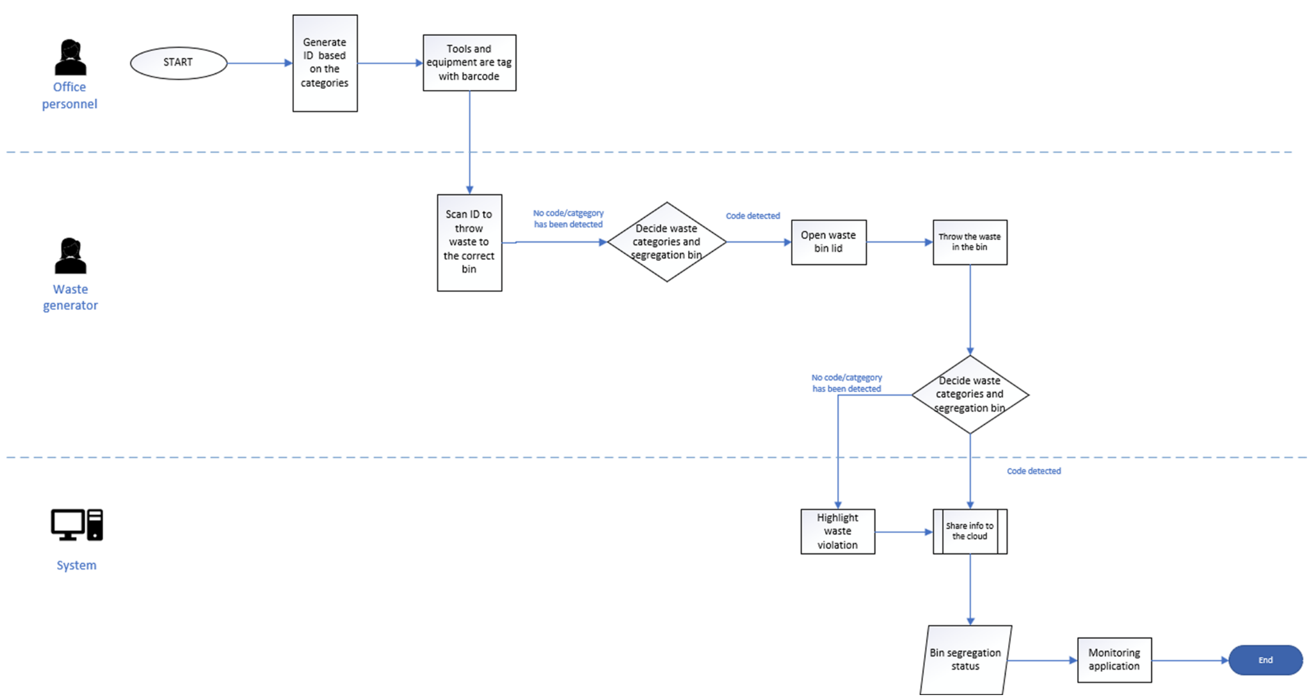

Fig. 5 Activity diagram of the developed communal segregation digitalization systems for medical waste

correctly. However, the idea is limited as segregation still must be done manually, and there is always the potential for waste violation.

Proper waste segregation has improved waste management a lot. Waste can be treated according to the exact number of wastes produced by the categories. A specific budget can be allocated to the waste-appropriate form of treatment without any doubt. Digitalization of waste segregation could give users a better understanding of waste categorization even though training has been provided to the employees. Human intervention in segregation inspires the proposal of waste tagging at the root of waste generation, simultaneously reducing the potential for human error.

Tagging the waste may need an upfront cost, but it can influence the proper financial plan for waste management. This system benefits by reducing human intervention during waste segregation. Tools and equipment that the code of the waste categories has tagged will be used as a guide to categorize the waste. The chosen transporter discussed is the barcode, which can be easily printed and cheaply. Hospitals and other healthcare facilities deal with thousands of tools and equipment daily; thus, barcodes can be an economical option to tag the items. However, the barcodes can only be scanned in a line direction with sufficient light support. On the other hand, the utilization of RFID can be better as it functions to detect the tags in the bin by radio waves. The results can be more precise and accurate, whereas RFID tags work better but may use up much of the budget as they are costly, expirable, and cannot be printed from the facilities office.

Time-consuming can be another thing to be worried about as healthcare facilities are busy places. All work usually needs to be done quickly but precise. This system may consume more time than the manual approach, but if this can help manage waste better, then the idea can be worthwhile.

With the application of coded tags, waste could have the potential to be segregated into a better categorization to promote recycling and introduce a circular economy. However, all waste generators should still attend training to understand the importance and effectiveness of proper medical waste management. Training for medical waste handlers is still poor, sometimes ineffective, or unsuitable [22]. Any waste generator can easily present scanning of waste codes, but the core knowledge of handling waste is still needed. Best environmental practices should include source reduction, resource recovery, proper collection and transportation, and recycling [12]. Waste segregation must be the first approach as this procedure demonstrates the contribution to environmental responsibility in waste management. Clear standard procedures and rules have a clear policy implication in waste composition [54].

6 Conclusion

Waste management monitoring is currently conducted manually, including the procedure of segregation. In the healthcare industry, since the waste can be infectious with thousands of types of bacteria, viruses, and diseases, missegregation or mixture of waste can increase the number of infectious wastes. Disposing of infectious waste can cause a lot of pollution. In many countries, including the United Kingdom, infectious waste has been treated with expensive incineration processes, which caused air pollution. In some other countries, infectious waste is dumped and may cause water, soil, and odour pollution.

The increasing amount of medical waste generated in healthcare facilities, particularly during pandemics, requires efficient waste management strategies. Waste sorting is considered an effective alternative to reducing environmental pollution and promoting recycling. This procedure is crucial to reduce the amount of waste that needs to be incinerated and lower the cost of waste management. Using code tagging on medical equipment and tools can help segregate waste and monitor its condition. The better allocation of the amount of waste to send for incineration can be controlled better with this solution. Segregated waste supports the world's sustainability in ensuring a clean environment and air, thus should be taken more seriously.

Moreover, real-time notifications and monitoring through mobile applications and monitoring sites can facilitate waste segregation, and waste management could benefit from tracking and tracing waste throughout the waste management procedures. Tagging every tool and equipment can be expensive for waste management procedures. By obtaining good segregation status, the waste can be treated most appropriately precisely and can be a caution step in maintaining or reducing the amount of budget used to process infectious waste.

Moreover, this method can affect the waste for resources, such as recycled or remade products from the healthcare industry. With effective waste management strategies, medical waste can be handled sustainably and safely, minimizing its impact on the environment and human health. As the world is transforming to the era of a circular economy, segregated waste can enhance the acceptance and value of waste from the healthcare industry. If the segregation of normal waste can be done confidently from the infectious, this could be given a chance to the waste to be segregated better according to the material or usage groups in the future.

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Declarations

This research does not include any human participants and data. All information is cited as a literature study for the proposal framework.

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