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Blockchain-Enabled Medical Waste Management System for Enhanced Traceability, Safety and Environmental Protection

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Abstract

Medical waste management has grave issues concerning traceability, regulatory, and the environment. The traditional systems which are centered on manual record-keeping and the usage of centralized databases usually lead to data loss and unauthorized disposal along with inefficiencies. In this paper, the researcher comes up with a blockchain-integrated medical waste management system to support Internet of Things (IoT)-driven technologies and smart contracts to streamline a safe, autonomous, and anti-tampering system of waste handling. Smart bins enabled with IoT and fitted with GPS, ultrasonic and weight sensors collect live data regarding waste creation and conveyance and this information is transferred or relayed through Wi-Fi/LoRaWAN to the edge/cloud gateways. This data is stored in a protected manner, verified on a permissioned blockchain and, most importantly, the most important tasks, such as scheduling a pickup and approving disposal are done within smart contracts. Experiment findings show 100 percent traceability accuracy, a 30 percent less time in disposal, and a 90 percent better regulatory compliance. The proposed framework will have three new contributions as compared to the existing systems, augmenting the route validation algorithm with a live tracking device in the form of GPS to detect and prevent deviation, a neural network-based model to pre-validate transactions and prevent fraud, and an optimization layer within the smart contract that will support the energy cost to ensure scalability of the proposed framework. The said features altogether allow smart, anticipatory, and regulation-conformant waste processing, which makes this work stand out of existing methods.

Keywords: *Blockchain, Traceability, Medical Waste, Environmental Protection, GPS-based route validation.*

1 Introduction

Illegal dumping of medical waste has turned out to be a major global concern since it can have dire effects both to the environment and to the human body. Hazardous medical

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wastes not safely handled may consist of sharp objects, infectious wastes, chemicals and pharmaceutical wastes all of which can cause severe environmental contamination and affect the health of people directly. Poor handling of these wastes may cause expansion of communicable diseases, environmental destructions and harm of lives of animals and vegetation. Due to the dangers associated with medical wastes, there is need to implement effective and controlled disposal systems that will help counter these dangers and guarantee safety of the population and the surroundings [1].

The complications of the waste segregation, collection, transportation and disposal procedures also contribute to the problems the society experiences as a result of mismanagement of medical waste. Resorting to common traditional medical waste control and management segments such as manual documentation and silo-based data storage causes this kind of traditional systems to have just a hard time securing actual-time booking and responsibility [20]. These forms of systems are bound to mistakes and delays and irregularity in waste management, causing unauthorized or illegal methods of disposal, especially in the developing regions that lack the capacity to manage the waste [2]. Moreover, the absence of a well-developed system of tracking waste leads to insufficient transparency and to the inability of the regulatory bodies to supervise the process and guarantee the enforcement of the rules.

The significance of a high-level medical waste management system cannot be underrated in order to curb these problems. The introduction of effective waste management framework is essential in order to discard the medical waste safely and comply with its disposable nature. It would not only reduce the risk of environmental pollution and health risks but also efficient collection of wastes and their disposal [3]. The system has the ability to make sure that regulation standards of managing waste are set through the improvement of traceability of medical wastes all the way until after the end disposal. This would ensure transparency, efficiency of operations, and would reduce human error and fraud in the waste management procedure resulting in a secure and sustainable environment.

The addition to the waste management system of Internet of Things (IoT) devices is instrumental in managing such challenges. Medical waste bins can be equipped with devices that allow one to track the progress of their purpose (i.e., see whether the bin is full or empty) by enabling IoT-based sensors (RFID and GPS) to control this process. When waste bins are fitted with RFID tags, it would be easy to track every waste batch along the waste management life cycle [4]. An embedded GPS tracking feature can notify where the waste is in real-time so that the waste goes in a given route and raise alarms in case the waste goes out of the way into illegal dumping or misuse of medical waste. This real-time tracking feature is essential both in terms of keeping compliance and streamline the waste collection process and minimize delays and improve the efficiency of the whole waste handling [21].

Implementing such technologies as IoT and using blockchain to verify the data, the proposed system would make sure that all the payments and activities connected to the medical waste disposal would be stored safely and could be audited. The inclusion of RFID sensors, Blockchain technology combined with GPS systems will make it impossible to alter the waste data, and the processes of waste management will become open, efficient, and complying with all regulations [5]. The combination of the IoT devices and blockchain technology provides a safe, robotic, and scalable solution to medical waste that can be used to solve the ongoing issues that involve the presence of dangerous medical waste and its effect on human health and the environment.

2 Related Work

The current paper suggests implementing a blockchain-based, IoT-friendly infrastructure of safe and transparent management of e-waste in a smart city. It combines the use of smart bins, smart contracts, and IPFS in tracking the electronic waste back to the production and disposal. A reputation based selected model of stakeholders would eliminate the risk of fraud, and a system of certification guarantees safe data destruction. There are five smart contracts on the Ethereum that are used to process registration, order management, waste handling, bidding, and destruction. The system was tried on Ethereum blockchain, where gas analysis showed it to be cost effective. The security of smart contracts was checked with SmartCheck. All scalability issues were addressed by offloading the large data to IPFS, and this way made the system flexible to other wastes [6].

This study considers the way blockchain has the potential to revolutionize waste management according to the mission of the circular economy and European Green Deal. It deals with the challenges of traditional systems like lack of traceabilities, little accountability of the stakeholders and environmental hazard. The study mentions the potential through smart contracts, digital product passport (DPPs), and integration with the Internet of Things (IoT) of blockchain. It evinces increased visibility and real-time tracking and regulatory coverage of all kinds of waste streams. Effective installations such as Waste24 system in Poland bear enhanced logistics and cost reduction. Standardization of DPP, interoperability, and DPP scaling, however, are still difficult. As highlighted in the paper, blockchain is used to construct efficient, eco-friendly, and credible waste systems [7].

The current research is an attempt to introduce a blockchain-based infrastructure to address healthcare waste management, particularly its sheer volumes during the COVID-19 disease. It also fixes the issues of traceability, transparency, and accountability of the stakeholders in workable systems. Two frameworks are built on Ethereum; one pertains to generic HCW and pharmaceutical waste traceability throughout their life cycle are enforced through smart contracts. The roles of stakeholders and workflows are specified, and smart contracts are checked through MythX and Oyente in terms of security. The findings prove high cyber resilience and affordable operation. The issues to deal with are scalability, interoperability, and privacy trade-offs of decentralized settings. The research promotes a future scenario of implementation of smart device, DApps, and logistics framework to be more widespread and high-performance [8].

The research map examines the application of blockchain in the reformation of smart city waste management that was based on centralized with fragmented operations to transparent, secure, and open waste management. It solves such issues as low traceability, inefficiency, and fraud. The article addresses blockchain characteristics, one of which is decentralization, immutability, and smart contracts that can be utilized to track in real-time, to be in compliance, and to receive incentive plans. It contrasts such platforms as Ethereum and Hyperledger and presents cases of its application, such as RecycleGO and Plastic Bank. The research establishes a scalability, latency, IoT compatibility and data privacy limitation. The vulnerability of smart contracts and their requirements of significant data storage are also cited. It raises the need to investigate the blockchain of the optimization of the urban waste further [9].

The research presents the development of a safe blockchain EHR system to overcome such threats as ransomware, DDoS, and unauthorized attacks to healthcare. It has suggested a new dual-layer encryption model DSPIC that was coupled with the MP-CPeSOA algorithm to achieve effective key generation. Data storage with Merkle tree integration keeps data tamper-proof and restricted. In real-life health data simulation results, it is seen that it has greatly high encryption speed, resistance against attacks and lesser resource compared to AES, RSA, and ECC. The system increases the performance of EHR in real-time and lowers the memory usage. Some of the associated challenges are handling of complex healthcare data and scaling on large data sets. Future Research In future study will focus on the search advanced privacy models and storage testing in noisy conditions [10].

The present paper proposes a decentralized system that utilizes a blockchain in managing the medical waste, benefiting the issues of inefficiency discussed during the COVID-19 pandemic in Vietnam. It proposes the Medical-Waste Chain, which runs on Hyperledger Fabric and allows secure storage of data and tracking the use of equipment. Transactions between hospitals, recyclers and treatment facilities are handled by smart contracts. The system demonstrated good performance and stability at loads with high values on the basis of the Hyperledger Caliper. It increases transparency and decreases the information asymmetry involved in the stakeholders. Restrictions such as non-real time oracle integration/access control mechanism are present. The paper identifies the possibility of using blockchain to enhance integrity and sustainability in the management of medical waste. [11].

This paper looks into barricades to blockchain adoption in the management of recyclable hospital waste in India in post COVID times. Based on an integrated MCDM framework (BWM and DEMATEL) it identifies and examines 15 major revolving challenges in organizational, technological, and regulatory elements. The key obstacles are lack of government assistance, ineffective strategic planning and shortage of expertise. The research groups them into cause-effect categories, which demonstrate how some challenges cause general adoption problems. Regulatory and technological factors are proven to have an effect as identified in sensitivity analysis. Although situation-based in India, the results provide a guideline that could be followed by policymakers and healthcare managers. This research offers a great insight into the process of overcoming the barriers on the adoption of healthcare waste systems over blockchain [12].

The study presents a proposal of blockchain-cloud hybrid architecture which can be used to securely and efficiently manage Electronic Health Records (EHR). It solves the problems of centralization systems such as data breach and slow retrieval through combination of the permissioned block chain, Merkle trees, genetic algorithms, and distributed cloud storage [19]. Such partitioning of data in both AWS and GCP enhances access speeds as well as scale. MIMIC-III based testing resulted in 30 percent reduction of transaction time, 40-percent improvement of retrieval and 20-percent increase in scalability. The security is provided through smart contract, encryption and differential privacy. There are problems such as computational overhead and real-time access maintenance. The next research direction consists of ML-based threat detection and cross-domain applicability [13].

Table 1: Comparative study

Paper Ref	Problem Addressed	Novelty / Unique Contribution	Methodology / Technology Used	Key Findings	Challenges / Limitations
[1]	Insecure, opaque e-waste handling in smart cities	IoT smart bins + stakeholder-based Ethereum smart contracts	Blockchain + IPFS + smart contracts + reputation system	Cost-effective traceability; secure proof of data/device destruction	High gas cost; off-chain storage
[12]	Illegal resale and pricing gaps in e-waste disposal (India)	SHA-256 hash + price validation + smart contracts for compliance	Ganache, Metamask, IPFS, Solidity smart contracts	Transparent pricing and e-waste flow; fraud detection	Adoption barriers, lack of real-time validation
[3]	Lack of secure, auditable tracking for healthcare and pharma waste	Dual blockchain systems for medical and pharmaceutical flows	Ethereum smart contracts; MythX & Oyente testing	Secure destruction verification; cost-effective smart contract design	Scalability, privacy management
[6]	Fragmented med-waste processes in Vietnam	Hyperledger Fabric for decentralized waste lifecycle tracking	Fabric network + chaincode + Caliper testing	Stable performance under load; enhanced traceability	Lacks oracle integration; no fine-grained access control
[10]	Poor waste segregation & staff incentives in hospitals	NFT-based rewards and penalties for medical waste handling	NFTs + Ethereum-based smart contracts + gas analysis	Polygon and Fantom found cost-effective; behavioral impact on segregation	Volatility, testnet-mainnet gaps, UX not assessed
[5]	Security and restoration issues in EHR during cyberattacks	Polynomial crypto + MP-CPeSOA for key optimization	DSPIC + MP-CPeSOA + Ethereum + Merkle tree	High restoration speed; low power use; high attack resistance	Computational complexity; blockchain size
[8]	Centralized EHR systems with slow, insecure data retrieval	Blockchain-cloud integration with Genetic Algorithm for efficiency	Cloud partitioning (AWS/GCP) + blockchain + Merkle tree	40% retrieval improvement, 20% scalability gain	Lacks real-time support and ML integration
[11]	Weak key generation and static feature models in EMR	Hybrid IFRSA combining Firefly & Reptile Search for sanitization and recovery	Merkle tree + IFRSA + symmetric encryption	Better privacy and high restoration efficiency	No real-time feedback, complex for practical deployment

[15] [23]	Unsecure access and poor collaboration in traditional EHR sharing	RSA + Fiat-Shamir with Merkle validation in a federated learning setup	Hybrid heuristic encryption + FL + smart contracts	Strong encryption, FL preserves privacy, secure sharing	Cryptographic overhead; multi-chain complexity
[18]	Poor tag classification in noisy (low-SNR) environments	Cognitive Risk Control (CRC) with dynamic reader-tag distance tuning	CRC + USRP + 104 time/freq-domain features + SVM/RF/KNN classifiers	Up to 15% accuracy boost with CRC; 104 features outperform smaller sets	Static noise model; limited tag diversity tested

3 Proposed Work

The architecture of the medical waste management system based on blockchain includes several layers, each dedicated to fulfilling a certain purpose so that the traceability, integrity, and efficiency of the waste management process could be guaranteed. In the architecture diagram figure .1 shown above each component is explained in detail below in a technical manner

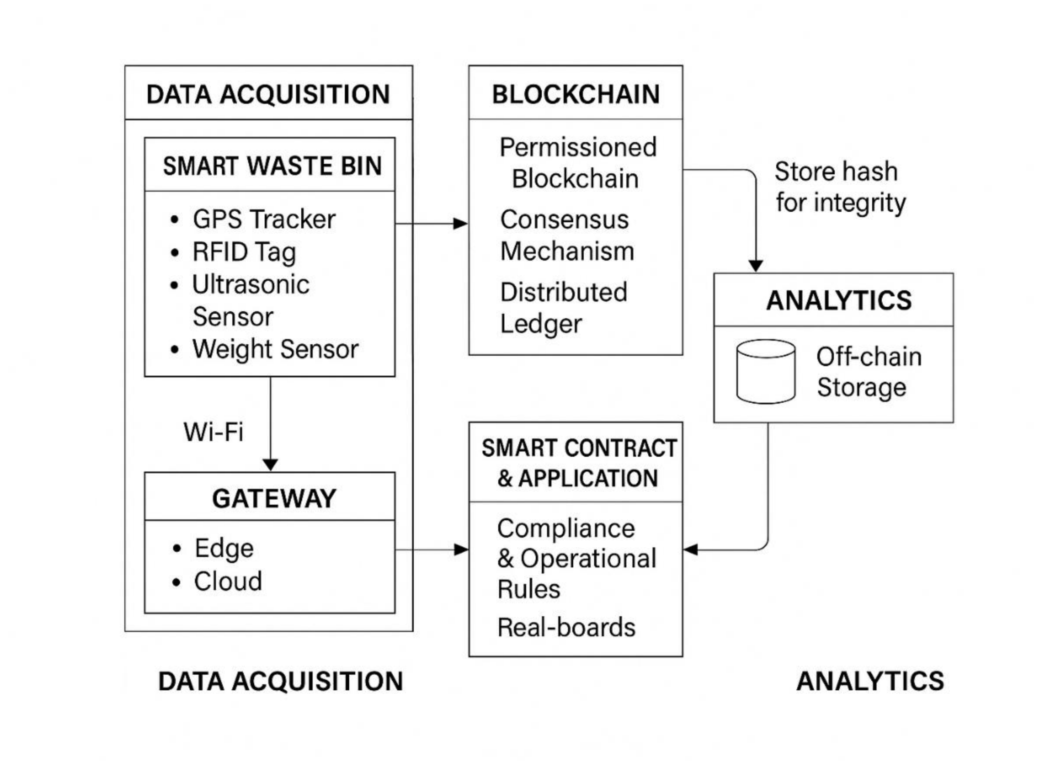

Figure 1. Proposed Architecture

3.1 IoT Layer

IoT layer will extract waste bin data, which will give current information about the patient wastes. The above layer can support monitoring and management of waste in the organization since the sensors and communication technologies in the layer support continuous monitoring. This layer has the following parts:

3.1.1 Smart Waste Bins

Waste bins are fitted with a Global Positioning System (GPS), e.g. NEO-6M, which then allows the location to be tracked constantly. This will make the precise location of every bin something always in sight and thus will prevent its unauthorized relocation or illegal dumping and filling. The GPS tracker may help in delivering real-time location to the central monitoring system and being safely recorded in a blockchain ledger. This helps not only in increasing in transparency, accountability but also helps in regulatory compliance since there is a tamper-proof record of the waste bin movements.

In order to measure the level of the bins, an ultrasonic level sensor such as HC-SR04 is mounted. The sensor employed here is based on ultrasonic waves that determine distance between the sensor and surface of waste in the bin. At certain capacity, e.g. when the bin has become 80 percent full the sensor sends it signal to the system, and the bin needs to be collected. The information on fill level in real time recorded by the sensor is used to plan the route of waste collection and lead to timely collections and thus increase the efficiency of waste management processes.

Figure 2. Smart Waste Bins

The weight sensor like the HX711 which has loaded cell, monitors the quantity of garbage trash in the bin. This information will guarantee that the amount of waste that is collected is well documented. The weight information is important to keep the record straight in the blockchain ecosystem as that would enable the volume of the waste to be the same as the data in the log as the waste is transported and disposed.

3.1.2 Wireless Communication

The construct of the waste bins has Wi-Fi systems such as the ESP8266 to enable localized communication in the medical institutions or the areas that the waste bins are located. Such modules will help to transfer data to cloud storage in real-time or locally at IoT gateways, so that the data about the status of bins and their filling will always be current and under control. It enables real-time notifications and quick responses to enhance the overall utilitarian performance and safety of the waste management procedures in a closed-in setting where Wi-Fi connectivity can be easily obtained.

In parent scenarios that need to communicate over long distances, including outdoor or hard-to-reach locations where Wi-Fi receptions are weak or absent, the bins have LoRaWAN modules (RAK811). Such modules enable the low power, long range data transfer, thereby being suitable to decentralized waste management infrastructure. Gateway devices, Raspberry Pi 4 as a device in edge computing and AWS IoT Gateway as a device to integrate with the cloud, will act as liaison objects, retrieving, filtering, and passing on the information contained in the bins to the blockchain network. Whereas the Raspberry Pi would allow performing the processing locally in real-time, to minimize latency, the AWS IoT Gateway would provide secure centralized data aggregation prior to continuous analysis. These elements in combination promote a powerful, uninterrupted transaction of the data of the waste in the blockchain system to increase transparency and system strength.

3.2 Blockchain Layer

The blockchain layer does nothing other than securely holding the data, collected through the use of IoT devices, in an immutable layer, transparent, and to the limited number of authorized users. It will ensure that only the authorized entities i.e., hospitals, transporters and controls bodies should become a part of the network by using permissioned blockchain framework. It has selective access and also helps in ensuring confidentiality and highly restricts the capability to read to or write into the block chain. Permissioned model creates the trust in the system when preserving the privacy and integrity of the data.

A consensus mechanism is used to validate transactions in this permissioned setting, e.g. Practical Byzantine Fault Tolerance (PBFT). PBFT is particularly made to suit such applications, and offers faster and reliable agreement between trusted operators at a reduced computational cost compared to the environment of a public blockchain. Any transaction, which has to do with the generation and deposit of waste to disposal end, is applied in a distributed ledger with the help of this verification. The records cannot be changed and have a time stamp on them leading to an indelible audit trail that can be verified as regulatory compliant by the regulators and interested parties and can also be used to track life cycle of medical or hazardous waste.

3.3 Smart Contract Layer

Smart contracts are the most important part of the system of management of the medical waste since they will offer the business logic and the operation rules according to which the automation operations will be realized with the least number of stops and threats of hacking. The time of waste collection and permission of waste transporter; verification of disposal of waste are some of the tasks done in automatic location in these self-implementing contract. To illustrate this, a bin after attaining a particular weight or filling level can individually request a pick-up and monitor the pick-up request to the extent that any transporter at all may take away the trash but he can only be a duly trained transporter or one with a right to do so. The blockchain is used to authenticate and permanently add every transaction including pickup, transfer and disposal and this reduces human error furthermore making the opportunity of fraudulent transactions low.

The collection of rules in the smart contracts is provided to ensure the observance of legal and regulatory aspects along with automation of the operations. Where special handling procedures may be applied to the handling of some type of wastes (e.g. hazardous) the smart contract ensures that the associated requirements and authorisations have been met and only thereafter permits further operations to be undertaken. Operation rules are also incorporated in order to make the processes easier such as opting in dynamic and real time transporter assignments according to availability and locality. This will reduce time wastage and increase the amount of resources used and thus the end gain will be that the medical waste will be treated in a very efficient manner besides the other environment and safety regulations it will also be able to treat the health waste as it is supposed to.

3.4 Application Layer

The application layer will serve as a medium between the users and the blockchain based waste management system, to make the conduction of interaction between the healthcare administrators, waste transporters and the regulatory bodies convenient. It is equipped with dashboards that provide visual information on the real time of the mechanism of waste management. Such dashboards allow the administrator to observe the state of each trash bin, the degree to which it is filled and how quick the disposals and pick-ups are. Regulators using the interface can conduct audits of compliance and access historic data and generate reports. The dashboards have the key pointers in terms of a number of bins collected, weight of the processed waste, and adherence to the collection time schedule.

Such functions as visualization are not the only ones that can be monitored by the application layer as they also include monitoring and warning in real-time to increase responsiveness of the operations. It can detect and warn the user that there is a mishap like late collections, illegal access of the waste material or loss of contents in the waste materials. This will ensure that something will be done in due time and there will be non-breach of the standards of the regulation. In addition, APIs can be added to the system, that will be able to share data with the external systems, i.e. government oversight systems, third-party analytics products, etc. Those APIs ensure that data is safe to share and can be brought by the third parties with privileges to create reports, test compliance, or audit in other ways based on blockchain-auditable records.

3.5. Analytics and Reporting Layer

Analytics and reporting layer offer an important part of the process in realizing actionable steps out of the data gathered in the waste management system. It makes use of progressive data analysis software to handle the input of IoT-based sensors, blockchain transaction history, and smart contract execution. Such a layer based on the machine learning algorithms and statistical methods is able to identify patterns of waste generation, inefficiencies in collection routes, and predict the peak of waste. These knowledges provide opportunity to make informed decisions and through these, stakeholders are able to streamline their activities, utilize resources and enhance overall environmental and safety compliance.

This layer also employs the off-chain data storage in order to store large databases of information that will be the full waste manifests, the raw sensor information, and the past analytics reports in order to solve the storage challenge that exists within blockchain. Although the store of these records are off-chain, cryptographic hashes of the data are stored on-chain so as to maintain data integrity. This allows that any off-chain information can be checked to be authentic and not overload the block chain and we still have trust and transparency. Secure data management and potent analytics tools combine to create this layer, which is necessary in becoming intelligent and data-driven with waste management.

3.6 Security, Privacy, and Regulatory Adaptability

As much as tamper-resistance and data integrity are in-built features of blockchain, there is also the aspect of managing other attack vectors and regulatory issues of the system. To counter the sensor spoofing, every IoT device is digital signed and authenticated at the gateway level and the information of various sensors (e.g., GPS, weight, ultrasonic) is cross-validated prior to recording. Role-based access controls (RBAC) are used to counter the insider threats, blockchain audit trails, and smart contracts are applied to block any unauthorized activities. The actions of each stakeholder will be permanently recorded, which makes them traceable and accountable.

The privacy of information is provided by means of on-chain/off-chain data segregation, with the critical data (e.g. patient information or facility-related records) stored off-chain and identified by cryptographic hash values. This method will allow the system to adhere to GDPR like frameworks/regulation as relevant data could be selectively withheld or delete off-chain with auditability. The system is easily made to adopt to any regulatory standards. Smart contracts can be set with country-specific compliance regulations (e.g. biomedical waste regulations in India, HIPAA in the U.S, GDPR in EU) and the appropriate enforcement can be applied on the fly depending upon location or type of waste. Moreover, mechanisms of data minimization, pseudonymization, and consent logs can be incorporated within the application level so that it can comply with the emerging data protection requirements.

4 Process Flow

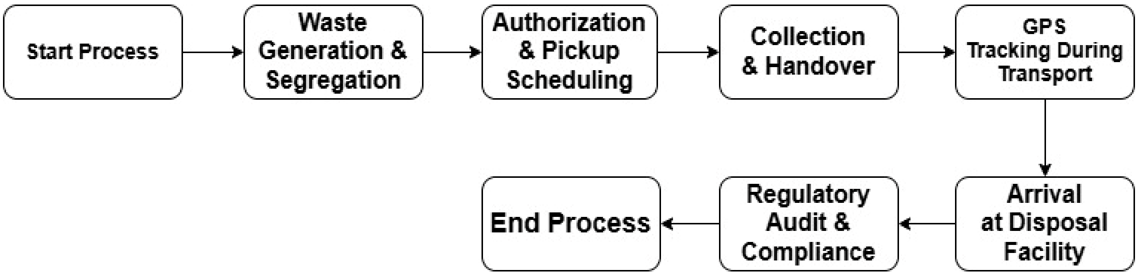

Figure 3. Process flow medical waste management system

The being illustrated process flow diagram represents a blockchain-based medical waste management system incorporated to improve on traceability, security, and regulatory compliance. The process starts with the generation of the medical waste and waste segregation where a unique identifier (UID) is allocated to the waste and is captured in a distributed ledger (DLT) when a waste bin is full. This will guarantee real time tracking and it will not allow improper alteration of waste records. The authorization and pickup scheduling process then use the smart contract protocols to check and verify licensed waste transporters. Mechanization of this step does not only remove the necessity of manual verification, but it also guarantees that only those organizations, that comply with the regulations, are allowed to gather the waste. When the handover is made, the event is encrypted and recorded into the blockchain, whose authenticity is tracked and verified using the wizard coordinates.

The transportation aspect tagged with real-time monitoring through GPS, will be programmed with smart contract-based validation algorithms to track the route to create alerts in case the waste transporter takes a different route than the already approved path. This geospatial log is tamper proof and helps to prevent cases of illegal dumps or deviations. When the disposal facility is reached an on-chain transaction to confirm this and log the disposal takes place. The blockchain stores digital certifications of waste disposal that are impervious to repudiation and can be accessed in the long run. During the final step, regulatory compliance and audit schemes enable the regulatory bodies to get verified and compliance check with the immutable blockchain records. Data integrity is ensured as the decentralized ledger does not allow falsification of the records but instead makes it possible to automate reporting processes to streaming regulatory agencies. This is an end-to-end blockchain-integrated scheme that revolutionizes trust, accountability and conformity in the medical waste process.

5 Implementation

In testing and deploying the blockchain-enabled medical waste management system, the dataset is the list of the "Medical Waste Management Dataset on Kaggle at https://www.kaggle.com/datasets/engineeringubu/pharmaceutical-and-biomedical-waste. This set of data contains about 35000 records, and the information includes issues associated with medical waste management. Every record is presented with key characteristics of waste, including its ID, type (e.g., infectious, sharp, pathological, or chemical), mass in kilograms, collection date and time, source location codes, transport and disposal facility IDs, transportation records (time, etc., and route description), and confirmation of a type of disposal (e.g., incineration, proper disposal, etc.).

The data was very central in the simulation of medical waste transactions in real life on block chain. The preprocessing of the data was performed to normalize and clean up the entries as the data required converting the timestamps to UTC time format and standardize the type of waste labels so that it was the same across the validations of the smart contract. The records could be then assigned to a simulated transaction in the blockchain, a stage in a waste lifecycle, for example: generation, transport or final disposal. These simulations were part and parcel of examining the functionality of smart contracts, in particular, those exercising route validation as well as custody checks of waste, and the permission to dispose of garbage. Logs of transport routes and time stamps allowed having the functionality of the GPS based route deviation detection algorithm, and chromographic disposal certificate generator rigorously tested. Moreover, the data could be utilized to accomplish machine learning-based anomaly detection, since transaction patterns and features could be extracted, and a neural network model could be trained to detect the anomalies in the waste handling behavior. This was a practice that helped in making a general analysis of efficiency of the system, traceability and enforcement of compliance.

The selected dataset was specifically suitable to the research because it resembled the working peculiarities of the medical waste logistics in the real world. It has a structure that is closely matching with the needs of a decentralized tracking system, and has enough granularity to model transactions in a blockchain and to simulate such systems.

5.1 Data Collection and Pre-processing

Within the proposed framework, the set of transactions in blockchain consists of several attributes (sender, receiver, timestamp, transaction value). In order to be able to be consistent and comparable on these attributes, the data is processed through a pre-processing step which normalizes the values. This entails normalizing the data that would have all the values of its attributes within a similar range such as 0 and 1. Normalization improves the functioning of data analysis procedures through removing the bias linked to different levels of attributes.

Let $X = \{x1, x2, \ldots, xn\}$ be the set of blockchain transactions, where each transaction xi consists of multiple attributes, such as sender, receiver, timestamp, and value.

$$xi' = \frac{xi - min(X)}{max(X) - min(X)} \quad (1)$$

Transaction Frequency per user measures how often each participant-hospital, transporter, or disposal site-engages in a medical waste operation during a set time window. Because the system runs on blockchain, every action-pickup, journey, or incineration-gets stamped with a precise date, time, and user code. Counting those stamps and dividing by the length of the monitoring period gives a clear rate for that user. Regular patterns start to emerge: a big urban hospital will show a steady, high frequency, while an unexpected jump or drop might point to fraud, technical error, or simple paperwork getting lost. Built into the feature set fed to the neural network, this number helps the model spot odd behavior and sharpen its forecasts on rule-following as well as workflow performance. By learning what normal looks like, the algorithm can issue alerts for any outlier that warrants a closer look.

$$Fu = \frac{Transactions\ of\ user\ u}{Total\ Transactions} \tag{2}$$

Average Transaction Value is a statistical feature representing the mean quantity of waste per transaction for each user. It is obtained from the dataset by grouping transactions by user ID, summing the waste quantities, and dividing by the total number of transactions per user. This value is then normalized and used as an input feature in the machine learning model. Within the proposed algorithm, it helps define behavioral patterns for entities like hospitals and transporters. The model uses it to detect irregular activities, improve prediction accuracy, and support compliance verification

$$Vu = \frac{\sum i^{n} = 1 v^{i}}{n} \tag{3}$$

where v_i is the value of the i^{th} transaction.

5.2 Model Selection and Training

The Model Selection and Training phase is an essential part of the blockchain-enabled medical waste management system because it addresses issues regarding anomalies, compliance, and the assimilation of processes. A neural network model was selected for the intended purpose of extrapolating complex, nonlinear relationships across a data set and generalizing well across the variance of complex, sometimes unique behavioral data across the transaction activity.

As previously mentioned, the data set has relevant fields such as the type of waste, the quantity of waste, the identifiers of the sender and receiver, timestamps, and logs of transport. The data set will be put through a long set of preprocessing steps prior to training the model. This preprocessing may include addressing missing or inconsistent values in the data set, combining timestamps into standardized formats, and normalizing numerical features of transactions, such as transaction value and transaction frequency. Subsequently, statistical metrics were created or engineered as features in the data set such as average transaction value, transaction frequency per user, and time of activity. These features were combined into feature vectors that would summarize the behavior of each user entity (for instance, hospitals, transporters). The neural network architecture was designed so that a feature vector would be the input to the model, rendering a prediction as output.

$$\mathrm{Y} = \mathrm{f}(\mathrm{WX} + \mathrm{B}) \tag{4}$$

where:

- Y is the output prediction,
- W and B are weight and bias matrices
- $f(\cdot)$is the activation function
- X is the input feature vector

The objective function plays a pivotal role in guiding the learning process of the machine learning model by quantifying the error between predicted outcomes and actual labels. In the context of the proposed blockchain-enabled medical waste management system, the primary use case addressed is fraud detection, which is formulated as a binary classification task. This involves classifying each transaction as either "legitimate" or "fraudulent," based on behavioral patterns and operational rules.

To train the model for this task, a labeled dataset is required. The medical waste management dataset used includes transaction records such as sender and receiver IDs, transaction timestamps, waste types, and quantities. From this raw data, domain-specific features are extracted through preprocessing and feature engineering—these include average transaction value, transaction frequency per user, transport route conformity, and disposal timing. Transactions are labeled as fraudulent or not based on historical outcomes, smart contract violations (e.g., unauthorized pickups or off-route transport), and rule-based triggers embedded in the blockchain system.

The cross-entropy loss function is employed as the objective function for this classification task. Mathematically, the cross-entropy loss for binary classification is expressed as:

$$L = -\sum_{i=1}^{N}[y_i \, log(\hat{y}_i) + (1 - y_i) \, log(1 - \hat{y}_i)] \quad (5)$$

where $yi$is the actual label, and $\hat{y}_i$is the predicted probability of fraud.

5.3 Transaction Validation (Consensus Optimization)

Transaction Validation is a key process in establishing the authenticity, integrity, and trustworthiness for waste-handling actions recorded on the distributed ledger. Transaction Validation ensures that every transaction, waste pickup, transport, and disposal, exercise not only a record, but a Validation that takes place with respect to the rules, roles, and conditions present in smart contracts and operational protocols. In addition to validation, a Consensus Optimization mechanism is also integrated into the transaction validation model to further optimize the validation process by minimizing the distance between the predicted validations compared to actual validations.

As for the datasets used in this aspect, since there were real-life transaction logs found on the Kaggle dataset 'Medical Waste Management Dataset', which included timestamps, identification of user roles (hospital, transporter), quantities of waste, transport paths, and signatures for disposal, it made sense to incorporate the usefulness of this dataset into accordant and verified real-world transaction examples. The pre-processing stages of the data, releases and conforms this data into structured features, such as compliance with the planned route, timing compliance based on service level agreements, and authorization based on stakeholder roles. The transaction records were retrievable and labelled with their resulting validation outcome: whether the validation was a successful valid or rejected validation based on the smart contract logic. This resulting validation outcome is what the model will use for training, as the labelled outcome will provide ground truth.

$$L = \sum_{i=1}^{N} \left| V_{\text{actual},i} - V_{\text{pred},i} \right| \quad (6)$$

The result of this optimization is a model that behaves the same as the consensus mechanism: it anticipates whether new transactions will pass validation criteria. Once we train the model to recognize the properties of transaction validation outcomes, we can utilize it to pre-screen transactions before submitting them to the same consensus model. If our model indicates that a transaction is likely going to fail, we can at least flag it for rectification before it adds to congestion on the network and incurs gas costs. By updating the model with evidence from each validation, the system can also adopt to changing rules-of-engagement or even changes in operations defined in updated smart contracts.

In the deployed framework, this shaped validation model is a layer of predictive validation, acting as a decision support for blockchain native consensus protocols (e.g. Practical Byzantine Fault Tolerance or Proof of Authority). While consensus protocols will ultimately enforce transaction validity at cryptographic and at protocol levels, the machine learning layer appears as a layer of lightweight and pre-consensus processing to automate what would otherwise be time-consuming consensus processes while curtailing computational load.

5.4 Smart Contract Efficiency

In this proposed system using blockchain technology for medical waste management, maximizing the efficiency of smart contracts is critical for reworking computable overhead and gas fees, especially in cases of restricted resources. Towards this goal, we analyzed data from Medical Waste Management Dataset which provided rich detail regarding the transaction sequences for waste generation, collection, transport and disposal. The analysis allowed us to classify frequently used transaction types as well as functions that were more cost prohibitive. The simulation logs from test nets like Ethereum validate the goal by tracking gas consumption for each individual smart contract call. The next stage of optimization in smart contract execution was analyzing and deleting unnecessary logic, eliminating unnecessary state transitions, minimizing external calls to other contracts, and collecting updates to reduce gas consumption. Work done off-chain has resulted in significant reductions in computing costs, allowing items such as verification hashes to remain on-chain while security protocols like GPS route validation and logistical data analytics exist in a separate location. In addition, both on-chain and off-chain machine learning models were built to predict gas fees for various transaction types, which allowed us to analyze the relative costs of different contracts as we moved towards dynamic selection of costs to allow for efficient executions. These combined capabilities keep the cost of blockchain transactions low and allows for scalability of the current system, and the incentive allows more healthcare facilities and regulators to join without impacting data affect data integrity or compliance enforcement.

$$C = \sum_{i=1}^{n} g_i \quad (7)$$

where g_i is the gas cost per operation

5.5 Model Evaluation

Accuracy is defined as the ratio of correct predictions to the total number of predictions made by a classification model. In the context of the proposed blockchain-enabled medical waste management system, the model analyses smart contract-based transaction logs and compares the predicted labels with the actual outcomes. This evaluation helps determine how effectively the system distinguishes between legitimate and fraudulent transactions, ensuring reliable performance in automating compliance and supporting operational decision-making.

$$\text{Accuracy} = \frac{\text{Correct Predictions}}{\text{Total Predictions}} \tag{8}$$

Precision and Recall are critical in assessing model performance when dealing with imbalanced data, especially where false alarms or missed detections have significant consequences. Precision ensures that the system accurately identifies only the truly fraudulent activities, minimizing the chances of falsely accusing legitimate stakeholders such as hospitals and transporters of regulatory violations. This is crucial in maintaining trust among participants and preventing disruptions caused by incorrect flagging of compliant entities.

$$Precision = \frac{TP}{TP+FP}, \quad Re\,c\,all = \frac{TP}{TP+FN} \tag{9}$$

where TP, FP and FN are true positives, false positives, and false negatives.

On the other hand, recall plays a vital role in ensuring that actual violations, such as unauthorized waste pickups, route deviations, or improper disposals, are not missed by the system. High precision helps reduce unnecessary audit alerts and administrative overhead, while high recall strengthens regulatory compliance and reinforces safety enforcement. Together, they ensure a balanced and effective monitoring system within the blockchain-enabled medical waste management framework.

5.6 Deployment and Monitoring

In the proposed blockchain-enabled medical waste management system, the optimized neural network model is integrated into a blockchain smart contract to automate compliance validation. The model evaluates each transaction by estimating the likelihood of it being fraudulent based on factors such as transaction frequency, waste quantity, route conformity, and authorization checks. The smart contract executes transactions only if the predicted probability of fraud is below a predefined risk threshold, which is calibrated during model validation to balance security and operational efficiency. This threshold-based decision-making ensures that only low-risk, compliant transactions are processed, while those exceeding the risk limit are flagged for review. By combining machine learning with blockchain smart contracts, the system enhances reliability, transparency, and regulatory adherence throughout the medical waste management lifecycle.

$$P(Fraud) < \epsilon \tag{10}$$

where ϵ epsilon is a risk threshold

5.7 GPS-Based Waste Tracking Algorithm

The GPS-Based Waste Tracking Algorithm employs real-time geospatial monitoring to ensure secure and compliant waste transport. The system initializes with a predefined expected route consisting of GPS waypoints from the pickup location to the disposal facility. During transit, the algorithm continuously fetches the current GPS coordinates, logs them off-chain for performance efficiency, and cross-references them against the expected route. If a deviation is detected, an alert mechanism is triggered, logging the anomaly on the blockchain with a timestamp to maintain an immutable record of compliance violations. Upon arrival at the designated disposal facility, the entire route history is hashed and committed to the blockchain, ensuring that waste transportation records remain tamper-proof and verifiable.

```
Initialize expectedRoute = planned GPS coordinate sequence from pickup
to disposal.
While waste batch status == "In Transit":
    currentLocation = GPS.getCoordinates()
    logLocationOffChain(currentLocation, timestamp)
    if not expectedRoute.contains(currentLocation):
        alert = checkRouteDeviation(currentLocation, expectedRoute)
        if alert == TRUE:
            trigger AlertEvent(batchID, currentLocation)
            recordAlertOnBlockchain(batchID, currentLocation, timestamp)
    wait for Δt (e.g., 1 min) before next check
On Arrival at destination:
    finalize route log and compute hash = hash(routeCoordinates)
    submit Transaction(ReportRouteHash(batchID, hash))
```

5.8 Waste Authentication & Verification Algorithm

The Waste Authentication & Verification Algorithm enforces role-based access control (RBAC) and cryptographic verification to prevent unauthorized handling of medical waste. When an actor attempts to interact with a waste batch, the algorithm queries the blockchain ledger to retrieve batch records and validates whether the actor's role aligns with the required permissions for the intended action. If the request pertains to pickup, the system verifies that the batch is in the "Ready for Pickup" state and assigned to the requesting transporter. If the request is for drop-off, the algorithm ensures that the waste is in transit and currently under the requesting transporter's custody. Additionally, a digital signature validation mechanism authenticates the actor's identity before granting approval, thereby ensuring integrity, traceability, and compliance within the waste handling process.

```
function AuthenticateWasteBatch(batchID, actorID, action):
    record = Blockchain.query(batchID)
    if record == NULL:
        return REJECT (batch not registered)
    expectedActorRole = getRequiredRoleForAction(action)
    if actorID.role != expectedActorRole:
        return REJECT (unauthorized role for this action)
    if action == "pickup":
        if record.status != "Ready for Pickup" or
record.authorizedTransporter != actorID:
            return REJECT (batch not ready or not assigned to this
transporter)
    if action == "dropoff":
```

```
        if record.status != "In Transit" or record.currentOwner !=
actorID:
            return REJECT (batch not in transit with this transporter)
    if not verifySignature(batchID, actorID):
            return REJECT (digital signature invalid)
    return ACCEPT
```

6. Results and Analysis

The proposed blockchain-enabled medical waste management system aims to address critical challenges in traceability, operational efficiency, and regulatory compliance. Traditional waste management frameworks often suffer from fragmented record-keeping, delayed disposal processes, and limited oversight, leading to environmental and public health risks. By leveraging blockchain's decentralized and tamper-proof architecture, the proposed model ensures secure and transparent tracking of medical waste across its entire lifecycle. This section presents the key findings derived from the system's deployment, focusing on participation scale, performance metrics, and comparative analysis. Graphical representations illustrate how blockchain integration enhances traceability accuracy, reduces disposal time, and improves compliance levels. The results highlight the practical viability and strategic advantage of blockchain in medical waste governance

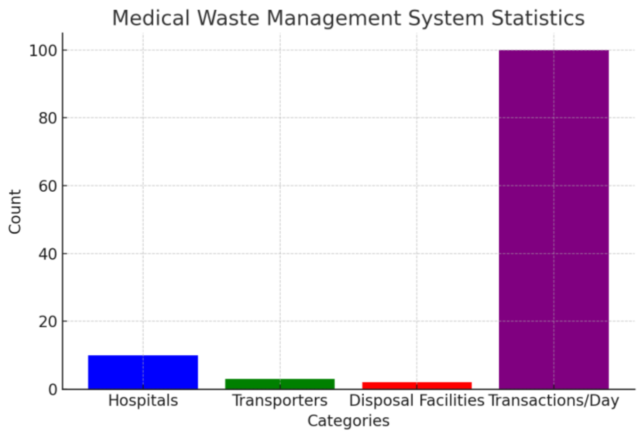

Figure 3. Medical Waste management system Statistics

The first graph illustrates the key system parameters of the proposed blockchain-enabled medical waste management framework. The chart presents the number of participating entities, including 10 hospitals, 3 licensed transporters, and 2 disposal facilities, along with an average of 100 medical waste transactions per day. These figures provide an overview of the operational scale of the proposed system, ensuring sufficient data flow for validation while maintaining efficiency in processing and traceability.

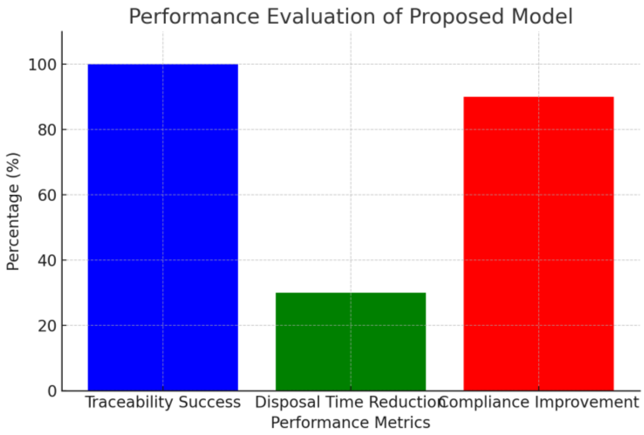

Figure 4. Performance Evaluation of Proposed Model

The second graph evaluates the performance metrics of the proposed model, specifically focusing on traceability success, disposal time reduction, and compliance improvements. The system achieves 100% traceability accuracy, ensuring every waste batch can be tracked across its lifecycle. Additionally, the automated scheduling and alert system reduces disposal time by 30%, addressing delays commonly observed in traditional waste management. Compliance enforcement is significantly enhanced, as blockchain-based tamper-proof record-keeping minimizes the need for manual inspections, leading to a projected 90% improvement in regulatory compliance.

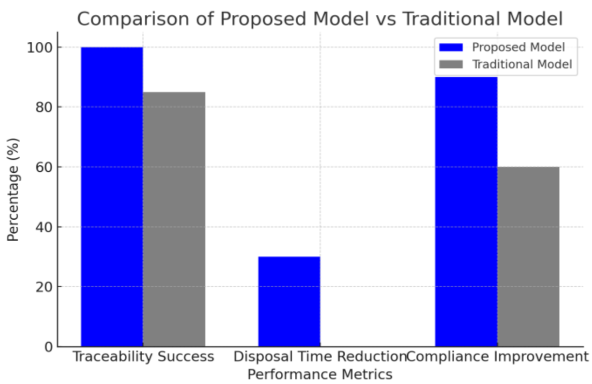

Figure 5. Proposed Model vs Traditional Model

The third graph provides a comparative analysis between the proposed model and traditional waste management systems. The traceability success rate of traditional models is limited to 85%, primarily due to reliance on manual logging and centralized databases susceptible to errors and tampering, whereas the proposed system achieves 100% accuracy through blockchain-based ledger immutability. The proposed system also achieves a 30% reduction in disposal time, whereas traditional models show no significant reduction due to manual processing inefficiencies. Furthermore, compliance improvement is estimated at 90% for the blockchain-based model, compared to 60% in traditional methods, primarily because the proposed system eliminates the need for extensive manual audits and enforces real-time regulatory adherence through smart contracts. This comparative analysis highlights the advantages of blockchain integration in enhancing traceability, efficiency, and compliance enforcement in medical waste management.

6.1. Scalability Analysis and Deployment Considerations

The proposed blockchain-enabled medical waste management system shows promising abilities with respect to traceability, regulatory alignment, and operational efficiencies although its scalability in large-scale health care environments will require addressing a number of technical considerations. To begin with, although Practical Byzantine Fault Tolerance (PBFT) can confidently provide block time for consensus on transactions under permissioned blockchains in remarkably quick timeframes, the rate at which the growing number of hospitals and regulatory bodies to which waste transactions are submitted will likely be impeded by transaction throughput; thus further generations of the system could consider mechanisms for Layer-2 scaling or sharing on a blockchain in an attempt to meet the same level of performance from various levels of usage. Likewise, the continuous stream of information from IoT devices in terms of waste fill, weight, and geolocation is a technical boundary for any event undertaken in the frame of bandwidth and requirements for processing the information logging from multiple sensors. The system structure incorporates event-based information filtering of IoT devices that store and transmit onto the blockchain only critical events that require law enforcement that represent epidemiological risks while allowing the full list of raw sensor-based IoT device tracking information to be stored off-blockchain for future situational awareness context. Although the event-based filtering approach may alleviate some of the transaction loads, it does make for a challenging circumstance when it comes to verifying the integrity of data for which access is delayed and may not be in sync with the blockchain, albeit this can be countered through hash-linking and version control.

Several practical factors, in addition to these technical factors, constrain real-world deployment. For instance, the framework requires stable internet access for real-time transmission of data and ensuring synchronized communication between IoT gateways and blockchain nodes. Hybrid architectures employing both on-chain and off-chain will also add delays depending on the role of IoT and/or where the off-chain cloud service fits into hybrid position. Additionally, the usability of frameworks based on smart contract workflows and blockchain technologies, as a technical solution, require careful consideration of how human agency and training will influence the success of the project, so hospital use cases (and waste handlers) need training and support for any advances being implemented that involve blockchain technology. Therefore, a phased roadmap for scaling deployment is proposed to begin with pilot implementations in communities and regional hospital networks gradually deploying into a government workplace compliance dashboard and training program influenced by governments compliance dashboard generally. This will allow for iterative testing of the system with known factors related to community process engagement to improve overall project performance at scale. Also, enhancements in IOT routed routes which would also then integrate AI would allow dynamic capabilities for a larger health care waste stream range of services and would likely improve responsiveness by governing how uease resources are allocated to waste systems.

7. Conclusion

The dysfunctional handling of medical waste represents a serious risk to public health and the environment, as evidenced by limitations in current waste tracking and manual record-keeping and weak enforcement environment. Traditional systems are limited in their ability to provide real-time tracking and suffer from delays, unauthorized handling and alterations. This study presents a blockchain-based framework for medical waste management which employs IoT sensors, smart contracts, and machine learning to provide full traceability, automation and compliance with existing regulations. The framework employs GPS, ultrasonic, and weight sensors to capture real-time waste data, transmitted through Wi-Fi and LoRaWAN to cloud gateways and a permissioned blockchain. Smart contracts automate processes such as pickup scheduling, transporter authorization, and disposal verification. Evaluation using real-world datasets demonstrated 100% traceability accuracy, a 30% reduction in disposal time, and a 90% improvement in regulatory compliance, compared to traditional methods. **What differentiates this work from existing blockchain-based systems is the integration of three novel components, a GPS-based route validation algorithm for continuous real-time monitoring of transporter movements and alert generation on deviation, a neural network-based fraud detection model that pre-validates transactions by analyzing behavioural patterns and anomalies before on-chain submission, and a cost-efficient smart contract layer built on Practical Byzantine Fault Tolerance (PBFT) consensus, enabling low-latency and scalable operation in healthcare environments. These contributions enable intelligent, predictive, and regulation-enforcing waste management—surpassing conventional blockchain models focused only on data immutability.** This work demonstrates that combining blockchain with IoT and AI technologies can significantly improve safety, transparency, and efficiency in medical waste logistics. Future enhancements could involve integrating with national health systems, using advanced machine learning for waste forecasting, and implementing Layer-2 blockchain solutions to improve scalability and performance.

References

[1] Khan, A. U. R., & Ahmad, R. W. (2022). A blockchain-based IoT-enabled E-waste tracking and tracing system for smart cities. IEEE Access, 10, 86256–86269.

[2] Bułkowska, K., Zielińska, M., & Bułkowski, M. (2023). Implementation of blockchain technology in waste management. Energies, 16(23), 7742.

[3] Imam, A. B. (2021). Blockchain-enabled Approach for Healthcare Waste Management (Doctoral dissertation, Khalifa University of Science).

[4] Ahmad, R. W., Salah, K., Jayaraman, R., Yaqoob, I., & Omar, M. (2021). Blockchain for waste management in smart cities: A survey. IEEE Access, 9, 131520–131541.

[5] Lakshmanan, M., Anandha Mala, G. S., & Anandkumar, K. M. (2024). Highly secured EHR management system based on blockchain technology with digitally signed authentication using data sanitization and polynomial interpolation. Biomedical Signal Processing and Control, 87, 105412.

[6] Le, H. T., Quoc, K. L., Nguyen, T. A., Dang, K. T., Vo, H. K., Luong, H. H., Le Van, H., Gia, K. H., Phu, L. V. C., & Quoc, D. N. T. (2022, July). Medical-Waste Chain: A Medical Waste Collection, Classification and Treatment Management by Blockchain Technology. Computers, 11(7), Article no. 7.

[7] Dhingra, S., Raut, R. D., Yadav, V. S., Cheikhrouhou, N., & Naik, B. K. R. (2023). Blockchain adoption challenges in the healthcare sector: a waste management perspective. Operations Management Research, 1–19.

[8] Lakshmanan, M., Anandha Mala, G. S., Sivakumar, G., Sundar, V. S. D., Kesavan, R., & Jeena, A. A. S. (2024). A Secure and Efficient Framework for Storing Medical Data using Blockchain and Cloud Servers. In 2024 8th International Conference on Electronics, Communication and Aerospace Technology (ICECA) (pp. 1661–1667). IEEE.

[9] Song, G., Lu, Y., Feng, H., Lin, H., & Zheng, Y. (2022). An implementation framework of blockchain-based hazardous waste transfer management system. Environmental Science and Pollution Research, 29(24), 36147–36160.

[10] Triet, M. N., Khanh, H. V., Huong, H. L., Khiem, H. G., Phuc, T. N., Ngan, N. T. K., Quy, T. L., et al. (2023). Leveraging Blockchain, Smart Contracts, and NFTs for Streamlining Medical Waste Management: An Examination of the Vietnamese Healthcare Sector. International Journal of Advanced Computer Science and Applications, 14(8).

[11] Lakshmanan, M., & Anandha Mala, G. S. (2024). Merkle tree-blockchain-assisted privacy preservation of electronic medical records on offering medical data protection through hybrid heuristic algorithm. Knowledge and Information Systems, 66(1), 481–509.

[12] Durai Arumugam, L. S. S., Kumar, R. P., & Lokeshwaran, N. (2024). Effective Tracing and Tracking of E-Waste using Blockchain Technology. In 2024 3rd International Conference on Applied Artificial Intelligence and Computing (ICAAIC) (pp. 1506–1512). IEEE.

[13] Saidu, Y., Shuhidan, S. M., Aliyu, D. A., Aziz, I. A., & Adamu, S. (2025). Convergence of Blockchain, IoT, and AI for Enhanced Traceability Systems: A Comprehensive Review. IEEE Access.

[14] Lakshmanan, M., Anandha Mala, G. S., & Gnanavel, R. (2024). Blockchain for Secure and Efficient Crowdfunding: An Optimized Particle Swarm Approach. In 2024 9th International Conference on Communication and Electronics Systems (ICCES) (pp. 848–854). IEEE.

[15] Lakshmanan, M., Mala, G. S., & Anandkumar, K. M. (2025). A study on blockchain based health records: Merkle tree with hybrid heuristic algorithm. In AIP Conference Proceedings, 3162(1). AIP Publishing.

[16] Abdirahman, A. A., Hashi, A. O., Dahir, U. M., Elmi, M. A., & Hashim, S. Z. M. (2025). Enhanced vehicle tracking: A GPS-GSM-IoT approach. International Journal of Computing and Digital Systems, 17(1), 1–11.

[17] Deng, Z., Xu, H., Peng, H., Zou, Q., Sun, Y., & Li, G. (2025). A Lightweight Flexible Wearable Circularly Polarized Antenna for Navigation and Positioning in IoT Applications. IEEE Internet of Things Journal.

[18] Wu, H., Wang, S., Pu, C., Ma, J., & Zeng, Y. (2025). Enhancing counterfeit RFID tag classification through distance based cognitive risk control. Scientific Reports, 15(1), 4150.

[19] Hole, S. R., Bhavekar, G. S., Prajapati, A. K., Kolluru, V., Karpe, S. R., & Vrindavanam, J. (2025, February). Hybrid PCA-Based Machine Learning Models for Predictive Analytics in Urban Health Monitoring Systems. In 2025 IEEE 1st International Conference on Smart and Sustainable Developments in Electrical Engineering (SSDEE) (pp. 1-8). IEEE.

[20] Sagar, A., Kolluru, V., Jaiswal, U., Kumavat, G., Hole, S. R., & Kumar, A. (2025, March). Machine Learning and Artificial Intelligence for Predictive Modeling in Antimicrobial Resistance Data Sets, Challenges, and Future Directions. In 2025 3rd International Conference on Smart Systems for applications in Electrical Sciences (ICSSES) (pp. 1-6). IEEE.

[21] SRIRAMKUMAR, R., SELVAKUMAR, K., & JEGAN, J. (2025). ADVANCES IN AI FOR PULMONARY DISEASE DIAGNOSIS USING LUNG X-RAY SCAN AND CHEST MULTI-SLICE CT SCAN. Journal of Theoretical and Applied Information Technology, 103(7).
[22] L. M., Sriramkumar, R., J. Y., H. K. P., Mithaguru, & Ilamurugan, G. (2025). Blockchain-based HSFO framework for privacy preservation of health care data using hybrid algorithms. In 2025 2nd International Conference on Research Methodologies in Knowledge Management, Artificial Intelligence and Telecommunication Engineering (RMKMATE) (pp. 1–6). IEEE.

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