Medical-Waste Blockchain Technology

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Keywords: medical waste management ; blockchain ; smart contract

1. Introduction

The problem of waste collection, classification, and treatment is becoming more serious. It is estimated that the world produced about 1.3 billion tons before 2019, and this is expected to increase to 2.2 billion tons of solid waste per year in 2025. On average, each person emits about 0.11–4.54 kg of stable waste per day [1]. These solid wastes can come from technological products in daily life (e.g., phones, computers, cameras) or medical care activities (e.g., masks, syringes). One of the reasons that the growth of waste has almost doubled since 2019 is the impact of the COVID-19 pandemic. Indeed, the amount of household and medical waste has increased dramatically since the outbreak of the disease in the city of Isfahan, Iran [2].

Since the last months of 2019, the COVID-19 pandemic has highly affected our lives. The peak of the pandemic in 2020 and 2021 caused an all-time-high demand for COVID-19 medical equipment and supplies. To meet this urgent need, most systems, methods, and technologies today leverage the supply chain of medical equipment and supplies for COVID-19 prevention. However, the waste of these products post-usage is not efficiently managed. Klemevs et al. [3] recognized the harmful effects of vaccine production as an attempt to prevent the spread of the pandemic: their production damages the environment, causing a shortage of energy sources for the world. Remarkably, the cold chain is estimated to account for 69.8% of the energy consumed during the vaccination life cycle, in which around 26–99% is dependent on the transport distance. Furthermore, building equipment to meet storage and distribution needs is costly, especially in developing countries. Hence, a system for managing and classifying waste as well as medical supplies during the pandemic is extremely urgent [4]. A sustainable supply chain model that responds to an emergency agreement should be emphasized while also considering equity to reduce environmental harm [5].

In the current collection, classification, and treatment model, many medical supplies and waste management systems are constructed based on (i) centralized data processing, or (ii) leveraging cloud-based centralized resources to process waste-related data [6]. For the centralized processing model, all processing and classification activities are handled independently, lacking cohesion, and are challenging to share with partners [7][8]. For the cloud-based decentralized processing model, the centralized storage and processing of data from multiple sources often leads to data inconsistencies among the involved parties, thereby creating limited cooperation opportunities for stakeholders [9][10]. In addition, this model is flawed in providing traceability, reliability, operational transparency, security, and reliability features in processing [11][12]. On the other hand, a significant factor in the current epidemic problem is the ability to encourage non-face-to-face interaction (i.e., limit face-to-face meetings) to avoid transmission, which has presented a complicated issue for the community, the management of equipment, supplies, and medical waste. As a result, a blockchain-enabled waste management strategy helps make better decisions, improves productivity, is cost-effective, and ensures compliance with [1] waste regulations.

Blockchain-based systems developed for waste management mainly focus on solid waste such as electronics, household waste, and agricultural waste. Implemented systems for the treatment and segregation of waste in the medical environment are few and need to be developed in detail. Current blockchain-based projects developed for waste management have implemented several types of services rather than sorting and disposing of waste, e.g., waste collection process management [13], vehicle-based shipment monitoring [14][15], waste classification [1], and auditability of waste handler actions [16]. A detailed analysis of the approaches and results achieved by start-of-the-art methods is given in the Related Work section. Most of the existing studies are designed on the Ethereum platform to provide a reward-and-punishment mechanism for the stakeholders involved in managing, classifying, and treating waste. The system ensures compliance with user actions via a series of waste management rules defined in the smart contract. However, a technique developed based on Ethereum will be greatly limited in funding and transactions per second (TPS) [17][18][19].

2. Background of Medical-Waste Chain

2.1. Blockchain Technology

Blockchain is well known for the success of Bitcoin [20] and is commonly characterized as a transparent, reliable, and decentralized ledger on a peer-to-peer network that manages transaction data on several computers at the same time. As a result, blockchain is seen as a trust circle that allows parties to be autonomous without relying on a single third-party confirmation [21].

The public, private, and consortium blockchains are three universally acknowledged forms. Bitcoin and Ethereum are examples of public blockchains. Any anonymous users may join the network, view the blockchain's content, execute a new transaction, or check the integrity of the blocks. Meanwhile, GemOS, MultiChain, and Eris are typical examples of a private blockchain in which only permitted users can join the network and write or send transactions to the blockchain [22]. A consortium blockchain is semiprivate, on the border between public and private blockchains. It is typically connected with the use of enterprise to better business. Hyperledger Fabric [23] is a business consortium blockchain framework. Ethereum [24] also allows for the creation of consortium blockchains (Golang).

Numerous features and components make blockchain technology useful and advantageous to the participated stakeholders. The smallest data unit on the blockchain that includes records, contracts, and information is called a transaction [25]. Any entity connecting to the blockchain is referred to as a node [25], and transactions are confirmed by particular nodes (known as miners) by examining the sender as well as the transaction's content. The nodes combine the complete transactions into blocks [25][26] and are in charge of determining if the transactions are valid, and if they should be stored on the blockchain.

- Ledger [27][28] is a data storage on a blockchain that uses a consensus algorithm to store immutable, sequential entries in blocks. For each channel, each node keeps a copy of the ledger. For efficient processing, the shared ledger encapsulates the whole transaction history for each channel and adds query capabilities.

- Cryptography [28] is one of the essential components of blockchain, which allows relevant access, and stores data in immutable blocks with a fixed sequential order, and establishes identity and authenticity.

- Consensus [28] is another crucial component of blockchain that is connected to how data submissions are accepted onto the distributed ledger. Consensus algorithms [29] are used in blockchain technology to maintain a single history of blocks by synchronizing the data inside the chain of blocks to ensure that no contradicted or invalid transactions exist. There are many existing types of consensus rules, such as Proof of Work (PoW), Proof of Stake (PoS), Proof of Authority (PoA), and Proof of Elapsed Time (PoET). According to these algorithms, all participating nodes must prove something for someone to be granted permission to add a block to the current blockchain.

2.2. Smart Contract

2.2.1. Ethereum

Ethereum [30] is a decentralized platform to run smart contracts with the support of Turing-complete programming languages. Ethereum is executed by the Ethereum Virtual Machine (EVM) and written in high-end programming languages such as Solidity, Serpent, Low-level Lisp-like Language (LLL), and Mutan. Withdrawal limitations, loops, financial contracts, and gambling markets are possible on the Ethereum platform. Ethereum is now the most popular platform for smart contract development.

2.2.2. Hyperledger Fabric

Hyperledger Fabric [23] is an open-source enterprise-grade permission-distributed ledger technology (DLT) platform designed for large-scale commercial use. It has a few essential features that set it apart from other DLT or blockchain systems. Similar to Ethereum, Hyperledger Fabric is also Turing complete. However, unlike Ethereum, which executes smart contracts on virtual machines, Hyperledger code is executed in Docker containers, allowing smart contract applications to run with minimal overhead while sacrificing isolation (i.e., applications in one container are running on top of one operating system). Fabric succeeds in supporting traditional high-end programming languages such as Java and Go (also known as Golang) rather than building Ethereum's smart contract languages.

The support of multiple programming languages facilitates the development and maintenance of the Fabric platform. Additionally, Fabric assists in mitigating operating costs, including storing and querying information inside the blockchain, and quickly setting requirements for security features and user authorization.

In this research, researchers engage the Hyperledger Fabric platform in building a process that consists of a smart contract to manage the blockchain's stored data flows and back-end APIs to process input and output data. Then, all these components will be deployed on a container independently run on the peer-to-peer network system inside the Docker-compose platform.

2.3. Hyperledger Caliper

Hyperledger Caliper [31] is a standard blockchain apparatus; a Hyperledger project facilitated by the Linux Foundation. It is utilized to gauge the productivity of the particular blockchain execution with a predefined set of usage cases. The performance reports, transaction latency, and resource usage are produced by the Hyperledger Caliper so that the other projects of Hyperledger might leverage these resources. Hyperledger Caliper is an open-source project contributed by Huawei, Hyperchain, Oracle, Bitwise, IBM, and Budapest University of Technology and Economics.

3. Related Work

As explained in the introduction section, medical device management or reverse logistics activities (RLA) play an essential role in adequately managing devices in a medical environment. These operations preserve equipment at the end of its useful life and anticipate the necessary replenishment of missing equipment. However, refurbishing medical devices and anticipating their necessary replenishment is not a straightforward process, as there are many challenges associated with their appropriate repositioning into the medical market. This research uses blockchain-based technology as a possible solution to establish connections with recycling facilities for medical devices and recycling medical waste while considering regulatory-security- and transparency-related compliance. Moreover, in the COVID 19 pandemic, the requirements for handling medical equipment and waste are highly urgent. The essential requirements in this phase are how to provide enough medical supplies, and to limit direct contact between stages. This section summarizes the management systems in three sub-sections: blockchain-based management systems, blockchain-based medical systems, and blockchain-based waste management systems.

3.1. Blockchain-Based Management Systems

Blockchain is a state-sharing and consensus-building technique that fulfills transaction record retention and synchronization of distributed network participant systems [32]. The main benefits of a blockchain-based system are the following: (i) there is no centralized server; (ii) all the executed transactions are logged; (iii) information is shared on the distributed ledger for the parties' assessment; (iv) information is organized into blocks when a new transaction is generated. Within a blockchain structure, researchers can classify three main types: public, private, and consortium (also known as hybrid). According to the developer's requirements, they can define the corresponding structure and platform; for instance, Bitcoin Core, Ethereum, Hyperledger Fabric [33].

Supply chain management integrates core business processes and information. The process goes through many steps, including customers and retailers, wholesalers, manufacturers, and suppliers, which add value to customers and other stakeholders [34]. The system incorporates a highly complex process that requires synchronization of various activities, resulting in randomness and supply chain risk [35][36].

Moreover, Casino has synthesized systems that apply blockchain technology in measurements, including supply chain management, as well as medical supplies [25]. There are very few articles that offer blockchain-based approaches to device management. One of them, by Douladiris et al. [37], introduced a medical device management model based on blockchain technology. In [38], based on structured interviews, the authors assessed the benefits and risks of incorporating the blockchain model in equipment management practices. Farouk et al. [39] have developed a theoretical framework that uses blockchain to enhance transparency and information sharing in electronic supply chain management activities for general device management procedures. In the same year, Dasaklis presented a blockchain-enabled architecture and a proof-of-concept implementation of mobile operations [16]. In addition, Le et al. [40][41] also exploit the advantages of blockchain technology to apply the cash-on-delivery model. Furthermore, in the process of delivery and receipt of goods between shippers, Ha Xuan Son et al. developed a transport model based on a blockchain-based decentralized mechanism [42].

Hyperledger Fabric is an open-source distributed ledger platform designed for developing permission applications at an enterprise grade. Fabric provides a platform to build fast, efficient, and secure enterprise blockchain applications. It is characterized as being suitable for business-to-business (B2B) transaction services, and its membership services limit the entry of unauthorized participants [43]. Due to having a node for verifying the transactions during transaction processing, it is possible to remove uncertain transactions early and quickly. Due to these benefits, and some advantages in the Background section, researchers intend to design a Hyperledger Fabric architecture-based system for blockchain-based management.

3.2. Blockchain-Based Medical Systems

Healthcare is one of the prominent fields where Blockchain is supposed to make a substantial impact. It generates a wide range of opportunities and possibilities in current healthcare systems. Specifically, in 2018, Kumar et al. [44] exploited the potential applications of blockchain technology in current healthcare systems to address the trustless and ambiguous aspects of such systems positively. A year later, Marcela et al. [45] introduced a blockchain-based peer-to-peer medical platform to manage electronic medical records (EMRs). Their proposal kept the encrypted data in the blockchain and allowed the patients to share the decryption key only with healthcare professionals they trust. Similarly, Wilber et al. [46] also surveyed the blockchain-based medical system to highlight the most important requirements in meeting the need for sensitive data protection. Moreover, some papers applied the blockchain architecture to define a healthcare system for specific diseases such as diabetes [47] and COVID-19 [48].

On the other hand, research on blood supply-chain management has been conducted by several approaches. Blockchain application in the healthcare supply chain is not as common as in other areas; they are considered “vital”. Blockchain solutions are more suitable for healthcare supply chains; however, there are as yet no blockchain solutions in use for healthcare. Although research investigating the application of blockchain in this sector is increasing, it is mainly used for data sharing and recording data, while using it for supply-chain management is rare [49]. Some companies, like Imperial Logistics and FarmaTrust, use blockchain to manage pharmaceutical supply chains [50]. Other experimental projects such as OrganTree and Dhonor Blockchain also use this technology to connect organ donors, recipients, and practitioners by using incentives such as paying for funeral costs [51]. Several articles have investigated blood donation tracking. BloodChain and SmartBag focus on preventing contamination in the supply chain and reducing the spread of HIV in developing countries [52]. Another project, called BLOODCHAIN, focuses on motivating blood donors by giving monetary compensation. Wust and Gervais (2018) have proposed a flow chart to emphasize the importance of blockchain applications in tracking the origins of donated blood [53]. The model is presented and discussed in the research to see whether blockchain can solve the problem; however, the situation has not been solved well. Nga et al. [54] applied blockchain to store and deliver the volunteer blood donations.

Several blockchain-based systems are introduced to define authorized users (i.e., parties) who can process the patient’s privacy data for healthcare emergencies. For instance, Son et al. [55] developed a blockchain-based technology for dealing with crises in patient-centered systems, where the patient is allowed to define the privacy policy for all data collection requests in an emergency. In other words, these data could not allow access in a normal situation without permission from the owner. Moreover, Trieu et al. [17] extended this model to give more management power to patients. Researchers define the access control model, in this paper, as more fine-grained in the privacy policy. Specifically, the users can explain the procedure depending on the time or place rather than the fixed policy.

Some approaches use a blockchain-based system to share the collected data among the healthcare centers, and to support the users in controlling their medical data. It means the patients could choose what kind of information related to their health history will be shared with the clinics, including sensitive information [56]. Moreover, Nghia et al. [57] introduced the SmartCare system to combine the history of medical resources from the other centers in the diagnosis phase to improve the treatment process.

3.3. Blockchain-Based Waste Management System

The removal or segregation of wastes, especially medical waste, continues to contaminate our ecosystem [58]. As an obvious example, 99% of items (including medical equipment and supplies) become trash within the first six months of first use [59]. This problem can be viewed as a catastrophic failure in material recovery. In particular, the circular economy (CE) aims at the elimination of both waste and misuse of resources. This system focuses on reusing, repairing, and recycling in a secure method. Thereby, researchers can ultimately reduce input materials and prolong the time of usage (instead of only six months on average) of equipment and supplies, minimizing pollution and the intorduction of other wastes into the environment. Morseletto et al. [60] have defined a circular economy as "an economic model directed at the efficient use of resources through waste minimization, long-term value retention, and resource minimization primary and closed-loop of products, product parts, and materials within the boundaries of environmental protection and socio-economic benefits." According to the above definition, a CE-based production and consumption system focuses on maintaining the utility and the value of products and materials.

To this end, the Ellen MacArthur Foundation [61] has introduced a series of principles (e.g., reuse, repair, refurbish, remanufacture, recover, recycle, and regenerate from waste streams). The primary purpose of the CE system is to achieve a world without waste.

Moreover, CE is considered a model of the future toward a green economy. For example, to reduce waste and increase recycling, Amazon has created CE loops based on partnerships and offers options for customers to reuse, repair, and recycle their products [62]. However, to be able to apply CE in the natural environment is exceptionally challenging [63], especially in a medical setting. A typical example drawn from the COVID-19 pandemic is that the waste treatment process is performed asynchronously, leading to a considerable amount of waste (e.g., personal protective equipment [64] and COVID-19 vaccines [65]). This also contributed to many subsequent waves of infection [66].

The management and classification system of medical equipment and supplies acts as a decentralized trading environment in the current context. The system consists of participants who share and authenticate data, and are solely responsible for the shared data. These data can be inventory data, digital assets, types of equipment, supplies, or any other kind of information [67] used in a healthcare environment. Understanding the demand for medical equipment and supplies is extremely important; it contributes to reducing the spread of COVID-19 disease in the community [68]. Blockchain-based management systems were introduced to address this problem. The next section focuses on exploiting waste management systems and medical supplies developed based on Blockchain technology.

Gupta et al. [13] proposed an Ethereum-based system called Electronic Waste Management (EWM). Based on the constraints defined in the smart contract, EWM has ensured compliance with waste disposal guidelines for electrical and electronic equipment (EEE). In EWM, the author proposed three main stakeholders offered by the system: manufacturers, consumers, and retailers of electronic components. Smart contracts calculate, record, report, and provide incentives for consumers to send back EEE waste to retailers to address the post-use waste problem. Furthermore, in the context of retailers, smart contracts focus on verifying that waste is received for all sold EEEs. Specifically, the retailer ships the EEE waste to the producer and pays a portion of the original cost of the EEE to the consumer. Smart contracts have also imposed penalties on EEE manufacturers if waste is not collected from retailers within a predetermined period.

Poongodi et al. [14] have proposed a 5G enabled system that supports tracking electronic products throughout their life cycle, based on blockchain technology. The system is deployed on the Ethereum platform. The system was built around five actors: manufacturer, supplier, retailer, customer, and e-waste facility. In particular, e-waste facilities offered rewards and incentives to customers if they sorted waste for treatment before sending it to e-waste treatment facilities. To accomplish this, the authors built a smart contract-based computation suite. Specifically, it required all related parties to comply with the rules outlined in the treatment of waste by escrow. This action encouraged stakeholders to take responsibility for e-waste segregation practices. Finally, the escrow and incentives were returned to the stakeholders when the smart contract logic-based calculations were evaluated.

Laura et al. [15] introduced an Ethereum-based management system to assist users in monitoring solid material waste (e.g., computers and smartphones). What differentiates this system from previous approaches is that it allows the owner to monitor and track the waste in transit from the receiving location (i.e., user address) to the substance-storage waste plant. The proposed system was based on the interaction between four actors: the collection manager, storage manager, transaction manager, and processing manager. The collection manager generated and stored a QR code (i.e., a QR code referring to a package containing solid waste on the blockchain). The transportation manager recorded the solid-waste-transport vehicle's status, location, and route information. This information was updated to the distributed ledger. In addition, to temporarily store encrypted data related to solid waste without affecting the entire system's performance, the authors used an off-chain storage system. However, to balance security and throughput, the system can use multiple blockchain platforms. Thereby, the problem, in this case, is how to synchronize between different blockchains.

Schmelz et al. [69] also presented an Ethereum-based system that could track waste across borders in a secure, tamper-proof, and privacy-preserving manner. In particular, sensitive and non-disclosure information (e.g., assets and waste processes) were stored locally and not on-chain. The system kept a log of the processes executed during the processing of audit-critical data. Specifically, it assigned a signature to the data before the transaction by applying a one-way hash function. On the other hand, the authorities examined and verified the reason for the delay in transportation access between the exchanged locations, the volume transported, and the validity of the waste treatment methods based on the information stored in the smart contract. However, they did not impose any penalty for violations in the transportation and disposal of waste.

The lack of transparency in waste collection and treatment activities could cause frauds that affect the entire system. To address this issue, Ahmad et al. [1] proposed a framework for traceability of personal protective equipment (PPE) for healthcare workers against COVID-19. In particular, based on image analysis related to waste collection, the authors presented a system that used analytical techniques to identify fraud. They compared data before and after the collection/treatment processes to identify fraudulent practices, i.e., calculated similarity index between two captured images, estimated garbage weight, location position, and time difference of two captured images. After computing such data, it determined what behavior was (not) allowed in garbage collection. Correct actions would be encouraged; otherwise, violators would be fined. However, blockchain's contribution to the system is somewhat ambiguous. Specifically, the technique used blockchain technology to securely transfer crypto-currencies to users as an incentive to collect waste. Moreover, another study conducted by Dasaklis et al. [16] proposed a blockchain-based system to track all remanufacturing/refurbishing processes for smartphones. However, the authors did not pay much attention to the reproduction/refurbishment process in either of the above approaches.

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