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Waste 4.0: Blockchain-Enabled Peer-to-Peer Communication Among Medical Waste Stakeholders

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Abstract

Medical waste management has been receiving increasing attention in recent years. The National Health Service (NHS) of the United Kingdom has started planning its waste strategy to comply with its Net Zero Goals. Waste management does not only involve waste disposal; the process includes segregation, collection, storage, and the transportation of waste from one point to another. Unusual characteristics of waste from the healthcare industry are that waste can be infectious and needs special storage conditions and specific transportation criteria to maintain the waste's quality. However, entities working with the waste lack knowledge about the waste they receive and need assistance to verify the quality of the waste as well. Limited knowledge can lead to injuries, contamination, or the spread of pathogens. The global monitoring guidelines of medical waste are studied to understand the monitoring requirements and the stakeholders who are working with the waste. Application and research contributions to the digitisation of medical waste monitoring are scrutinised to look for the monitoring gaps. This paper proposes a digital system designed to connect all waste stakeholders within a blockchain environment, supported by automated data collection. A framework for stakeholder communication with data is designed. The data gathered from transporters is analysed before sending the status to the blockchain. Furthermore, the paper outlines a dashboard showcasing the digitisation of waste management, backed by a case study used for validation. A hypothetical case study in managing waste using existing manual waste monitoring in the United Kingdom is compared with monitoring using the system. By employing a proving method of all activities approach with blockchain technology, this method has achieved a 25.17% improvement in medical waste management time-taken efficiency and a 27.85% improvement while virtually eliminating the risk of fraudulent documentation.

Keywords: blockchain; digitisation; Ethereum; medical waste; net zero goals; product service; waste management

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1. Introduction

Medical waste is generated in hospitals or healthcare facilities and poses risks of infectious, harmful, and containing viruses. Sharps waste increases the risk of transmitting the human immunodeficiency virus (HIV), hepatitis B and C, tuberculosis (TB), diphtheria, malaria, syphilis, brucellosis, and other infections [1]. The World Health Organisation (WHO) has reported that the mismanagement of waste has led to 21 million cases of

Hepatitis B, 2 million cases of Hepatitis C, and 260,000 cases of AIDS [2]. Appropriate management of medical waste is critical to prevent potential risks to human health and the environment [3]. Untreated or improperly disposed waste can contaminate water bodies, soil, and air by releasing hazardous substances into the environment [4]. Rapid population growth worldwide and the increase in viral pandemics have raised concerns that threaten the health of people, animals, and the environment [5,6].

In response to the Sustainable Development Goals, governments globally are working to improve waste management, aiming for sustainable cities and communities. In many countries with transitional economies, medical waste practices are often unregulated and frequently disregard WHO guidelines for proper disposal [7]. Waste management has become a significant concern for many authorities, prompting researchers to focus more on this area [8]. Furthermore, waste management not only focuses on disposal but also includes the segregation, collection, storage, and transport of waste.

Traditional waste management approaches lack the sophistication required for efficient and robust management [9]. Various IoT-based solutions have been proposed to establish an effective waste management system; however, they typically depend on third-party services for payment [10]. For instance, the United Kingdom relies on the National Health Service (NHS) to comply with legal requirements concerning the waste hierarchy to transition towards recovery [11]. Medical waste management involves not only waste disposal but also other procedures, which require the collaboration of multiple parties. Therefore, effective communication among stakeholders is essential for ensuring quality management.

In recent years, waste management has attracted increasing attention from researchers focusing on maintaining and enhancing sustainability. This has become particularly significant since recent pandemic outbreaks, as the volume of healthcare waste has risen sharply, overwhelming facilities with limited resources [12]. Traditional waste management systems are inadequate for handling such large quantities of waste, which may continue to harm biodiversity and ecology. Moreover, conventional methods are often labour intensive, prone to error, and lack real-time monitoring capabilities, resulting in suboptimal disposal practices and increased contamination risks [4].

Recycling in the healthcare industry is currently limited. Medical waste is often treated through incineration, and while chemical and sterilisation methods are sometimes employed, they are not widely accepted for recycling. However, with a system that verifies the quality and status of waste at each stage of waste management, the promotion of medical waste recycling could become more feasible. Adopting a circular economy approach allows waste to be used as a resource in producing new products. The proposed system serves as a platform to verify the quality of waste and its treatment history, thus providing assurance to buyers and manufacturers interested in using waste from the healthcare industry.

The lack of resources and infrastructure has slowed down strategic planning for waste management. Following standard operating procedures and guidelines remains the most common approach [13]. However, regulations and management practices alone are insufficient to enhance the efficiency of waste management. Digitisation offers a valuable opportunity to improve management processes. Digitisation can connect people working with medical waste in various ways. This approach has already been introduced in several Asian countries, such as Malaysia and Singapore [14,15]. It involves establishing structured networks for transportation consignments and delivery tracking. Other approaches, including unstructured centralised and decentralised networks, have their respective advantages and disadvantages. This paper identifies the challenges in waste management, particularly regarding communication among stakeholders, and proposes a digitisation solution for improvement. A decentralised network is chosen as it meets the requirements for immutable data and transaction records. The blockchain-based waste management en-

vironment connects all stakeholders while providing automated updates on waste quality, ensuring both effective communication and verification of all actions taken. Blockchain is not a new introduction in solving waste monitoring issues. There are a few research studies that have brought forward the idea of blockchain. However, the ideas mostly do not cover the entire waste monitoring procedure. Communication is mostly focused on tracking the shipping status and the weight of the waste, which can be insufficient to prove the quality of work done and the quality of the waste. Generally, six required elements need to be monitored to ensure the quality of medical waste management [16].

1.1. Challenges to Stakeholders' Communication

Medical waste has long been treated separately from municipal waste. However, it often remains unsorted and improperly segregated, posing significant risks to the public and employees who come into contact with it. Employees handling waste face numerous risks, including potential injuries and infections. Improper waste management practices can also result in illegal pollution or fraudulent activities [17]. Effective communication is essential to monitor waste conditions and inform stakeholders about the status of waste. Attention should be given to the entire system, including handling medical waste from the point of generation to collection, transport, and finally, environmentally sound disposal.

Traditional communication strategies do not provide sufficient information on waste conditions. For example, waste should not be stored for more than 48 h in hot weather or 72 h in cold weather. However, no entity currently verifies whether waste treatment has occurred, whether the correct storage temperatures are maintained, or whether this information is shared among stakeholders. Additionally, waste quantities are not regularly checked, increasing the potential for fraud or misuse. Unsterilised syringes and needles stolen from used medical equipment have been identified as a source of outbreaks [18]. Improper communication and tracking associated with waste lead to waste being sent to landfills [19]. While some proposals for digitising medical waste monitoring have been made, a comprehensive platform is needed to oversee the entire waste management process. This comparison is made through digitisation and a digital approach to waste management through the research contribution. Most existing solutions focus on specific objectives, which is a positive start; however, they should also serve as an auditing platform for waste management.

1.2. Objectives of Study

This paper proposes a digitisation approach for improving communication among waste management stakeholders, benefiting both the stakeholders and monitoring authorities. Traditional waste documentation is outdated and does not accurately reflect waste conditions. While waste management is an essential service, there are opportunities to obtain accurate data. Digital monitoring enables occupiers to gain a comprehensive understanding of the waste collected or received, facilitating better planning for subsequent actions. To explore the potential of the proposed solution, the following research questions are examined:

1. What are the critical parameters for monitoring waste procedures effectively?
2. What is the current method for monitoring medical waste management?
3. How can decentralised network digitisation enhance waste monitoring?

Effective monitoring is crucial to ensure safe waste transfer. The advantage of this system is that all transactions can be verified and validated within a closed network. The system is designed to communicate with stakeholders through a decentralised network where all transactions are immutable and recorded. Any party can check the status of the waste or any treatment it has undergone during its transfer. Automated data verification

ensures stakeholders have clear guidelines for waste management. By providing proof for each action or treatment, the proposed system aims to build trust among waste buyers, enabling them to accept waste from the healthcare industry with confidence.

This paper is organised as follows: Section 2 reviews existing research contributions on digitisation proposals and approaches. Section 3 details the proposed digitisation techniques; Section 4 discusses the proposal's development and presents a case study. Finally, Section 5 evaluates the proposal's impact on the medical waste industry.

2. Medical Waste Monitoring

2.1. Traditional Method of Waste Monitoring

Traditional waste monitoring methods remain basic. The approach of manual circular documentation is still practical, even in developed countries. Waste management procedures—segregation, collection, storage, transportation, and disposal—are conducted and communicated manually, with paper-based systems being predominantly used. The United Kingdom continues to connect waste stakeholders using the Waste Transfer Note and Hazardous Waste Consignment Note [20]. Consignment notes for vehicles carrying hazardous healthcare waste should include the necessary information in case of accidents or official inspection. In some developing countries, such as Malaysia, circular waste notes are filled out in six copies [21]. In India, reports are completed, submitted, and analysed manually, leading to misunderstandings about which organisation generates the waste and encouraging delays and corruption. This has shown that the chances of document fraud or forgery can easily occur with manual documentation. In India, unnecessary costs incurred in the transportation of medical waste amount to as much as 43% [22]. Five hundred thousand waste records are kept by 30 waste management entities in Sweden without any quality control or pre-defined criteria to record the data, resulting in only a fraction of the dataset being usable [10].

Traditional methods require greater sophistication to achieve efficient and robust waste management [9]. For instance, Estonia, a country known for its use of blockchain and digitisation, has made efforts to build waste management facilities in two hospitals, equipped with appropriate technical installations for waste collection, recovery, or disposal [23]. While this effort is a good start for controlling waste management, it may be burdensome for countries with high populations.

The traditional waste chain has specifically caused many problems. Opportunities for waste-related crimes arise from illegal transfers and exports. Waste crimes occur to avoid landfill taxes or incineration expenses [24]. The lack of digital archiving in the waste sector allows criminals to exploit transfers and illegally divert waste to unauthorised sites, evading landfill taxes or facilitating illegal export. Waste management has historically recorded high levels of crime and illegal dumping [25]. A European Union report from 2020 found that 40% of hazardous waste was detected as disappearing from the market [26].

Documentation fraud is also unmanageable through traditional methods, as cheating and manipulation can occur if there is no proof of the amount of waste generated and disposed of. Manual and traditional communication in inspecting water plants requires a lot of time and effort and may not be thoroughly monitored. Traditional waste management systems do not incentivise reducing waste production; thus, cheating is often used as a means to reduce expenses [27]. For example, only a small number of medical institutions report their waste to the authorities [28].

2.2. Digitisation in Monitoring Waste Management

Digitisation has become increasingly common in waste management. Research has shown that waste management without human intervention can achieve 97.94% accu-

racy [29]. With the growth of the Internet of Things (IoT), many digitisation approaches have influenced this industry. For instance, the Republic of Korea has started collecting waste with RFID bags from citizens [30]. Smart waste management solutions can help mitigate waste challenges by monitoring the fill levels of trash bins and optimising waste pick-up routes [31]. IoT sensors are installed in waste bins to measure waste levels, improving collection routines. Amsterdam has started using sensors to control fuel consumption and gas emissions in waste management [32]. Spain's government has installed sensors in 250 recycling bins in Madrid, saving 11,880 pick-up journeys in a month [33]. In Singapore, the usage of bins was enhanced eightfold after level sensors were fixed on digital waste bins [34]. The area of digitisation mainly focuses on waste collection, and analysis of these projects has successfully shown the positive impact of digitisation on waste management.

In the medical sector, digitisation in waste management is growing slowly but has become more prevalent in Asian countries. Malaysia now has a webpage for daily updates on waste generation and also uses it for consigning shipments from waste storage rooms to disposal centres [35]. RFID tagging was introduced in the Republic of Korea to track waste disposal during pandemic outbreaks [36]. Some research contributions have proposed approaches for waste management in the medical sector, but these primarily focus on waste collection and segregation procedures [18,22,37]. The Republic of Korea has established an online communication platform to update waste movement in real time; however, it does not provide detailed information on the quality of work done on the waste [38,39].

Proposals to connect with geospatial sensors (GPS) have also been presented to locate waste bins, enhance collection, or monitor routes during waste transportation [18,40,41]. Other research suggests using GPS for driver and vehicle tracking and landfill selection [41–43]. Some proposals for waste segregation have included using robotic arms to classify infectious waste into appropriate groups to prevent mixed-waste issues [37].

These digitisation solutions address their respective challenges. However, they may not be capable of auditing all procedures involved in medical waste management. Waste stakeholders still lack confidence in the quality of waste when they receive or transport it. Communication with stakeholders is crucial to verify the quality of the waste based on the procedures used. A platform to communicate waste quality would enhance accountability for waste generation and management [3].

Most current technologies for managing forward supply chains or services, including waste management, are primarily based on cloud computing and IoT. However, communication among those handling waste remains inadequate, and waste quality is often unknown. Typically, waste handlers do not know if the waste has been stored or treated as required, leading to insufficient auditing information to represent the quality of the waste management service. Information about waste treatment quality is either unavailable or ignored.

It is widely acknowledged that medical waste is hazardous; thus, data validating waste treatment procedures could provide valuable insights into each transaction.

2.3. Blockchain Communication

Great teamwork will be enhanced with strong communication [44]. This applies to every industry where teamwork is essential. In the healthcare industry, most tasks are performed collaboratively. Team communication can be improved using a blockchain system, which aims to enhance trust by verifying all shared information rather than undermining it. In healthcare, this technology enables the secure exchange of medical data, assisting in disease diagnosis and patient treatment [45]. China's National Health Commission has launched a pilot project to build a medical waste supervision system based on IoT-enabled blockchain technology [37]. Blockchain technology has also been proposed for remote

patient monitoring, managing clinical trials [46], and data transmission [47], demonstrating its potential to facilitate reliable, team-based decision-making.

2.3.1. Blockchain

For over a decade, blockchain has been recognised as a trustworthy method for tracking transactions in a distributed, peer-to-peer, decentralised network [48]. Blockchain provides a decentralised framework that removes the need to trust a central authority. It offers robust privacy protection through innovative optimisations, incorporating insights into many industries from economics, psychology, sociology, and other disciplines. Its effectiveness is enhanced by multiparty incentive systems and rational participant models [37]. Blockchain can be used to record and track data or assets in supply chains, real estate, financial transactions, and voting systems [41]. In waste management, it ensures transparency and security, preventing fraudulent activities by maintaining an immutable, shared transaction log without requiring an external entity [49].

Blockchain technology offers enhanced transparency, security, and efficiency. The decentralised and distributed structure eliminates intermediaries and ensures data integrity and authenticity through consensus mechanisms [50]. Various blockchain privacy-preserving techniques enhance network and data security. Transactions are grouped into blocks and stored in a distributed ledger, ensuring that all nodes have the same copy. Consensus techniques validate transactions and create new blocks, reducing errors and duplication. This decentralised structure minimises the risk of data breaches and unauthorised access, offering an extra layer of security over traditional systems.

Blockchain also facilitates real-time data sharing and updates between different parties [51]. Its decentralised nature minimises the risk of single points of failure, promoting transparency and trust among participants [52]. While blockchain is one option for connecting peers, other network structures—such as centralised, structured, and unstructured—can also be used. To better illustrate these network types, Table 1 compares different peer-to-peer network approaches.

Table 1. Digitisation types of communication network.

Peer-to-Peer Category	Description	Advantage	Disadvantage
Structured	Networks with a predetermined topology that organises data using specific techniques.	Effective data arrangement, retrieval, and consistent performance	Complex setup that may be inflexible and less adaptable to changes
Unstructured	Networks that facilitate unrestricted data exchange and retrieval	Increase flexibility and ease of setup and maintenance	Ineffective data retrieval and slowdown may occur from haphazard searches
Centralised	Unstructured networks that allow for unlimited data retrieval and exchange	Faster initial setup, simple architecture, easy to maintain and control	Single point of failure, scalability problems, and reduced consumer privacy
Decentralised	A paradigm in which multiple peers can function as both clients and servers and where no single entity is in charge of the network	Better fault tolerance, enhanced security, better dependability, and increased user control and privacy	Slower data retrieval is possible, and more intricate data organisation is needed.

Decentralised systems are computational architectures that, instead of depending on a single authority, divide control and processing capacity across several nodes, frequently dispersed among several locations. Although each node operates independently, the stakeholders work together to accomplish shared objectives. Unlike centralised systems, where a single server manages all operations, resources, and data and serves as the primary point of

contact for processing client requests, this design improves fault tolerance, scalability, and resilience [53]. Three types of decentralised blockchain systems can be distinguished based on the accessibility of information: partially decentralised private blockchains, which prioritise high efficiency by limiting access to reading, validating, and publishing new blocks to a select group of trusted users [54]; fully decentralised public blockchains, which, while less efficient, mandate consensus mechanisms for security and data integrity, allowing open participation by giving each member a copy of the blockchain and virtually preventing tampering [55]; and semi-decentralised consortium blockchains, which involve predefined groups of nodes that validate transactions through consensus mechanisms to speed up transaction processing [56].

Since decisions on decentralised networks are made by agreement rather than by a single authority, this network encourages a more democratic approach. The decentralised system relies on cooperation and has an autonomous network that significantly lessens administration responsibilities. Centralised and closed-source apps, on the other hand, rely on users' confidence in their security protocols. This mistrust of closed-source networks' security poses a serious obstacle to the wider use of blockchain technology in asset management applications [57]. Centralised networks, though faster and more efficient, are more vulnerable to attacks due to a single point of control, whereas decentralised networks, though slower, offer greater security through their distributed architecture [58].

Organisations are therefore free to choose what information they want to keep confidential and what information they want to share with the public [59]. This is particularly true in sectors like healthcare, where maintaining patient data security is crucial. Particularly in the context of medical waste management, a decentralised strategy can improve accountability while maintaining the security of sensitive data. Table 2 outlines the main benefits of a decentralised strategy.

Table 2. Purposes of Blockchain approach in peer-to-peer network [60–63].

Benefit	Reasoning
Transparency	Decentralised solutions ensure accountability and improve waste management methods by giving all stakeholders instant access to the same data.
Interoperability	Better integration amongst stakeholders can be facilitated by a decentralised system, which will enable them to exchange and validate information more effectively. This is important for trash management
Reduced Risk of Contamination	A decentralised system can assist in the prompt identification of possible waste-related concerns, lowering the risk of contamination and infections, by giving real-time data to all stakeholders
Stakeholder Empowerment	Decentralised networks provide direct access to pertinent information, empowering all stakeholders in waste management to take well-informed decisions
Integrity	Blockchain technology makes it possible to track tangible assets by keeping an eye on changes to transactions and guaranteeing integrity through public verifiability, which makes it possible for everyone to confirm the legitimacy of the waste transactions

Waste management procedures involve multiple stakeholders, and at the same time, each of these people will be needed to prove the work that was done to the waste. For specific management that includes a lot of important steps, such as medical waste management, the proven status of waste plays a big role in the next procedure that could be carried out. A decentralised system has been introduced with the existing waste notes currently used; however, this documentation does not provide full information on the time

to the next procedure and does not carry enough data to understand the status of the waste before and after any transfer.

A fully decentralised private blockchain can be designed to overcome the significant problem of a single point of failure found in centralised systems. Additionally, it addresses other fundamental weaknesses of centralised blockchains, such as transparency, fair access to resources, data integrity, transaction non-repudiation, and data immutability [64]. Each piece of information relates to the decision of the other party. Thus, unrevocable data can be helpful in a waste stakeholder's environment. The transparency of a decentralised system reduces the possibility of single points of failure and promotes confidence among the participants. Blockchain has been proposed in a variety of areas and industries, including finance, healthcare, and supply chain management, and thus is believed to be beneficial to product servicing areas such as waste management as well.

2.3.2. Smart Contract

Blockchain has developed to accommodate a wide range of decentralised applications, many of which rely on the platform's ability to execute smart contracts. A smart contract is an autonomous software program that operates independently under predetermined conditions to formalise an agreement between parties that do not trust one another [65]. Three components make up a smart contract: executable code, a balance, and contract storage. Through blockchain transactions, any node in the network can construct and deploy them. The code of a smart contract is immutable and unchangeable once it has been uploaded to the blockchain and cannot be removed. Any blockchain platform, including Ethereum, can be used to construct and implement smart contracts. Platforms differ in terms of programming languages, execution environments, and security protocols, among other elements that are specific to the development of smart contracts. For the explicit intent of creating smart contracts, some platforms even enable advanced programming languages. More significantly, in scenarios where conventional trust is missing, smart contracts promote trust between parties. This capacity has the potential to drastically alter standard corporate procedures [66]. Smart contracts are developed and then made available on blockchain platforms. To avoid any potential bugs, they must be thoroughly examined. Developers should also be aware of the patterns of interaction inside the contract in order to reduce the possibility of losses resulting from malevolent acts, such as fraud and attacks.

2.3.3. Blockchain in Waste Management

Blockchain can fundamentally change the traditional approach to collecting, storing, replicating, or tracking. The blockchain approach is also able to eliminate regulatory gaps and sew the gaps in the supervision of waste management. This approach is helpful in ensuring authenticity and validating information transferred among the people in the environment. It has also become clear that the development of blockchain technology has shown a potential long-term solution to the challenge of managing waste [67]. Blockchain allows for an immutable and decentralised record of all transactions in the environment and ensures validity, transparency, and accountability [45]. This gives a positive welcome to the future of blockchain, which works closely with the Internet of Things and could favour user involvement in closed-loop supply chain operations and, at the same time, minimise customers' hesitance and reluctance to accept the waste [68]. In the waste management sector, to be inclusive in world sustainability, the circular economy, and recycling, the quality of the waste can be promising by tracking the waste and tracing all treatments done to it. Prioritising medical waste, which can be infectious to people and the environment, every job has to be recorded. On-site treatment, such as microwave thermal and autoclave, can be an essential quality assurance to verify if waste is suitable for recycling or reuse.

Table 3 shows the interest in academic contributions towards the application of blockchain in waste management, including medical waste.

Table 3. Research contribution in the application of blockchain in waste management.

Type of Solid Waste	Waste Management Procedure				Transaction	Data Collection	Strength and Limitation	Study
	Segregation & Collection	Storage	Transportation	Disposal				
Medical	√	√	√	√	Manual	Manual	The system includes waste collection status and registration. However, it does not include information on waste conditions or the quality of the procedure.	[69]
General	Not specified				Not specified		The system presents the idea of communicating with the stakeholders, but the details of the system need to be specifically discussed.	[24]
Medical	√	√			Manual	Manual	The system provides information about waste collection and waste registration to the storeroom. However, it does not include information about the quality of the procedure.	[37]
General	√	Claimed	√		Automated	Automated	The system includes information on waste segregation and collection and automated consignment to transport out. No information on waste conditions has been collected.	[41]
E-waste	Not specified				Not specified		The system proposed the idea of trading the e-waste to the buyer. The weight of the waste collected and shared with the environment, but no waste procedure is detailed.	[67]
General	√	√	√	√	Manual	Manual	The system includes the status of the waste collection and registration. Segregation will only be included and done after waste collection. There is no information on waste condition, or the quality of the procedure included.	[70]
Medical	√			√	Not specified		The system provides information on segregated waste, including the waste level and collection. Decisions on disposal methods are communicated through the system. No data on waste condition and quality of procedure are collected.	[71]
E-waste	√			√	Not specified		The system can connect the waste chain from the consumer to the end of the recycling procedure, but it does not provide information on the quality of the waste collected.	[72]

Table 3. *Cont.*

Type of Solid Waste	Waste Management Procedure				Transaction	Data Collection	Strength and Limitation	Study
	Segregation & Collection	Storage	Transportation	Disposal				
General	√				Not specified		The systems connect the waste generator to an application to motivate waste segregation among citizens. However, the system does not present information on waste management.	[73]
Construction	Not specified				Not specified		A digital passport is created for the waste to be traded among the waste buyers. No condition of waste has been properly collected and discussed through the digital passport.	[74]
Medical				√	Automated	Automated	The systems include tracking the status of waste disposal. No details of waste conditions are being captured and shared with the environment.	[75]
General	√				Not specified		A platform to connect waste generators and buyers of recyclable wastes. The systems directly connect with the manufacturers of the products that need the material for new production and other vendors. The system charges for every service provided but does not identify any quality of sorted waste.	[76]
General	√		√	√	Manual	Automated	The systems provide information on waste and track the task done to the waste. This can help to prove that the waste has been disposed of correctly. No information about the quality of every procedure and process has been collected for monitoring the waste.	[77]

3. Medical Waste Supervision Model with Blockchain

A communication platform with a blockchain environment is being proposed to address the research gap. In producing a quality chain of communication, blockchain technology serves as a platform to share authentic information among the stakeholders. The blockchain is a decentralised system that allows stakeholders to validate all information without involving any third parties. The system is also encrypted for the users, and all transaction data and proof of the work done are authentic and unalterable. Communicating with stakeholders will be an excellent way to verify all information and work done to the waste. This technology includes a high level of trust, transparency, immutability, and traceability. Thus, at the same time, all the proof improves the confidence of other parties who are working with the same products. Blockchain is not a new approach in the healthcare industry; it has been introduced to establish mutual decision-making in the medical field [78]. Blockchain can change the traditional way for the stakeholders to convey information while collecting, storing, replicating, and tracing waste [79]. All waste transactions will be stored in the blocks, and these blocks will be linked together

to be available to the stakeholders. The main idea of blockchain technology is that each of the blocks contains hashed data that is immutable. Every transaction and work done will create a digital fingerprint to verify and validate block information. Each block in the blockchain contains a block number, a timestamp, a hash of the previous block, and a subset of transactions [72]. In a study of blockchain application in pharmaceutical industry, blockchain is discussed as a reliable tool in helping the governmental agencies to track hazardous drugs disposal [80].

To summarise the approach, this research has collected all advised monitoring parameters from the World Health Organisation (WHO) and revised all waste regulations and policies. Monitoring elements are listed to determine which parameters should be prioritised when communicating with the stakeholders. These elements can be inserted into the smart contract as the agreement and requirement of the transaction. The stakeholders and entities who are working with the medical waste are identified, and this environment will include the waste stakeholders, which are the hospitals or clinics, storage rooms, and disposal facilities. Stakeholders will be passing the waste from one to another after the job on the waste has been done, and by doing the handover, a transaction will be made. This transaction is fundamental to communication in the system. Table 4 shows the people who work with the waste and their role in medical waste management.

Table 4. Stakeholders of Waste Management in the Healthcare Industry.

Stakeholders	Role
Waste Generator	• Provide a clear description and understanding of waste categories and the harm they cause to humans and the environment. • Set up tagging for the tools and equipment in the hospital, including waste bags and waste bins. • Understand the need for on-site treatment for some of the waste categories. • Segregate the waste according to the categories and throw it in the correct bin.
Waste collector	• Collect the waste from the generators according to the schedule/as requested in case the bin is full. • Understand waste categories and their harmful effects on humans and the environment. • Ensure wastes are not mixed, and report if there is any case of segregation violation.
Storekeepers	• Log storage duration of the waste. • Ensure waste is stored in the correct condition and for the proper duration while waiting to be transported out.
Transport transfer	• Understand the requirement of transferring medical waste. • Understand the harm of medical waste to residential, water catchment, or environmentally sensitive areas.
Disposal Occupier/Technician	• Understand the waste categories and suitable methods of disposal. • Ensure waste is disposed of on time to avoid infection to the environment. • Ensure all disposal method requirements are followed and controlled.
Authorities	• Enforce the law and regulation of waste and related environmental issues. • Guide waste disposal enforcement. • Monitor the waste management procedures.

The blockchain environment acts as a communication platform for the waste stakeholders, mainly the hospital, storage room, and disposal facilities. Each waste transaction from one party to another will be recorded and approved by members of the environment. The environment will allow the stakeholders to change the transaction, check its status, and observe the waste condition for approval of the transaction. Figure 1 shows the environment of the medical waste blockchain and how the transaction takes place.

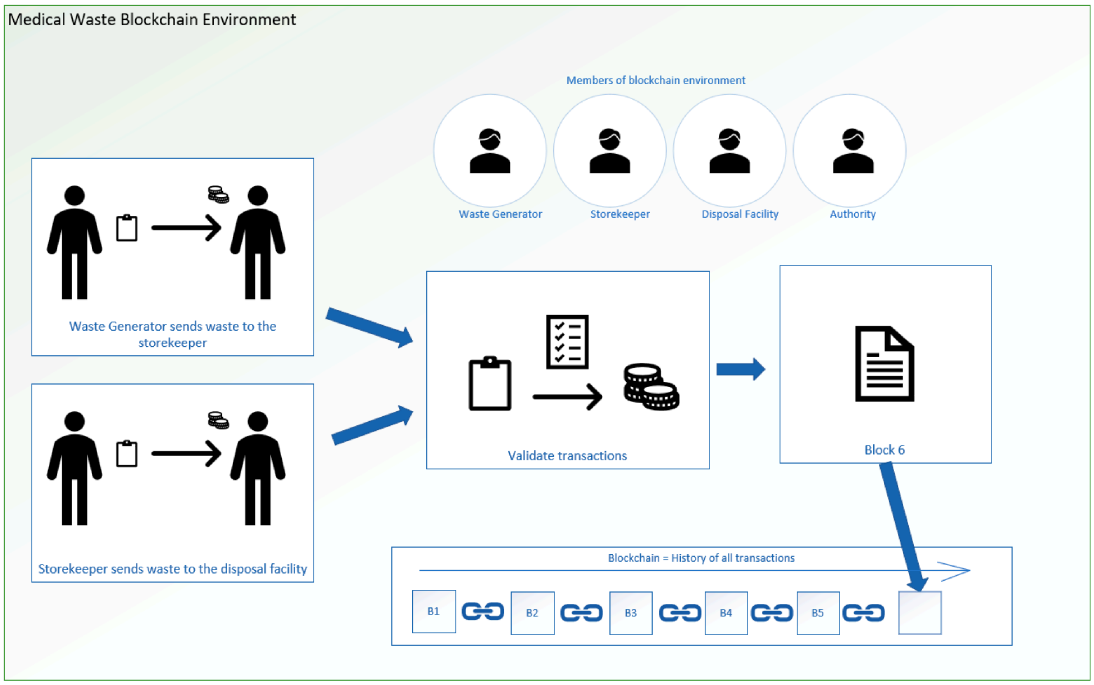


Figure 1. Proposed communication of stakeholders via blockchain environment.

While having transactions, the blockchain will also communicate the information that has been collected through the waste management procedure. Automated data will be collected through sensors and code scanning and be used as a medium to validate the quality of each of the processes. The stakeholders could refer to the data to understand the quality of the waste sent or received from one another. In this decentralised system, the records are integrated as proof of the waste's condition and any work done to the waste. The communication of the blockchain model can be referred to in Figure 2.

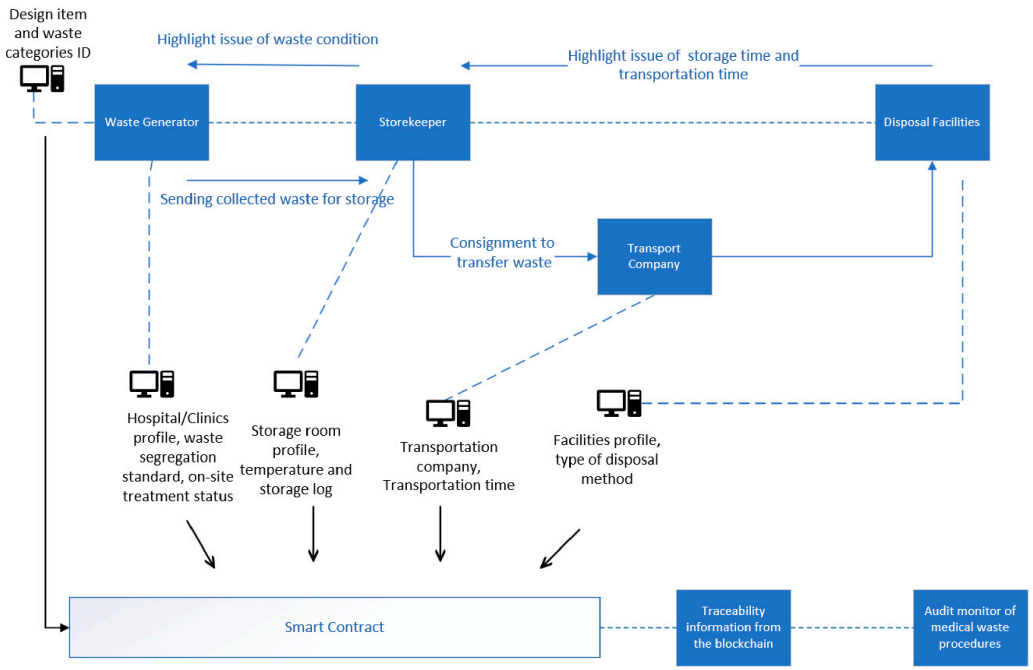


Figure 2. Communication business model of medical waste management.

3.1. Monitoring Parameter

Medical waste has been undergoing very tight management, which includes a few important parameters. Monitoring these parameters to obtain the quality of waste management is critical. As a harmful type of waste, every waste management procedure involves potential environmental risks. Segregation has been agreed to be the first step in addressing quality waste management [81]. Infectious waste in the healthcare industry can be dangerous and can easily be a medium to spread disease and viruses [35]. Segregating waste into groups can both minimise the potential for injuries to waste collectors and help determine the following procedure to be taken. For example, sharp injuries increase the risk of human immunodeficiency virus (HIV), hepatitis B and C, tuberculosis, diphtheria, malaria, syphilis, brucellosis, and others [1]. Genotoxic exposures through skin absorption and inhalation can cause dizziness, headache, nausea, and malaise. Properly segregated waste can control the amount of infectious waste to the smallest amount and could reflect the budget needed to dispose of it. The purpose of treatment is to reduce the potential hazards posed by the waste while endeavouring to protect the environment.

Some categories of waste will need to undergo on-site treatment before being stored in the storage room. These treatments are essential as proof of the waste condition, as it is now environmentally friendly and safe. One example of on-site treatment is that low-heat microwave treatment is enough to destroy microorganisms but not sufficient to cause the combustion or pyrolysis of the waste [16]. Autoclave is another method of steam sterilisation that is sometimes done on-site to destroy the lingering microorganisms [82]. The status of on-site treatment should be shared with the other stakeholders so that everyone understands how to deal with treated and untreated waste.

The growth of pathogens may be considered biologically active waste, and gas formation during storage should be expected. During storage, the temperature of the storage room needs to be controlled so that pathogens cannot grow. The World Health Organization (WHO) advised storing infectious waste in cool or refrigerated conditions at a temperature preferably no higher than 3 °C to 8 °C for a long period [16]. Otherwise, the storage must not exceed a period of 72 h during the winter and 48 h in the summer season. For countries with warm climates, infectious waste storage cannot exceed 24 to 48 h, depending on the cool and hot seasons. Pharmaceutical and chemical waste must be stored according to its characteristics. The characteristics of different chemicals to be stored and disposed of, whether they are inflammable, corrosive, or explosive, must be considered. The long-term presence of pharmaceuticals in the environment may cause acute and chronic damage, behavioural changes, reproductive disorders, and the inhibition of cell proliferation [83]. Radioactive waste needs isolated storage for at least ten times the half-life of the longest-lived radionuclide that exists in the waste. Thus, it has been shown that two main parameters that need attention during storage are the condition of the storage room and the storage duration.

Healthcare transportation is a challenging optimisation problem that requires considering human and environmental safety in addition to cost minimisation [12]. Drivers should be trained and vaccinated, and WHO has decided only to allow the transportation of medical waste in covered containers. Refrigerated containers could be used if the storage time exceeds the recommended limits or if the transportation times are long [16]. In some cases of waste transfer, the Republic of Korea limits waste transport to not more than four hours [30].

Waste must be disposed of according to the categories. Medical waste treatment includes sanitary landfills, chemical disinfection, microwave treatment, high-pressure steam sterilisation, plasma disinfection, pyrolysis, and incineration [6]. Mistreatment of waste disposal can cause environmental pollution and unpleasant odours, which welcome

insects and pests to breed and lead to the transmission of diseases such as cholera, hepatitis, or typhoid [28,84]. Chemicals that flow to drainage or any water source can pollute the water and make it unsafe to use [85]. Traditional waste disposal, like landfilling and burning of waste, produces toxic and hazardous pollutants that can be harmful to both humans and the environment [86,87]. Medical waste requires proper treatment, and it is agreed that incineration is the most preferred and hygienic method [82,88]. Infectious and pathological waste is usually treated by incineration. However, this method may need a high budget allocation. Healthcare waste generators should ensure that healthcare waste is sent to waste management facilities that are permitted to accept and treat or dispose of the waste intended for them. Figure 3 shows a list of essential parameters that need to be monitored in managing medical waste. However, these parameters are not fully noted in the current approach or research proposals for medical waste management.

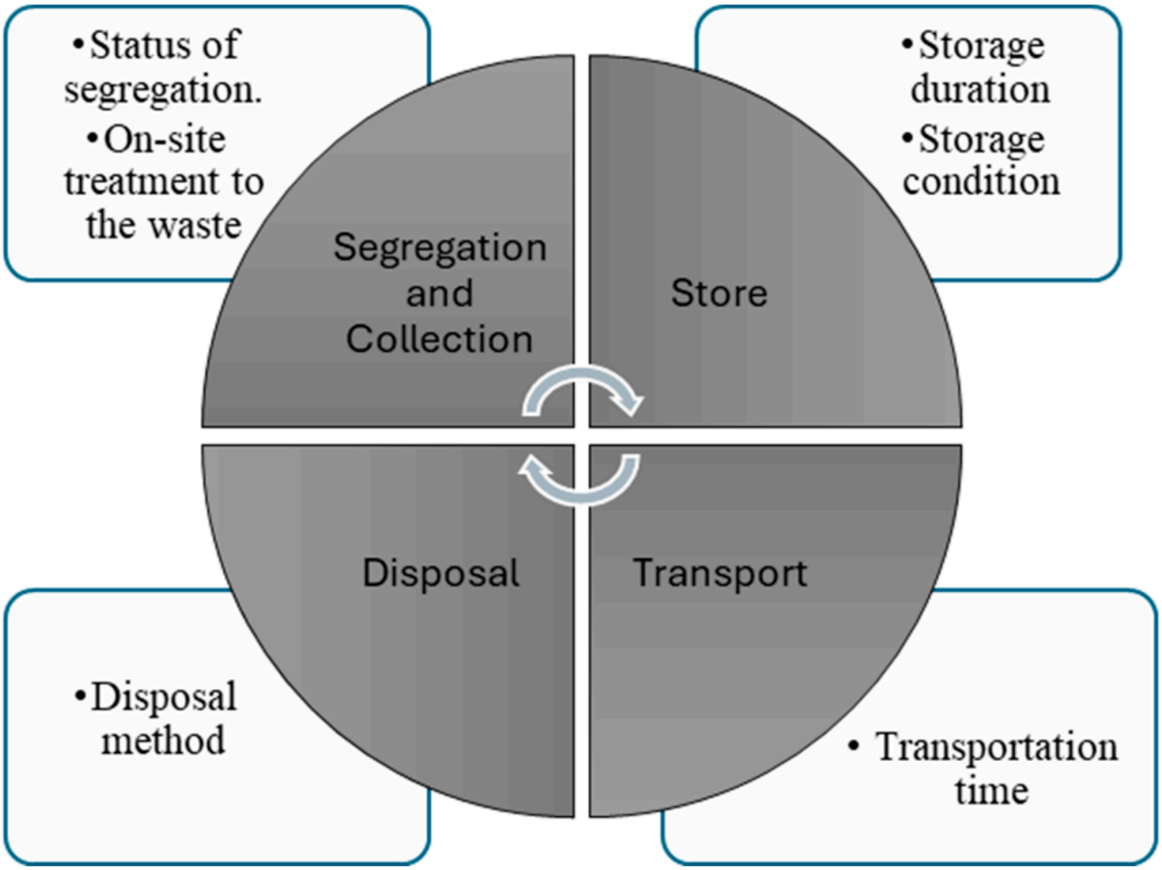


Figure 3. Important parameters in monitoring quality medical waste management.

Without a doubt, this information is essential for the stakeholders to understand the waste quality, which can help them plan the job better. Waste authorities usually conduct waste audits regularly, and thus, the quality of waste and management procedures should be critical factors in the audit. Looking towards the SDG goals, every piece of information should be counted to have and maintain a fresh, healthy, and clean environment. Six important waste parameters—segregation condition, waste treatment status, storage logs, storage room condition, transportation time, and the disposal method—will be integrated into processing and analysing the collected data. This data will appear as proven details and the history of the waste. Figure 4 shows the blockchain framework for managing medical waste for the proposed system.

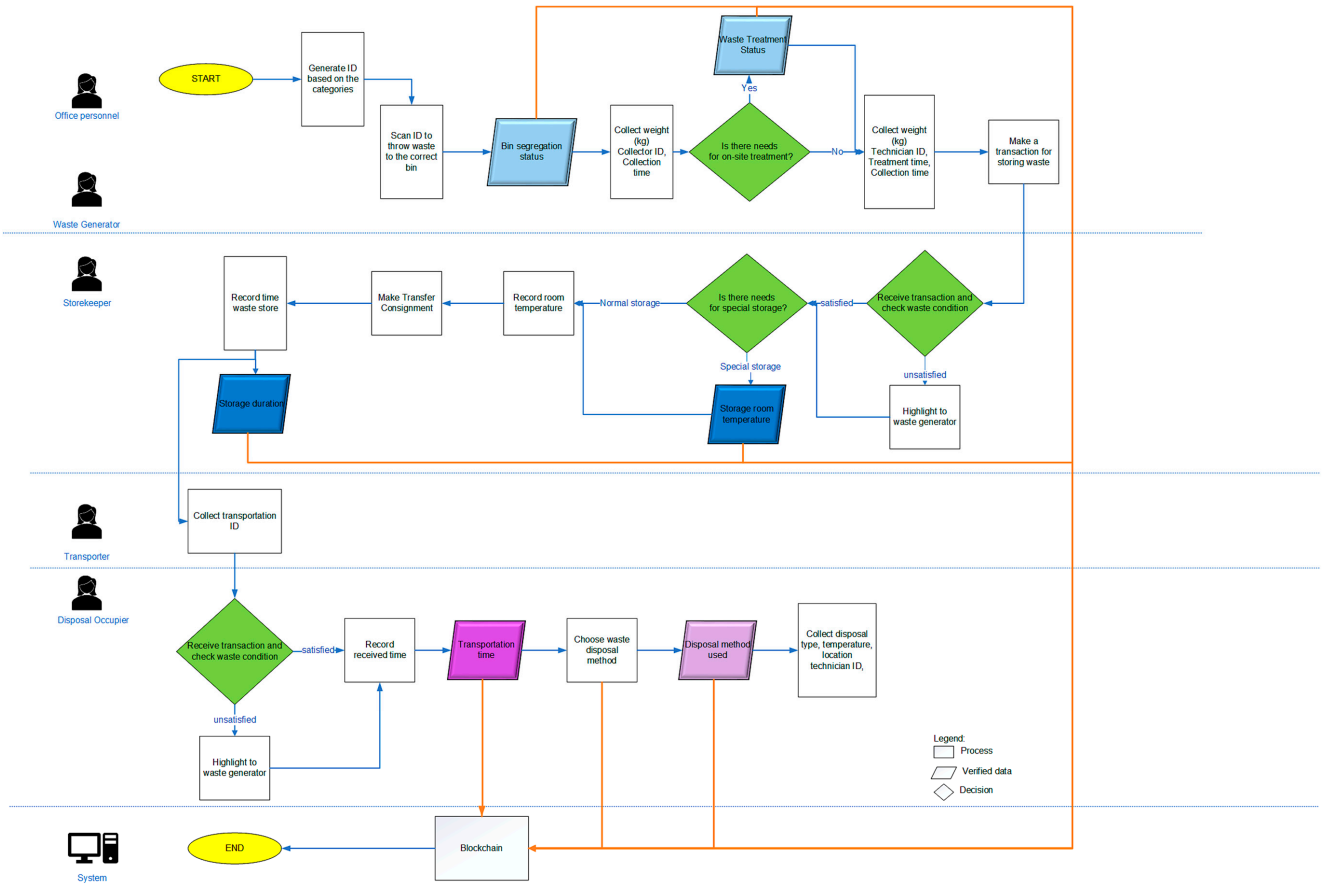


Figure 4. Framework of medical waste management digitisation proposal.

This model provides a convenient way for waste personnel to report and understand the quality of waste and the treatment done. Waste generator personnel begin the procedure by tagging the tools and equipment, including the waste bags, with a barcode. This barcode tagged on the waste bags will be vital in tracking and tracing in this system. All transactions by stakeholders, treatment, and automated data collection will be referred to by using the waste barcode. The detailed operation procedure is as follows:

(1) A transaction will be issued to transfer the waste from one party to another. The condition of the waste during collection will be recorded on the dashboard by referring to the waste bag barcode.
(2) Additional data on waste will be collected through sensor readings, barcode scanning on the bags, and staff credentials. This information will be automatically transferred to the blockchain system to update stakeholders regarding the quality of the waste and the status of any treatment done to the waste.
(3) The transaction will need to be verified by a member of the blockchain environment, and waste mishandling will be reported and highlighted back to the transaction sender. The condition of waste will be used as a guide to understand the quality of waste and treatment done.
(4) Verified transactions will be recorded on the dashboard and can easily be used for tracking and tracing.

To support this functionality, stakeholders' input and resources are collected automatically with sensors or by scanning the barcodes. Collection data will be directly recorded and will be an essential reference for each blockchain transaction, as illustrated in Figure 5. These collected data will be processed and analysed to aid in determining the six main

monitoring parameters of waste management. Table 5 shows a list of data collected from the stakeholders.

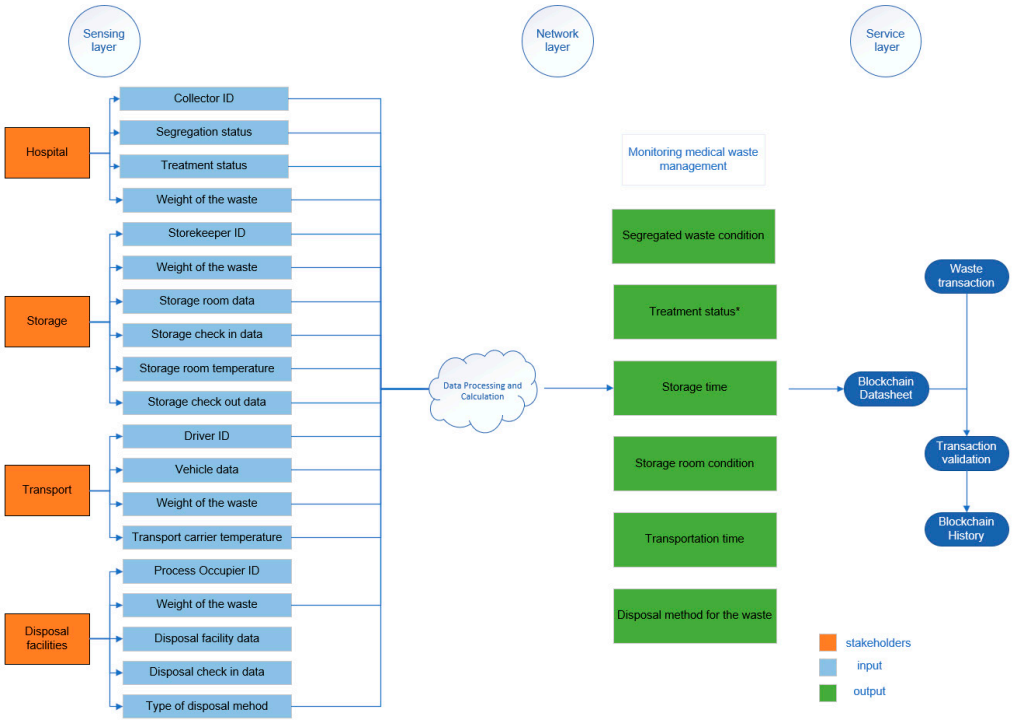


Figure 5. Digitisation data collection and analysis flowchart. * represents that it is an important step.

Table 5. Data collected from each of the stakeholders to support the proposed systems.

Stakeholders	Collection Data
Waste Generators	1. Facility resource 2. Collector ID 3. Segregation status 4. Treatment status 5. Weight of the waste
Storekeepers	1. Facility resource 2. Storekeeper ID 3. Storage check-in time (SCI) 4. Storage temperature 5. Storage check-out time (SCO) 6. Weight of the waste
Transporters	1. Company resource 2. Driver ID 3. Weight of the waste
Disposal facilities	1. Received time (RI) 2. Facility resource 3. Technician ID 4. Method of disposal 5. Method parameters

3.2. Implementation of Automated Data and Analysis

Variable input data, such as the waste categories and collectors' IDs, will be collected by scanning the barcodes. Constant data, such as the temperature of the storeroom and location, will be collected using sensors, including GPS. Tools and equipment will be

labelled with a barcode that represents the waste categories. The waste generators will need to scan the barcodes before the waste is thrown away. The flowchart of barcode scanning is shown in Figure 6. The scanner will connect the information to the correct waste bin and open the lid. This allows the waste to be segregated according to its categories and avoids waste violations. This information will be shared to update the segregation condition of the waste for collection.

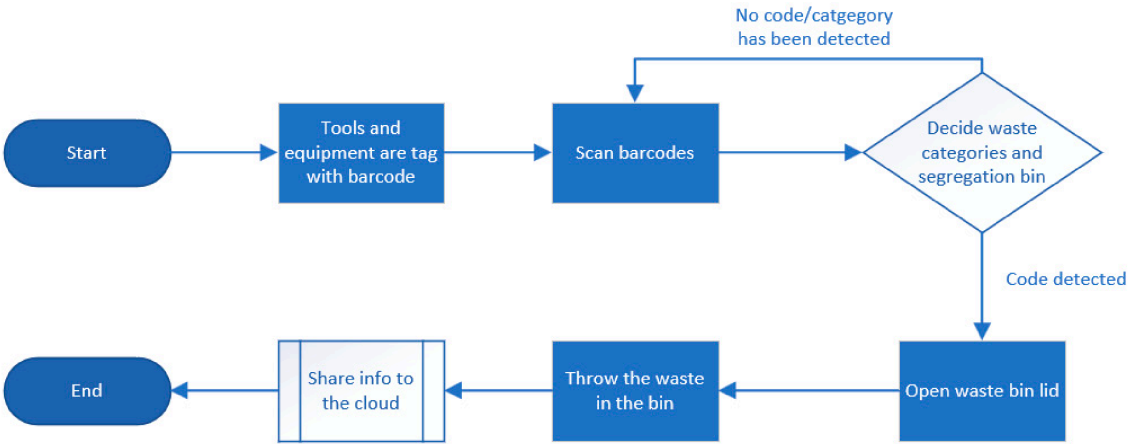


Figure 6. Flowchart for barcode scanning.

For constant data, the sensors will be set up and act as the transporters of data collection to the system. In collecting the storage room temperature, for example, a temperature sensor will be set up and channel the information to the system based on the waste registration scanned by barcode. The temperature will be collected and sent to the blockchain to prove the storage condition and be recorded on the dashboard. This value will be highlighted in red if it is unsuitable for the waste categories registered in the system. An example of a flowchart for data collected by the sensor can be viewed in Figure 7.

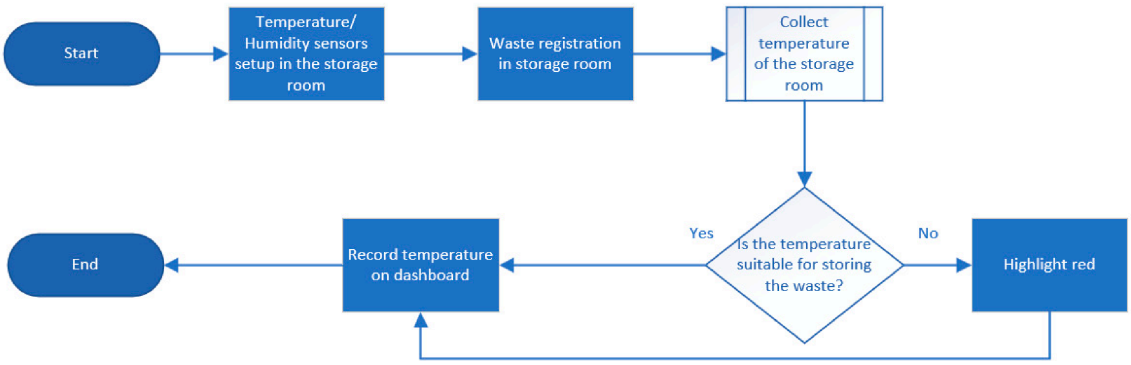


Figure 7. Flowchart for sensor collection.

The important parameters will need to be verified via the blockchain system every time stakeholders make any transaction. Thus, the database will become the guide for the stakeholders to get an idea of the condition of waste transferred from one to another. The proof of the work done gives a clear view of handling the waste based on its condition. The monitoring data structure is shown in Figure 8.

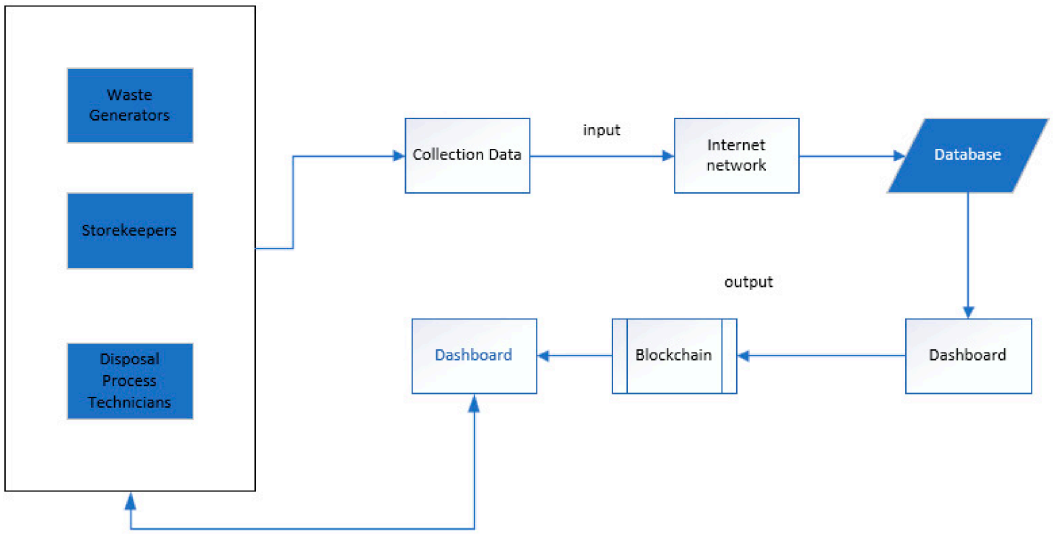


Figure 8. Monitoring data structure.

All data collected with the barcode scanning and sensors will be sourced through the internet connection to create the database. Processed data will be automatically transferred to the blockchain system. The storage duration and transportation time will be analysed using Equations (1) and (2).

$$storage\ duration = \mathrm{SCO} - \mathrm{SCI} \tag{1}$$

$$transport\ duration = \mathrm{RI} - \mathrm{SCO} \tag{2}$$

where

- SCO = storage check-out time
- SCI = storage check-in time
- RI = disposal facilities received time

The digital transformation of healthcare waste management systems presents both opportunities and challenges. While blockchain technology offers transparency, traceability, and accountability, the systems are designed to comply with data protection regulations. In healthcare contexts, sensitive information such as the details of waste and its origins, especially regarding pathological waste, the waste logs, and associated data related to patients or healthcare workers, is protected under privacy and legal compliance.

The capacity to present real-time and tamper-proof data directly supports data integrity and accountability needed by the regulations [89]. However, this immutability of blockchain may appear as a challenge to these regulations. GDPR, particularly in Article 17, grants the "right to be forgotten" [90]. In the context of waste management and healthcare, some workers may exercise this right following resignation or pension.

To address these concerns, the proposed system must adopt a permissioned blockchain infrastructure to control participation in the environment and data access for each participant. Sensitive data can still be shared with the chain, as the competence of the workers and handling activities will still be updated, associated with an anonymised identifier, such as an ID number that is controlled and managed internally by the employer. Personally identifiable information (PII) can be stored off-chain within the organisation's secure infrastructure and is only accessible under exceptional circumstances such as audits or legal investigations. This design ensures regulatory compliance while preserving the benefits of blockchain integrity and traceability.

As medical waste potentially contains patients' information, the most suitable medium should be a private chain. The nodes should be owned and securely managed by stakeholders' facilities. A team of people can be suggested to represent and access the private chain. The transaction and exchange of tokens are managed through these people. However, this system will also connect all staff, as the data will be collected throughout the process and this information will need to be scanned and sent to the system. The status of the waste could appear in the system to highlight the workers who have to work with the waste next. The staff will need to be trained in order to deliver the data collection to the system. Technical training involving node operation will be needed to ensure the quality of the whole procedure is smooth and accurate.

3.3. Implementation of Digitisation

Having a systematic system could simplify a lot of management work. However, in adopting technology in the industry, budget is one of the major factors affecting the decision. Nevertheless, there is no doubt that the adoption of digitisation is one of the strategies for better city planning. Food applications to advertise donations of leftovers from restaurants and cafés in Estonia have decreased the amount of food waste and, at the same time, reduced the food waste operation cost [91]. Amsterdam adopted underground garbage bins with waste level sensors, which have impacted the city's fuel consumption and gas emissions. The gas emission records have been gradually decreasing throughout the years [92]. Madrid has utilised smart waste bins that could connect to the waste collectors and have been operated to impact the collection schedules. This city reported saving 11,880 collection services every month [93]. The digitisation approaches show a good impact, benefiting the countries, even though they do not actually encourage any quality monitoring in waste management.

As medical waste is becoming a more critical challenge, monitoring the quality of the waste should not be taken lightly. Planners and policymakers should consider a holistic approach to biomedical waste management that balances cost efficiency with sustainability goals [75]. Planning and execution will need to involve various constraints based on the policies and laws, human and financial resources, and technology availability [82]. This study emphasized that adoption of digital technology and AI in medical waste management can improvise forecasting and decision making if the system could work with stable data availability [94]. Waste tracking systems with relevant information and connection to GPS and other IoT modules increase the transparency of logistic processes and reduce potential of unauthorised handling of hazardous waste [95].

Adoption of technology for medical waste is not an impossible task, as the healthcare industry itself is an industry that has adopted a lot of high-tech and modern machinery. Adopting new technology represents a significant investment for any country. Implementing new technology requires substantial upfront costs for purchasing equipment, infrastructure, and software. The potential significance of blockchain technology in augmenting security and preserving consumer privacy is exemplified by the healthcare sector. This is especially important considering that data breaches resulted in the compromise of over 133 million medical records reported as stolen, exposed, or impermissibly disclosed in 2023 [96]. Users' privacy can be safeguarded by anonymous digital signatures; blockchain technologies improve anonymity by employing methods like group and ring signatures [97]. By having both private and shared public keys, participants in group signatures enable any member to confirm transactions, which other members can validate using the public key. Blockchain networks give patients complete control over their data, while central databases storing patient medical data may be subject to security breaches [98]. The waste management service environment consists of personal data of the employees,

company and stakeholders' profiles, which need to be secured from any data theft or documentation forgery. Thus, blockchain here offers significant potential in the healthcare sector for maintaining, validating, and securely storing data. This is especially true for consortium blockchains, which are designed to allow controlled access for both node owners and miners. In consortium blockchains, the theory of consensus is applied to achieve an optimal number of validations recording the ledger with the characteristics of anonymity, tamperability, auditability, and autonomy, which is an effective solution for privacy-preserving medical data sharing [99]. This process ensures that data remains accurate and reliable, as it requires agreement among multiple participants before any changes are made [100]. By offering transparent and unchangeable records that boost stakeholder confidence, blockchain technology can greatly allay these worries.

The blockchain environment serves as a communication tool among the stakeholders. Every transaction between parties is recorded and approved by the members within the blockchain network. In making the transaction, the stakeholders are connected and validate the status of the waste; the environment can be created by private blockchain members.

A smart contract plays the role of an agreement between the parties. Thus, in having a smooth transaction, any activity must pass the requirements written in the smart contract. In quality management, quality criteria are typically established as a part of agreements between stakeholders, serving as a key determinant in transactions. If a product fails to meet the requirements set in the smart contract, it can be rejected and returned to the sender without disrupting subsequent procedures. In the waste management concept, the condition of the waste is probably not the best selection to set as the requirement of the transaction, even though that is the main point of managing this procedure. Rejection of waste due to misconduct may have effects on the environment. This system is suggested to use smart contract as a medium to control delivery and waste receipt. The quality criteria will serve as additional real-time data collected by the sensors and scanners and generated automatically on the user dashboard. The smart contract in this system works as a details validator to identify the correct entities and activities done to the waste. In a transaction, waste activity will include the details of the waste tag ID, sender and receiver account details, transaction dates, and expenditure, which relate to showing the number of tokens used for the transaction.

Miners are the members of the environment who work to validate the transaction. For the proposed system, miners will work to validate transaction histories and simultaneously highlight quality faults in the system. The concept of validation proof of work (PoW) can be implemented and serve as a validation checkpoint before a new block of waste activity is accepted. Since it is a permissioned chain, the validation is not used for open mining but rather as a lightweight consensus to ensure accountability of data from multiple stakeholders. This could not be used to correct the management directly, but the details can be useful to motivate the stakeholders to maintain quality work on the waste. A system with rewards and penalties functionalities can be implemented in future processes, based on the details generated through the validation process.

The proposed blockchain-based waste management system adopts a validation process as its consensus mechanism to ensure data integrity, transparency, and tamper resistance in a decentralised environment. Despite its high energy consumption, it offers the most mature and well-understood security guarantees among existing consensus protocols. This robustness is critical in the context of environmental waste management, where transaction authenticity, auditability, and resilience against data manipulation are paramount.

Smooth-running waste monitoring requires a lot of effort. Waste segregation and management awareness and training are included in most hospitals globally; however, it is proven that healthcare workers working in public hospitals were 91.2% less inclined to

follow proper practices in infectious waste segregation than those in private hospitals [101]. In having the blockchain concept of waste management, an effort is needed to provide training for stakeholders, professional personnel, market acceptance, and research and development [102]. The cost of this training should be also considered.

4. Demonstration of Medical Waste Blockchain Supervision

The initial phase towards developing the requirements for the dashboard for medical waste management was to analyse and identify any gaps in the present waste management procedures. This required knowing the precise requirements and features needed for the system to manage garbage collection, transportation, storage, and segregation efficiently. Subsequently, a smart contract was developed to protect and automate the process of managing waste. This included creating and implementing the smart contract's design and code to manage waste data, verify transactions, and guarantee openness in the blockchain setting. Extensive testing was done to guarantee security and dependability. Following that, the dashboard's front end was designed with an emphasis on making an easy-to-use interface that smoothly connected with the blockchain back end. Creating user-friendly interfaces and carrying out usability testing were part of the development. Figure 9 shows the flow of the demonstration preparation.



Figure 9. The flow of demonstration preparation.

The demonstration dashboard, shown in Figure 10, uses the MetaMask extension to communicate with the Ethereum blockchain ecosystem. Every waste management transaction involving this integration requires two levels of authorisation: network-level validation and user-level permission. A MetaMask transaction prompt facilitates user approval by allowing the user to examine transaction details and verify their consent. The waste stakeholders will be connected to the dashboard by logging into the MetaMask account. Any transaction begins with initiating a waste shipment to start the shipment process, delivering waste shipment if the waste has been out for delivery, and receiving the shipment to confirm it has been received. Before a transaction is permanently recorded, network validation that is achieved through Ethereum's consensus mechanism makes sure it complies with blockchain protocol criteria. Stakeholders can review the comprehensive criteria of the waste before approving anything to evaluate the state of the waste received. The clinical waste profile will guide the stakeholders in understanding the condition of received waste. Before moving forward with any approvals, it is imperative that all stakeholders have access to the necessary data and that process transparency is upheld. To reduce human error and guarantee adherence to pre-set criteria, the dashboard uses smart contracts to automate and enforce these rules. Through this system, the smart contract ensures that stakeholders note the waste condition before approving the received status and that all data needed are scanned and channelled before delivering it to the next step. Data integrity and system security are improved by the Ethereum blockchain's decentralised design. Since waste management is an essential service, outright rejecting and returning waste to the generator is not advisable, as this could result in repeated tasks, overstored waste, and potentially highly hazardous situations. Instead, rejecting waste should be used to highlight issues with the quality of the waste transferred. In the future, a system of rewards and penalties can be introduced, leveraging data from this system to improve waste handling and control more effectively.

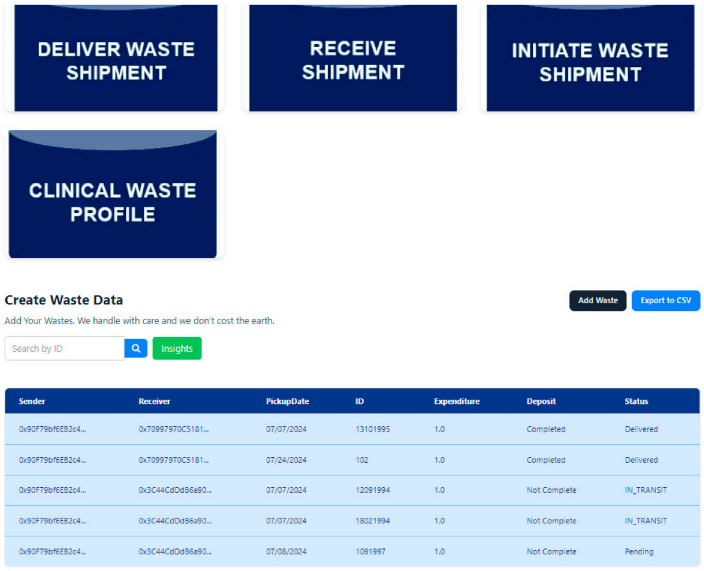
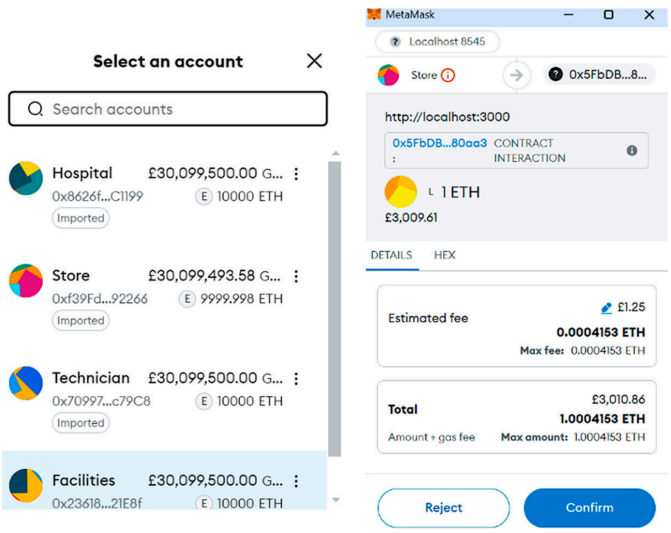


Figure 10. Dashboard for the stakeholders to make transactions.

The Ethereum platform uses consensus procedures and cryptographic hash functions to protect transaction records from illegal changes and tampering. A secure and unchangeable ledger is produced by encoding each transaction into a block and connecting it to the one before it. All transactions will be automatically logged and displayed on the dashboard for easy access to historical records. Stakeholders can get extensive representation of data and real-time insights through the dashboard's "insights" feature. One such interface for stakeholders is a registered account, as seen in Figure 11, which shows the consent popup for transaction confirmation. All parties concerned can check the comprehensive history of transactions that are recorded and kept up to date by the dashboard. Every transaction's traceability and auditability are guaranteed by the blockchain's tamper-proof storage of this historical data. The incorporation of this tracking feature facilitates ongoing oversight of the waste management procedure. By offering an auditable record of decisions and actions made throughout the waste management lifecycle, this feature not only improves operational transparency but also fortifies accountability among stakeholders.



(**a**) (**b**)

Figure 11. (**a**) Account created for the demonstration. (**b**) Approval of transaction.

When transferring money using Ethereum, a gas cost is needed in addition to the amount being sent, as Figure 11b illustrates. This gas cost covers the computing resources required to conduct the transaction on the Ethereum network. Calculating the gas cost is an essential component of transaction planning since it assists users in figuring out how much gas is needed for a smooth transaction. Users risk incurring excessive fees if too much gas is allocated; if too little gas is allocated, the transaction might not proceed or might take longer.

Better features like real-time transaction history are also available on the dashboard, enabling users to conveniently trace their activity and keep an eye on their balances. It has an easy-to-use interface with straightforward navigation that is intended to minimise complexity and user errors. The Ethereum network is seamlessly connected thanks to the integration with MetaMask, which also makes sending, receiving, and managing Ethereum-based assets easier. Additionally, the application offers users rudimentary support for managing several addresses and accounts, which can be very helpful when arranging various departments or transactions. It provides users with transparent feedback on their actions by supporting necessary features like transaction confirmation and status updates. With the help of these capabilities, the dashboard promises to make interacting with Ethereum's decentralised ecosystem more practical and approachable. The platform's overall goals are to facilitate user participation in the application, encourage wider acceptance of decentralised technologies, and provide a complete, safe, and easily accessible environment for managing Ethereum medical waste.

Proof of Concept Verification

The IoT-based and blockchain medical waste management model has been verified to show the capacity for efficiency, effectiveness, and the opportunity for documentation fraud. A hypothetical case study is plotted to validate the system's workings. Medical waste management and the transaction method in the United Kingdom are studied. The United Kingdom operates medical waste management using two paper-based documents, which are Waste Transfer Notes and Hazardous Waste Consignment Notes. The documents work as a medium to communicate between the storekeeper and the transportation company. Disposal facilities will be communicated with by using only the consignment note. The parameters collected using these two documents are examined to map to the country's waste monitoring requirement.

The United Kingdom requires five important parameters to be detailed in waste monitoring, and the clinical waste strategy was renewed in 2022 [103]. The constructed case study simulates waste transactions daily in a hospital. By making the monitoring element requirement the benchmark, both existing and proposed system approaches are compared. Table 6 shows the comparison of both monitoring methods. From the comparison, the proposed blockchain system is completely able to supply all required monitoring data, which is 60% better than the current implementation. This proposed method has fully connected all parameters suggested by WHO that can help to prove quality management of medical waste. Regardless of the transformation of waste structure in the United Kingdom, the NHS still does not fully monitor the whole procedure of waste management, even though one of the six targets in the strategy is to generate comprehensive and consistent data with up to 95% accuracy [104]. Accuracy of data should include all important monitoring data as required in the guidelines. This case study is expected to show the ability of digitisation to approach all waste management monitoring elements precisely, while improving the monitoring time efficiency and producing high-quality data to avoid any potential chance of fraud.

Table 6. Comparison of existing and proposed system benchmarked on the UK monitoring requirement [20,105].

		Segregation and Collection	Storage	Transport	Disposal
National monitoring requirement		Segregation of waste	1. Storage duration 2. Refrigerated temperature for extended storage.	Licensed contractor	Disposal method
Existing	Waste Transfer Note			√	
	Hazardous Waste Consignment Note			√	√
Proposed system		√	√	√	√

Volunteers of various ages and genders who represent waste-related workers were invited to experience both manual and digital systems. Twenty-five volunteers with digital academic backgrounds were selected to verify the usability of the system and were given training and some information on waste management. A set of questionnaires to measure the effectiveness and efficiency of both systems was provided for the experiment. These questionnaires were also set to see the chance of fraud in documentation happening in both systems. The volunteers needed to demonstrate the whole procedures of waste management and record them by using the existing documentation. A similar scenario was repeated, but this time it was recorded through the digitised system. The case study waste data of the digitised system, as shown in Figure 12, was collected automatically using barcode scanning and sensors and transferred to the system. Questionnaires were used to validate information on waste procedure accuracy and quality, like quizzes that can be brought to understand the efficiency and effectiveness of the systems. The responses on the efficiency and effectiveness of both methods were compared. The volunteers generally needed more time to monitor waste management using the recent NHS notes and, at the same time, made many errors in auditing. Some information was not recorded in the systems but had been unproven in detail. This section was tested on volunteers to observe the chances of inaccurate information, fraud documentation, and misinformation.

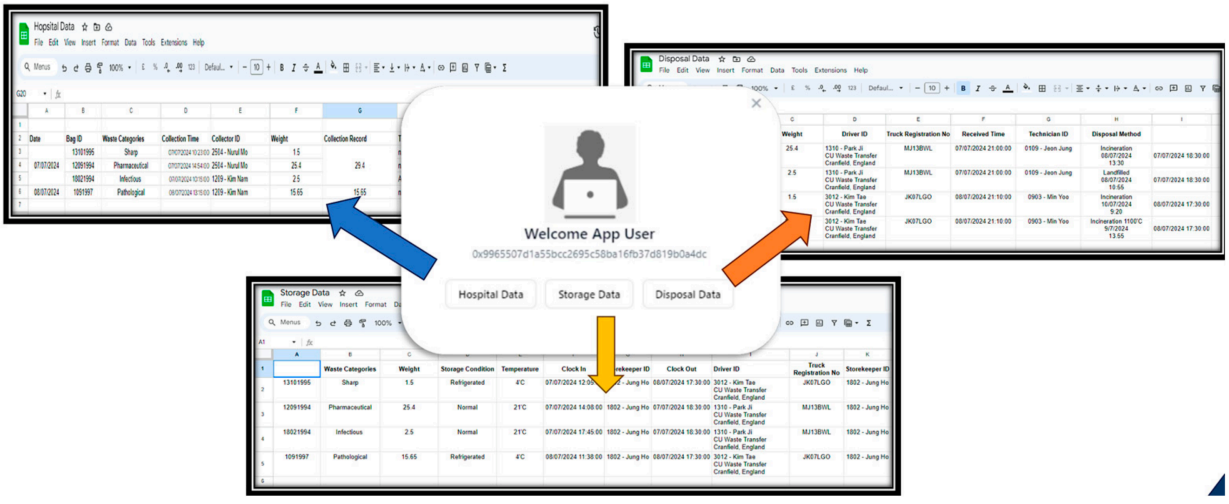


Figure 12. Automated data for case study.

This work explores and promotes digitisation in current systems and can positively influence the effectiveness of managing medical waste. In comparison with the traditional method, this system has entirely covered all required information, and the stakeholders

can easily extract data for monitoring. This information impacted on the quality of waste management in providing proof of activities done to the waste and the credibility of the employees who work with the waste. In terms of the case study, the volunteers easily followed the sequence of waste activities from the log and understood the quality of work done to the waste directly from the dashboard.

The proposed system, empowered with blockchain technology designed as needed for the country's requirement, has been dedicated to creating an effective environment for communicating with all stakeholders in medical waste management. As this case study simulates daily waste transactions, two recording methods are compared to evaluate the quality and reliability of the reports. The NHS clinical documentation strategy and the proposed blockchain-based digital system are compared by using two separate, but structurally identical questionnaires designed to audit the accuracy and completeness of the documentation. From Figure 13, the proposed system shows good effectiveness in auditing works while minimising the time taken in auditing. The potential for fraud and document forgery is measured by observing the audit done during the case study. In comparing both correct answers from the questionnaires, the proposed system has improved monitoring effectiveness by 25.17%. Time efficiency to monitor the whole procedure decreases to show how digitisation simplifies the job. By having a digital system, efficiency improves by 27.85%. Blockchain is again highlighted as a medium to prove the work done as it can eliminate the potential for documentation fraud and waste misuse. The system promoted an improvement of 52.59% in the chances of eliminating the potential for fraud in medical waste management.

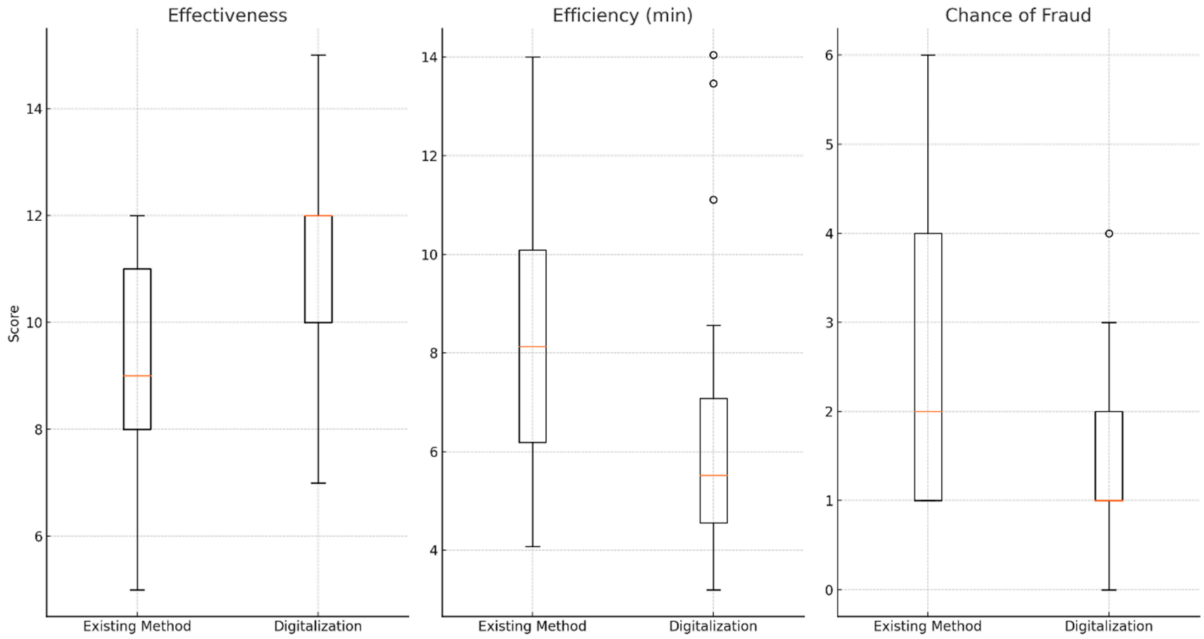


Figure 13. Comparison of recent NHS waste note method and the proposed system.

This case study was conducted in an open environment in which the volunteers were not working with waste management and were not familiar with monitoring the waste. Better effectiveness and efficiency percentages are expected to be achieved if the system can be examined in real industry and with people who have been familiar with working in monitoring medical waste management. The potential of zero chances of fraud can be easily achieved since these people are trained to understand the importance of waste management in the healthcare sector.

5. Conclusions

The procedure of medical waste management has been manually monitored with a traditional paper-based approach. The digitisation of this product service may improve the procedures to be more effective and efficient. Adoption of blockchain in waste management can be a method of upgrading the service by providing high-quality data. Blockchain-enabled systems are valuable not only for facilitating communication between the stakeholders and tracking the shipment of the waste from one party to another but also for monitoring parameters of waste management, including providing verifiable proof of completed tasks. This system promotes access to the monitoring elements from the dashboard that are automatically collected through scanning and sensors. All information shared is unrevocable and guides the stakeholders to understand the quality of waste management services provided for medical waste.

The adoption of blockchain has demonstrated significant improvements in the quality of waste monitoring, enhancing both the effectiveness and efficiency of the service. Hypothetically, the proposed system can collect 60% complete data compared to current methods. Additionally, the system improves the speed of recording and monitoring, increases overall effectiveness, and reduces the likelihood of documentation forgery to nearly zero. However, for better reach and results, this system should continue to be conducted as a pilot test in the real industry within a hospital setting to see the feasibility of the system in the real world.

Networking stakeholders with profile data stored in the cloud can encourage threats to data security and privacy. There will be hundreds of hospitals and clinics, with hundreds of employees in each country. Thus, a lot of data will be available and must be sourced and analysed through cloud systems. A further study focusing on the security of big data and profile privacy can be done to improve confidence in the proposed system. Data and cybersecurity studies are not yet extensively focused on in this proposal.

As a transformation to a digital-based waste management system will require significant investment, the government can act as a prominent supporter and motivator since waste management based on smart technologies requires a high level of movement, which can increase governmental incentives and announcements. This investment of resources in developing user-friendly applications with high reliability ensures users of the environmental and financial profits. Training is important to be provided in any application of technology, suggesting the need to follow a formal education and training approach to build a good blockchain environment, and this can influence the impact of the job market in a country. Technology experts are in demand, and academic institutions will need to offer many more STEM courses to meet the demand. However, if digital adoption is done accurately, this can benefit better waste management with precise waste disposal financing. Therefore, it is highly recommended to conduct a thorough review and analysis of the costs involved in implementing the change. Networking stakeholders with profile data stored in the cloud can encourage threats to data security and privacy. A further study focusing on the security of big data and profile privacy can be done to improve confidence in the proposed system. The fact that the best way to reduce the amount of waste is by eliminating it is undeniable. Research has shown that waste from healthcare facilities works for recycling. A pilot study in Kyrgyzstan sold treated plastic syringes and autoclaved needles to make coat hangers and flowerpots [16]. The recycled materials in clinical waste can be highly streamed because of the plastic content. In Malaysia, a hospital can come up with a recycling programme to support the recycling of hospital waste [13]. Illegal recycling or sales to private entities make the enforcement of the laws extremely difficult and may result in the loss of the waste's economic value. In the adoption of a blockchain environment, waste can be given a profile for any buyer or manufacturer in order to know the waste status, and with the growth of science and technology, much safer disinfection

treatments can be done. Additionally, having proof of the quality of work done can be a medium to convince manufacturers or buyers to welcome materials from this industry.

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