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Blockchain for Waste Management in Smart Cities: A Survey

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ABSTRACT Smart cities have the potential to overcome environmental problems caused by improper waste disposal by improving human health, protecting the aquatic ecosystem, and reducing air pollution. However, today's systems, approaches, and technologies leveraged for waste management are manual and centralized. This fact makes them vulnerable to manipulation and the single point of failure problem. Also, a large portion of the existing waste management systems within smart cities fall short in providing operational transparency, traceability, audit, security, and trusted data provenance features. In this paper, we explore the key role of blockchain technology in managing waste within smart cities as it can offer traceability, immutability, transparency, and audit features in a decentralized, trusted, and secure manner. We discuss the opportunities brought about by blockchain technology in various waste management use cases and application scenarios, including real-time tracing and tracking of waste, reliable channelization and compliance with waste treatment laws, efficient waste resources management, protection of waste management documentation, and fleet management. We introduce a framework that leverages blockchain-based smart contracts to automate the key services in terms of waste management of smart cities. We compare the existing blockchain-based waste management solutions based on important parameters. Furthermore, we present insightful discussions on several ongoing blockchain-based research projects and case studies to highlight the practicability of blockchain in waste management. Finally, we present open challenges that act as future research directions.

INDEX TERMS Blockchain, waste management, traceability, security, IoT, smart cities.

I. INTRODUCTION

Since the past decade, worldwide cities have been continuously generating an enormous amount of waste that is putting a harmful effect on human health and the environment. It is estimated that the world generates up to 1.3 billion tonnes of solid waste each year and it is expected to increase to 2.2 billion tonnes per year by 2025. On average, every human being generates around 0.11 to 4.54 kilograms of solid waste per day. It is reported that 33% of the generated solid waste in cities do not manage in an environmentally friendly and safer way [1], [2]. The improper management of waste can contaminate the oceans, cause disease spreading, and harm animals that eat waste (e.g., food waste or plastic bags) unknowingly. The proper management of waste in smart cities requires

close coordination and collaboration among the involved stakeholders such as waste generators, collectors, shipper, and waste treatment facilities. However, the existing systems leveraged to manage waste are highly disintegrated and face several challenges because of a lack of means to adequately share waste-related data among involved stakeholders in waste management processes [3]–[5]. Blockchain technology presents a single and unified platform that can be used by the involved stakeholders in waste management of cities to share data in an effective, secure, transparent, and verifiable manner [6]–[8]. Since blockchain follows a decentralized architecture, hence it is a highly fault-tolerant, robust, and trusted technology.

Modern cities face manifold challenges related to air pollution, deteriorating and inappropriate water management, sustainable and eco-friendly energy creation, and environmentally friendly waste management. Smart cities aim to

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improve citizens' quality of life, protect the environment, minimize traffic congestion, and increase the local economy by leveraging state-of-the-art Information Communication Technologies (ICT) [9], [10]. Effective and sustainable waste management policies assist in improving air and water quality and lessening carbon emissions to clean the environment. Many of the waste management systems are highly Internet of Things (IoT)-based and leverages centralized cloud-based resources to process waste-related data. IoT-based nodes sense, monitor, and transmit the capacity and type of waste in bins, temperature, and humidity levels, and estimate the arrival time and route data about the waste carrying trucks to the cloud servers for processing and decision making [3], [4], [11]. For instance, the smart bins capacity data can be used to forecast the availability of vehicles near the waste bin site [12]. The centralized data storage and processing often result in data inconsistency among the involved waste handling participants, thereby offering limited collaboration opportunities to the stakeholders. Also, the data stored on a centralized-based system is less trustworthy as it is highly vulnerable to modifications, fraud, or deletion by intruders. The credibility and trustworthiness of waste management data affect the decision-making by the involved stakeholders and lead to poor resource planning by the authorities in managing smart cities waste. Also, data silos created by highly disintegrated and centralized-based waste management systems can affect the performance and productivity of waste management processes. Blockchain-enabled waste management results in better decision making, improved productivity, cost efficiency, and compliance assurance with the waste processing regulations.

Blockchain is a decentralized technology that can assist in securing data and transactions by storing and executing them in a trustful manner. It follows a Peer-to-Peer (P2P) architecture to store and process data in a highly reliable, secure, transparent, and trusted way [13], [14]. Blockchain technology allows and provides incentives to the miners to participate in the consensus process to validate the transactions and create new blocks. Consensus algorithms secure the blockchain by ensuring that unverified transactions cannot be executed and stored on the blockchain [15]. Since blockchain platforms follow a distributed architecture, consensus algorithms such as Proof-of-Work (PoW) [16], Proof-of-Stake (PoS) [17], and Proof-of-Authority (PoA) [18] are obliged to ensure the agreement to the current state of the blockchain among all distributed nodes. Broadly, existing blockchain platforms are categorized as permissionless and permissioned. Permissionless blockchain platforms are public and allow users full access to the transactions stored on the ledger. Permissioned blockchain platforms are usually private and controlled by a designated organization. It offers access to a limited number of organizations to assure that data privacy and security are preserved [19]. Ethereum [20] is a decentralized and open-source permissionless blockchain platform that allows digitizing and tracking assets through smart contracts. Nevertheless, Quorum [21] that basis on the

Ethereum platform is classified as a permissioned platform. Similarly, Hyperledger Fabric [22] falls under the permissioned platform category as it allows the stakeholders to communicate in a private manner.

Smart contracts represent programs stored on the blockchain with terms of agreement between participants of waste management processes. They automatically execute and trigger events after meeting predetermined criteria in the agreement. Also, they assist the stakeholders in performing business operations in a faster, cheaper, and secure way compared to traditional systems that require intermediaries to commit the business operations. Based on the characteristics and lifetime of smart contracts, they are of several types such as dormant, active, prolific, self-destructed, and active. For instance, an active smart contract for waste management can register the participating organizations and issue certificates to the participants for identity management. Blockchain technology immutably stores encrypted waste management data and transactions in chronological order to provide a record of waste provenance [23]–[25]. Waste provenance data can confirm that all waste items are collected, processed, and handled in compliance with waste handling rules. It also assists in identifying the identities of waste generators or recyclers while ensuring data privacy. The highly transparent, secure, immutable, and trusted records stored on the blockchain can be accessed by the authorities to know which community in a city has the highest available waste for the waste treatment facility formation. Also, the waste ownership and provenance information can enable the government to correctly identify and issue rewards to the citizens who channelize their waste. The auditability feature uses immutable blockchain data to identify those waste handlers whose actions are non-compliant with the waste shipment or treatment laws [26]. Blockchain protects privacy by maintaining the anonymous identities of the citizens that are unlinkable to the true identities of the users. The existing studies that have employed smart contracts to automate the smart cities services have mainly considered smart grids, smart healthcare, smart homes, smart transportation, supply chain management, smart industries, and agriculture [23]–[25], [27]–[29]. Table 1 highlights the key benefits and features of blockchain technology for waste management applications in smart cities.

Blockchain-based systems developed for waste management have mostly focused on electronic, medical, domestic, and agricultural waste of smart cities. Existing blockchain-based projects for waste management have implemented several types of services related to waste management, assets tracking [10], [30], shipment monitoring [30], tokens transferring [31], waste sorting [30], and auditability of waste handler's actions [30], [32], [33]. The existing studies have followed Ethereum and Hyperledger Fabric platforms to issue rewards and penalties for the waste management participants and ensure the compliance of user's action with waste management laws [10], [31], [33]–[35]. The opportunities for blockchain technology in waste

TABLE 1. The key features and benefits of blockchain technology in waste management industry.

Feature/Benefit	Description
Data Loss Prevention	The guidance letters, weighting vouchers, and transportation documents (e.g., Bill of lading) related to waste management in smart cities are digitally recorded on the blockchain. Hence, such documents cannot be physically lost.
Credential Verification	The data provenance feature of blockchain technology can be helpful to verify the staff credential such as experience and educational certificates of the waste handling staff.
Fraud and Manipulation Prevention	Blockchain ensures that the waste management activities of the participants in cities comply with the regulated and environment-friendly waste processing laws. Any non-compliance with such rules or attempt to fraudulent the system while handling waste can be identified and verified using the traceability feature of blockchain technology.
Data Security	Blockchain technology secures waste-related data during data transit and storage using cryptography functions and consensus protocols.
Data Consistency and Immutability	The decentralization and distributed computing characteristics of blockchain make it a viable technology that ensures data consistency during waste management operations. The immutability feature ensures that the data of the blockchain can not be modified, deleted, or forged.
Cost or Resources Effectiveness	Blockchain technology can improve the cost and resource effectiveness during waste management in smart cities through increased speed, efficiency, and automation.
Supply Chain Transparency	Blockchain technology allows tracking of waste from the source to destination. During the supply chain process it enables participants to have full visibility and transparency of the transactions and data.
Breaking Down Data Silos	The majority of the centralized-based solutions cannot resolve the data silos problems of traditional waste management systems. Blockchain ensures that the data held by one organization can be accessed by the other authorized participating organizations.
Programmability and Automation	All business activities, operations, and terms between the waste managing stakeholder organizations can be automated through self-executing smart contracts.

management of smart cities are many, and technical, social, and organizational challenges in implementing such opportunities are unclear to researchers and practitioners. To the best of our knowledge, none of the existing studies have explored or reviewed the opportunities offered by blockchain in terms of waste management of smart cities. More specifically, we conduct this study to explore the role of blockchain in waste management, present several blockchain-based research projects and case studies, and discuss the challenges which need further research to improve waste management services in smart cities. The key contributions of this paper are as follows:

- We review the key opportunities brought about by blockchain technology for waste management of smart cities to improve operational transparency, traceability, security, and accountability in waste management processes.
- We present a blockchain-based system for waste management services and compare existing state-of-the-art blockchain-based waste management solutions based on important parameters.
- We report several blockchain-based research projects and case studies to demonstrate the practicality of blockchain technology in waste management of smart cities.
- We identify and discuss several open research challenges hindering the successful implementation of blockchain technology in terms of waste management within smart cities.

The rest of the paper is organized as follows. Section II presents the opportunities offered by blockchain technology in terms of waste management in smart cities. Additionally, it presents a tabular comparison of existing blockchain-based studies related to waste management. Section III discusses recent blockchain-based projects and case studies related to waste management in smart cities. Section IV presents a

discussion on research challenges in the waste management field. Section V provides concluding remarks.

II. OPPORTUNITIES FOR BLOCKCHAIN IN WASTE MANAGEMENT OF SMART CITIES

The rapid worldwide expansion of cities causes several environmental and social challenges. The increased rate of urbanization, economic development, world population growth, and the rise in the standard of living in developing countries are major causes of the amount, rate, and variety of generated waste [36], [37]. Figure 1 highlights the key opportunities offered by blockchain technology to enforce trust among participating organizations involved in the waste management of smart cities. Further discussion is provided in the following subsections.

A. TRACING AND TRACKING OF WASTE OF SMART CITIES

Smart cities generate domestic, commercial, medical, agricultural, and industrial waste. Such waste is often sent to landfills, waste recycling facilities, composters, and waste to energy generation plants. Tracing and tracking features can be useful to verify the authenticity of data and ethical practices involved in the collection, processing, and shipment of smart cities waste [38]–[41]. These features assist in monitoring the current location and state of the waste during their collection, segregation, shipment, treatment, and disposal or recycling. The traceability feature is valuable since it assists in identifying, storing, and managing detailed data about the activities and outcomes during waste management processes. The most important data which is recorded during waste management includes waste type, volume, shipping location and route, transit time status, and details about the waste handler and their actions in each waste management stage. Examples of smart cities' waste include liquid or solid household waste, medical waste, hazardous waste, recyclable waste, green waste, and electrical waste (E-waste). Today's centralized systems that are often employed to manage waste-related data

are vulnerable to modification and alteration by the planned or accidental damages [33].

Blockchain technology has the huge potential in replacing the slow and manual systems practiced in smart cities' waste management. Blockchain efficiently controls and monitors the waste shipment from the point of waste generation to the recycling center. It creates digital asset tokens (e.g., security tokens) that are associated with the smart cities waste for tracking and tracing purposes. Such tokens are helpful in following the history of recycled waste materials using ownership and digital transfer transactions and assist the authorities in waste management cost reduction and business optimization [42]. The traceability feature assures that the waste generated by smart cities is handled in compliance with the waste handling guidelines to protect the environment from pollution. It also enables users to efficiently track the end of life of the smart cities waste [43]. For instance, blockchain can be used to identify the type of healthcare waste that is processed at a waste recycling facility and is used in manufacturing medical equipment and devices. The improved assets traceability enabled by the blockchain transparency feature adds value to the waste supply chain operations and minimizes the cost of waste management operations such as waste collection, segregation, shipment, and processing. The industries can employ blockchain technology to identify which and from where leftovers and food waste are shipped to a waste recycling plant to make fertilizer. Based on such data, a new fertilizer production line can be established near the waste source to reduce the waste transportation cost. The tracking feature of blockchain technology enables users to record the current location of trucks shipping smart cities waste along with other data such as shortest route and waste weight. Such data related to the waste shipping location can be used to verify that the waste-carrying truck has traveled through certain stations before reaching the final destination. Waste is usually transported from different locations and communities, the blockchain can assist assuring using sensors attached to waste bags that hazardous waste does not get mixed with nonhazardous waste during its transportation for human safety assurance. Lastly, due to the transparency and immutability features, blockchain can be used to track the amount of waste shipped, received, and recycled at the recycling plant, credentials of the waste handler and their actions, and storage location of waste when it is segregated, sorted, and recycled or disposed of.

Based on the immutable record of data and transactions, the blockchain can verify and identify any missing waste by comparing the weight of received and shipped waste. Blockchain platforms are preferred only if the organizations involved in a business process are heterogeneous and have competing interests. Otherwise, centralized solutions are more appropriate for the implementation of waste management services. Since waste management involves heterogeneous organizations having competing interests, hence, blockchain technology can offer unlimited benefits to the waste handlers. For waste shipment tracking, the public

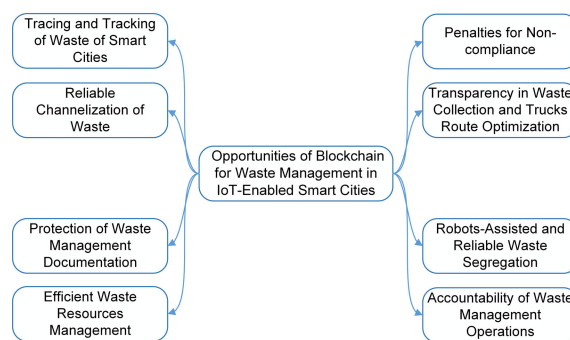


FIGURE 1. An overview of the key opportunities offered by blockchain in terms of waste management in smart cities.

blockchain platforms such as Ethereum are more suitable to fulfill the high data security, transparency, traceability, and visibility requirements of participating stakeholders. Ethereum is a secure open-source platform. It enables the waste handlers to securely send or receive micropayments as a reward for participation in waste management activities in its native cryptocurrency called Ether (ETH). Figure 2 highlights a blockchain-based system in which the smart city users store and retrieve waste management-related data using deployed smart contracts. The presented system allows citizens to view the current location and route trajectory of their generated waste.

B. RELIABLE CHANNELIZATION OF WASTE

The waste channelization deals with the process of waste collection at a designated waste collection center established by the authorized producers and refurbishing, dismantling, and recycling of waste materials in an environmentally sound way. The life period and reliability of many waste materials are different, and it truly depends on the composition and working environment of such equipment/products/materials. After the expiry of such materials, they should be recycled or disposed of responsibly at authorized waste recycling plants. For instance, many smartphone devices contain expensive lithium and cobalt materials that could be reused after smartphone expiry to manufacture new products [38]. Therefore, reliably channelizing the waste material can lead to a pollution-free and safe smart city. Producers of waste material of solid type such as scrap metal, vehicles tires, and smartphones are usually required to monitor such materials after their expiry [34], [44]. The technologies can assist to assure that waste material of all sold material is collected at the waste treatment centers. Through the lifetime of each solid material device and total supply in the market, it can be assured that waste of all sold-out solid materials is collected at the waste treatment centers. The producers can collect the waste using registered retailers, designated collection centers, or authorized dismantlers/recyclers. The domestic waste channelization refers to the waste collection and processing at the designated waste recycling center. The centralized-based solutions for channelizing waste are costly and less trustworthy. Moreover, such solutions are incapable

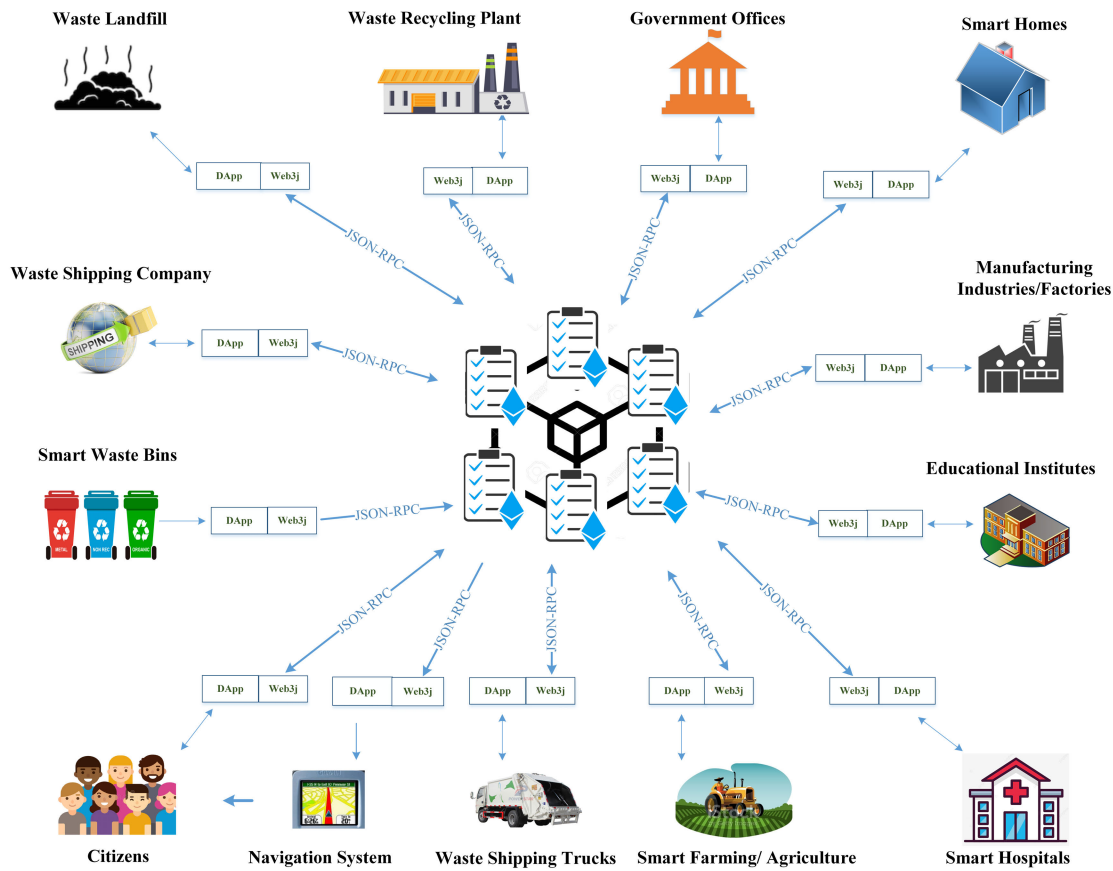


FIGURE 2. An overview of waste-related data storing and retrieving using the blockchain-based platform.

of providing trusted traceability of waste channelization operations. Moreover, full control on waste collection data, sensor credibility, fault-tolerance requirements, and low robustness due to unreplicable data are some of the challenges to the centralized based systems.

Smart cities’ users can use blockchain to channelize their domestic, medical, agricultural, and electronic waste, and incentives are issued to them on selling this waste. The auditable, immutable, and transparent features of blockchain technology can increase the trust of smart city users in monetizing their waste to channelize it. The faster settlement, enhanced security, immutability, consensus, distributed ledger, and decentralization features make blockchain technology irresistible [45]. The blockchain-based smart contracts are capable of increasing the cooperation and coordination among waste producers, segregators, retailers, shippers, and recycling units and automate the payments. The blockchain-based registration smart contract can ensure that only authorized users can view the data and transactions and participate in waste management affairs. The Ethereum blockchain platform uses Ethereum addresses for identity management. The Ethereum platform generates addresses for the identification of assets or stakeholders by using the Keccak-256 hash of the Elliptic curve digital signature algorithm (ECDSA) public key [46]. Further, smart contracts designated for waste management can enable the authorities to

monitor waste management activities and assist in regulating the amount and source of recycled waste. Smart contracts can be developed and deployed on blockchain to enforce customers to transfer an escrow amount into a smart contract wallet on purchasing a product. This escrow amount will be automatically released to the wallet of the consumer on returning the waste of the purchased product after their usage [10], [47], [48]. Hence, through blockchain-based data, it can be ensured that the waste of all products has been collected successfully. Usually, citizens are charged a flat service fee to ship their waste to sell it at a retailer or waste treatment facility. A smart contract calculating and automatically transferring cryptocurrencies in a consumer’s wallet based on the weight of the waste can motivate citizens to produce less waste. Blockchain in such a scenario can be used to settle payment-related issues, and it can identify the waste-related frauds [35].

Also, in another case study related to smart agriculture, the farmers can sell crop straws and animal residue to a company generating electricity from the waste. As a reward, users/farmers are provided with coupons against the provided waste in compliance with the rules stated in a smart contract [32]. These coupons can be used to pay their monthly electricity bills. Also, through smart contracts, blockchain technology can automatically calculate the wages to be paid to the participants involved in waste segregation. Because of

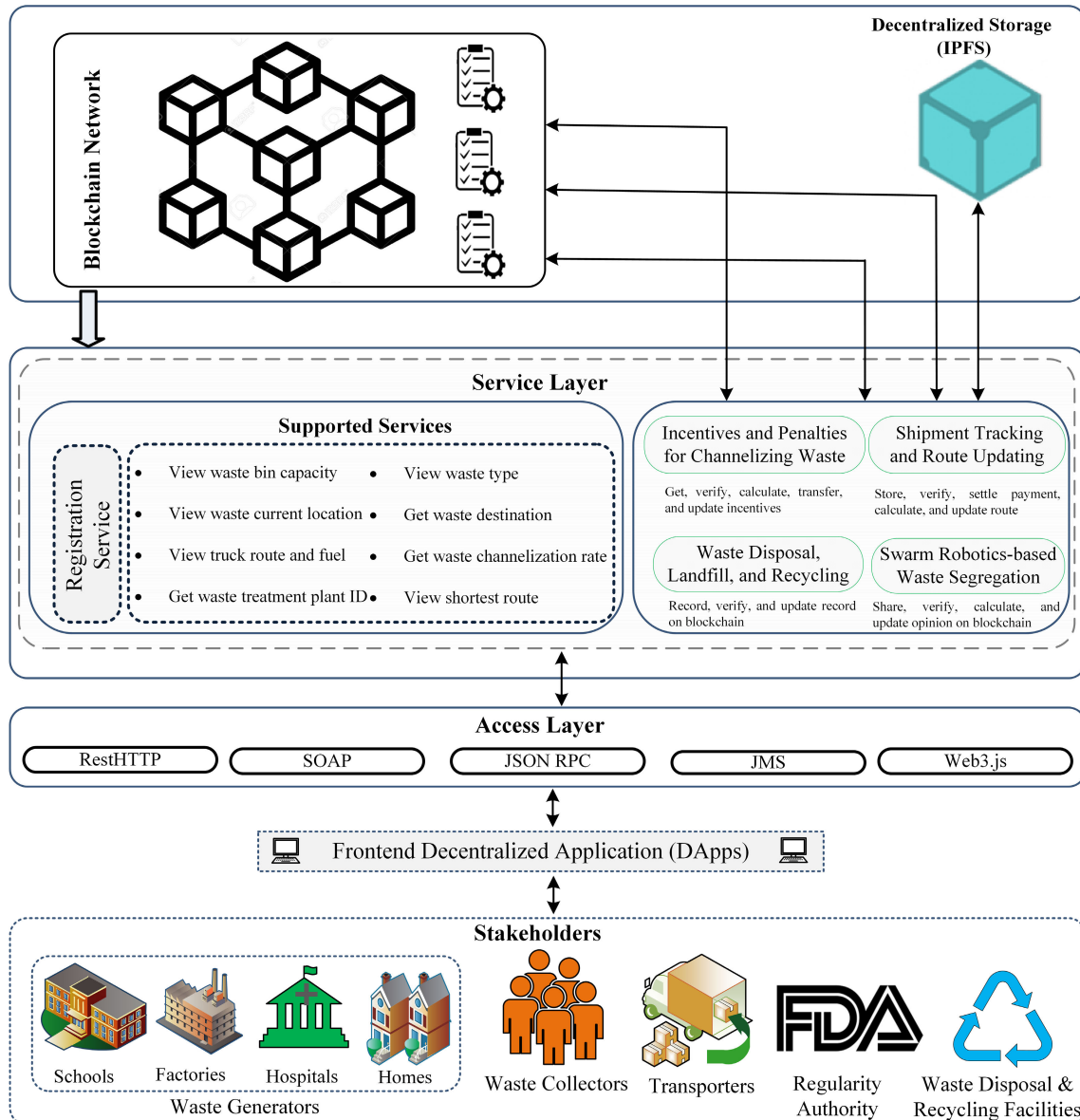


FIGURE 3. Highlighting stakeholders, system components, access layer protocols, and distributed blockchain network for a set of waste management services in smart cities.

the data privacy and security requirements of involved stakeholders, private blockchain platforms (e.g., Hyperledger Fabric and Besu) should be preferred to reliably and efficiently channelize the waste within smart cities. The Hyperledger Fabric platform [22] offers channels that enable the waste management participants to communicate in a private, secure, trusted, and privacy-preserving environment. The existing systems for waste management have channelized the waste through producer, manufacturer, and retailer modules [29], [47]. The Membership service providers (MSP) component in the Hyperledger Fabric platform abstracts all cryptographic methods and protocols involved in issuing and validating the user’s certificates for identity management. The transactions of the waste handling stakeholders are verified and endorsed by the endorser nodes who have full access to the ledger. The ordering service of Hyperledger Fabric assures that the

endorsement policy is satisfactorily followed and forwards the transaction proposal to the validators. In response, the validator nodes verify and confirm the transactions. The chain codes of Hyperledger Fabric can implement various types of waste management services such as stakeholders registration, buying, selling, and transferring products by the retailers and manufacturers, returning of the waste to the retailers and manufacturer, and updating the remaining quantity of the waste in the system [31], [32].

C. PROTECTION OF WASTE MANAGEMENT DOCUMENTATION

Today’s centralized systems leveraged for managing waste management within smart cities are less trustworthy as they offer limited transparency features. As a result, it is difficult to verify that waste management practices adopted by

an industry such as healthcare are complying with rules proposed by regularity for the safety of humans and the environment. The waste management-related certificates and documents state the rules, methods, and procedures to be followed during the collection, transportation, segregation, and recycling of waste. The key documents and certificates that are maintained by the waste handling organizations during waste management include waste disposal recycling form, waste declaration form, dangerous goods shipping document (e.g., asbestos or flammable liquids), waste management inspection plan document, and waste manifest form, to name a few [49]–[51]. The certificates of an individual or organization such as license documents are issued by the authorities to assure safe and environmentally friendly waste management. All waste management-related documents and forms are duly signed by the authorized and relevant organizations before processing the waste, and they can be used as proof to resolve the conflicts among organizations. Since these documents and certificates are managed manually or using centralized systems, hence they are subject to any accidental loss, damage, manipulation, and modifications performed by hackers.

Effective smart cities waste management policies require securely keeping records of many documents related to pay-rolls, invoices, purchase receipts, financial reports, and contracts. Such a large number of waste management-related documents create challenges to the effective management and protection of documents from adversaries. Blockchain's inherently decentralized nature makes it an ideal technology to store waste management-related documents in a secure and protected environment. The distributed network of nodes that constitute the blockchain can assist in validating the waste management documents entering and leaving an organization by comparing document signatures [52]. Blockchain technology can be used to minimize frauds related to documents (e.g., scraps and metal dealer licenses) maintained during waste handling within a city. It employs self-executing smart contracts and irreversible hash functions to speed up the waste management process, protect the documents from manipulation, and data inconsistency. The documents related to waste management should be encrypted and stored on InterPlanetary File System (IPFS) [53], [54] to efficiently utilized blockchain storage capacity. The hashes of such documents should be securely shared among the participating organizations through a blockchain platform. Any alteration to the waste management documents stored on the IPFS can be identified using the stored on-chain IPFS hash of the document. Hence, the participating organizations can quickly verify the authenticity of documents related to waste management and the licenses of the participants involved in the waste management activities. The consensus protocols that are proposed to commit waste management transactions and immutable data provenance make forging of license or waste management documents forging theoretically impossible.

Through inter-linked data blocks created using blockchain-centered hash functions (e.g., SHA-3), it can be verified who created a waste management document for shipment

handling, when it was created or modified, and who was the document issuer. The waste management documents are required to be stored and processed safely in order to fulfill GDPR laws (privacy), hence they should be stored on private blockchain platforms. Private blockchain platforms assure that waste management documents are visible to the authorized users only by enforcing access control policies. Private blockchain platforms are more secure as they allow only a limited number of organizations to participate in business transactions using the MSP component of Hyperledger Fabric or Orion node of Hyperledger Besu.

D. EFFICIENT WASTE RESOURCES MANAGEMENT

The IoT-based systems enable remote monitoring and assist in controlling smart cities through a network of deployed sensors to collect real-time data and getting insights from such data. Based on such data, plans and actions can be made to reduce congestion and traffic interruption, disease transmission, carbon dioxide emission, and make the environment cleaner and safer by timely collecting and processing smart cities waste [55], [56]. Through the analysis of smart city data, the idle resources in a city can be identified and optimally used. The key resources used in waste management of the smart cities include waste bins, transportation trucks, waste management workers, waste segregation or dumping location, waste-to-energy facilities, disposal sites, and residential waste places. These resources are required to be efficiently handled to minimize the waste management cost and improve well-being of citizens. The lack of transparency on the waste management resources and activities in existing centralized-based systems can lead to less trustworthy, inefficient, non-fault tolerant, and insecure systems. Thus, resource management decisions on the basis of potentially untrusted and modifiable data can be inefficient and costly.

Data immutability and fault tolerance features make blockchain a favorite technology for authorities to efficiently and quickly manage resources in smart cities. Blockchain assures data immutability by generating cryptographic fingerprints through hashing algorithms (e.g., Keccak256, SHA-2, SHA-3) and crash-free consensus algorithms. The cryptographic fingerprint of each block of the ledger is unique and irreversible. Because of shared, replicated, and synchronized ledger, the blockchain is a fault-tolerant technology. Blockchain can register the entities by issuing them unique addresses (e.g., Ethereum addresses) and the details about smart cities resources using a registration contract. Authorities can employ the deployed audit smart contract responsible for identifying underutilized waste management resources in a particular area within the city by using immutable data and transaction records. Usually, RFID sensors are attached to the waste management resources such as smart bins to periodically monitor and store data about their available storage capacity on the blockchain. Such sensor nodes can be authenticated using their registered blockchain addresses to assure that the adversaries cannot upload incorrect data on

the blockchain. Through the analysis of blockchain-based trusted and verifiable waste management-related data, it can be estimated with high accuracy that how frequently the waste bins request the transporters to move the collected waste to the waste treatment/disposal facility. Authorities can accurately estimate the volume of waste being transported from a particular area of the smart city using the analysis of such data. Based on this trusted waste data, authorities can shift the underutilized waste management resources to the needed areas for efficient utilization of existing resources. Also, the trusted waste data acts as a business opportunity to establish the waste treatment plants near the waste source. On identifying the type of waste in the collected food waste, the food industry can be strengthened by opening new restaurants in smart cities based on the food requirement of the citizens. The data related to the waste management resources including the wastebin location, storage capacity, and waste type should be published on the public blockchain platform to facilitate the citizens in channelizing their domestic waste. Also, the information about the available waste management resources such as waste bins or transportation facilities should be accessible to the authorities to carefully formulate policies for assigning resources for a quick and timely waste collection in a city.

Figure 3 presents a blockchain-based system that can be used to digitize the services of waste management in smart cities. The presented system has shown a set of services that can be implemented through smart contracts. For instance, based on the location data and capacity of the waste bins, the drivers can be notified by the shipment tracking and route updating smart contract about the shortest and fuel-friendly path to collect the waste in a smart city. The incentives in the form of cryptocurrency tokens are automatically transferred to the wallet of the waste collectors in a secure, verifiable, timely, and transparent way using smart contracts referred to as incentives and penalties for channelizing waste in figure 3. This smart contract also issues economic sanctions to the waste shippers on identifying unauthorized and illegal waste dumping in smart cities. The waste disposal, landfill, and recycling smart contracts ensure that the hazardous waste is disinfected properly before forwarding it to the recycling plant. Finally, the swarm robotics-based waste segregation smart contract assists the heterogeneous robots owned by different owners in deciding the type of waste during the waste sorting and segregation process using the collaborative voting technique. The presented system also highlights the supported services that can be accessed directly without requiring the consensus of the validators. The Recerrum [57] and Swachcoin [58], [59] projects have implemented the incentives sharing services for those who channelize their waste. The recycling activities, as can be seen in figure 3, assist the manufacturers in buying the waste to manufacture new and cheap products from the recycled material. A similar work to figure 3 has been proposed in RecycleGo [60] project for quickly incentivizing the participants of smart cities waste management.

A system presented in figure 4 highlights the interaction between waste collectors and waste recycling centers. The participants of this system include manufacturers, waste collectors, and waste recycling centers. The waste recycling center initiates the waste buying request and deposits the collateral amount (twice the cost of the requested waste quantity) in the system as a guarantee to behave honestly. This collateral amount is automatically detected by the smart contract if the participant cheats the system. The blockchain-based smart contract notifies the waste collectors about the pending waste buying request issued by the waste recycling center. In response to this request, the waste collectors ship the waste to the waste recycling center and receive the funds in the form of tokens once the waste has been received at the waste recycling center. Finally, the recycled material is purchased by the manufacturer to manufacture new products. The waste recycling part of this system has been inspired by RecycleGo [60] project.

E. PENALTIES FOR NON-COMPLIANCE

According to the Waste management Act 2016, the waste generators within a community are responsible to segregate and store the waste in appropriate bins, and handover it to the waste handling workers to dispose of it at the registered waste treatment facilities. In the design of IoT-enabled smart cities, all types of waste such as biodegradable and non-biodegradable, domestic hazardous, and industrial wastes should be stored in separate waste bins classified by different colors. The volume of waste generated by smart city industries depends on their size, type of services, and production level. Hence, based on the volume and type of waste generated by industries in smart cities, they are required to be registered under hazardous waste producers on producing more than 500 kilogram of hazardous waste in a year [44], [61]. Also, waste treatment processes of the waste treatment plants should be covered under certain environmental permits to protect the environment from the effects of harmful carbon emissions. Individuals, organizations, and industries are imposed heavy fines or penalties such as license cancellation for any non-compliance with the approved waste management practices.

The architectural decentralization, traceability through the timestamped transactions, and use of consensus protocols make blockchain a fault tolerance technology that drives the authorities to use it for assurance of compliance of actions with approved waste management rules. Further, it assists in automating the imposing of fines and issuing penalties on identifying any non-compliance with the approved rules in a transparent and audit-able way. For instance, during the pandemic caused by the COVID-19 outbreak, it was declared by the World Health Organization (WHO) that the users in COVID-19 hospitals or testing centers should carefully collect and store COVID-19 related waste to minimize the virus from spreading. Also, the bags carrying the COVID-19 related waste should be sealed properly to assure that they are not exposed by the handlers during their

shipment. Blockchain, in this case, can assist in monitoring the shipment and issue penalties to the waste handlers on identifying any non-compliance with waste transportation rules [33], [62]. It is desired that the COVID-19 waste should be transported by licensed users. Blockchain can assist the authorities to verify the license of a shipper through the immutable record of transactions and data, and issue heavy fines on identifying any non-compliance with the rules. Ethereum-based smart contracts can be developed and deployed on the blockchain platform to implement auditability services. The handlers of the functions in the smart contracts should be carefully and properly set to assure that only authorized stakeholders can call these functions. For instance, only government authorities should be allowed to execute the Penalty-calculation function of the auditability smart contract. The Penalty-calculation function verifies the blockchain-based data and imposes penalties for any non-compliance with waste handling rules. Proxy re-encryption techniques can be integrated with existing solutions to increase data security [63]. Minimizing the food waste in smart cities is another challenge for the authorities to protect the citizens from disease and infection. Blockchain can play a role in identifying and issuing penalties to an individual/industry involved in food waste. For this purpose, a smart contract can verify the type of waste generated by a community, and it issues fines on encountering non-compliance with the food waste-related rules. For instance, it can impose penalties on citizens on identifying that the average food waste per day is above a pre-defined threshold limit.

F. TRANSPARENCY IN WASTE COLLECTION AND TRUCKS ROUTE OPTIMIZATION

In smart cities, the IoT-enabled smart waste bins that are capable of monitoring the waste state inside the bins and transmitting real-time data to the central storage servers through wireless links are deployed [64]. The sensors attached to the smart bins can measure waste level, humidity, temperature, weight, and type of waste inside the bins. Data collected by such sensors about the waste can assist to predict the bins fill level, identify potential diseases in a community based on the type of collected waste, and forecast the volume of waste that will be collected in the near future based on the current waste generation rate by a community. The waste collection involves several stakeholders such as municipality workers, waste shipment trucks, waste sources, and environment protecting agencies. Waste collection in smart cities is a daily activity that involves truck route planning and optimization while considering environmental and socioeconomic factors. The route planning for collecting smart cities waste is affected by several parameters such as traffic jams, fuel costs, amount of waste collected per route, and the number of trucks available along with their capacity [48], [65], [66]. The route planning on the basis of a centralized-based system can be ineffective or costly since data can be compromised or tampered with. Also, the existing systems offer limited

transparency to the waste management data, which can affect the truck's route optimization.

Blockchain technology can assist in tracking the amount of waste collected, the details about who collected it, the location from where this waste is collected, and the current and final location of the waste. Through the data stored on the blockchain by the sensors, a route and schedule to pick up the waste can be formulated to minimize the fuel consumption rate of the trucks and maximize the amount of waste collection per route. The high visibility and transparency of the waste collection activities and sensor data can enable the authorities to assure that the filled waste bins are picked up timely by legitimate users. Blockchain technology links the data blocks to assure data transparency, security, and immutability by using asymmetric-key encryption techniques and registration-based access control mechanisms. The rules related to safe waste handling and policies for cryptocurrency-based incentive sharing can be programmed using decentralized smart contracts. The public blockchain platforms such as Ethereum and Bitcoin are open and offer high data transparency. On the other hand, private blockchain platforms such as Hyperledger Fabric and Besu are more concerned about handling data privacy challenges. Therefore, private blockchain platforms offer limited data and transaction transparency compared to public blockchain platforms. The smart contracts can trigger a notification to the truck drivers on identifying that the storage capacity of the waste bin has reached an unsafe threshold value. Also, other than the sensors located inside the bins, external sensors attached to the bins can continuously monitor their surroundings. Thus, through such sensors and rotatable cameras attached to the bins, any illegal dumping near the waste bin is identified and recorded on the blockchain along with the identifier of the individual who caused it. On encountering any such incident, the smart contracts can notify the authorities about such users for any legal actions. Further, an analysis of trusted healthcare waste data and food waste collected through trucks can enable authorities to identify common community diseases.

Figure 5 discusses the activities of stakeholders involved in waste to energy transformation processes. The main stakeholders involved in this use case scenario includes farmers, smart waste bins, waste-to-energy plants, and waste transporters. Smart waste bins are equipped with several sensors responsible for monitoring the type, capacity, and weight of the agricultural waste deposited by the farmers. This data is recorded on the blockchain using trusted gateways (full nodes) which are delegated nodes with full access to global ledger. These nodes are responsible for controlling and managing the sensors attached to waste bins. The manager in waste-to-energy plant can access the blockchain to issue a waste shipment request to the transporter. The transporter accepts the waste shipment request of the manager and enables the authorized stakeholders to track the shipment in real-time. On receiving the waste from the transporter, as highlighted in figure 5, the waste-to-energy plant incentivizes the farmers with tokens for disposing of their

waste properly [32]. Such tokens can be used to purchase food, pay utility bills, and exchange them for cash. The token sharing part of this system has been inspired by the Troventum [67]–[69] project.

In many cases, the connected IoT devices used in data collection throughout waste supply chain processes (e.g., waste to energy transformation as presented in figure 5) can be faulty or inappropriately deployed. As a result, such IoT devices can store faulty, incomplete, or imprecise waste management-related data on the blockchain. Making correct decisions in the context of waste management policies using such immutable garbage data becomes challenging and often results in inefficient waste resources management and economic losses [70], [71]. The resource-constrained IoT devices cannot directly communicate to the blockchain network; instead, edge nodes generate transactions to the blockchain for storing or receiving data on the behalf of IoT devices via wired or wireless links and various protocols such as HTTPS or TCP/UDP-based protocols. Through cryptographic tools and registration smart contracts for identity management, the nodes participating in the waste management process are registered and ensured that an illegitimate user/device cannot store waste-related data on the blockchain. Further, for connected IoT devices deployed in smart cities, the secure metadata binding can be employed to ensure high-quality data storing on the blockchain [72]. The edge servers annotate the data collected from the sensors with the metadata before issuing a data storing request to the blockchain. Metadata describes the information related to the connected IoT devices such as the precision and accuracy level of the deployed sensors. Such metadata can be assessed by the smart contracts and assured that data from the highly precise sensors can be stored on the blockchain. Also, the reputation-based smart contracts [73] can be used for issuing weights to the participating entities based on their behavior (trust calculation). The reputation-based systems ensure that the data of the highly reputed entities can be regarded as valid.

G. ROBOTS-ASSISTED AND RELIABLE WASTE SEGREGATION

Industrial and smart home waste such as paper and glass is recyclable. Therefore, recycling of such materials can increase their circular economy. The industrial and smart home waste in smart cities can be classified as hazardous waste, liquid waste, solid non-hazardous waste, and biodegradable wastes. Among all the aforementioned waste types, liquid waste includes wash water, organic liquid, waste detergents, and dirty water [74], [75]. The segregation process aims at identifying the recyclable materials from the waste to protect the ecosystem, save energy, reduce carbon emissions, and conserve natural resources. The older systems involved humans segregating the waste in the hazardous environment that, as a result, can affect their health. Modern waste management methods have started practicing robots to segregate the waste, thus minimizing the human interaction with hazardous waste [76]–[78]. The automated robots-based waste

segregation system highly depends on image processing techniques for object recognition and artificial algorithms (AI) algorithms to accurately classify the waste based on their type, color, or shape [79]. However, the existing robot-based waste segregation systems are less trustworthy because of the following of the centralized architectures.

A swarm consists of a network of heterogeneous robots that work together to perform the required task or actions. In the waste segregation process, a swarm of robots can automatically identify the recyclable materials from the waste by communicating with each other and sharing their opinion about the type of waste under consideration. Each robot is AI-enabled, thus it is capable of interacting with others by following a predefined set of rules. Blockchain technology enables robots to securely communicate with each other in a trusted way. Through this technology, swarm operations are autonomous, flexible, and even profitable. The information shared by the robots in a swarm is trustworthy for others since the sender uses its digital signature to sign it. Also, through a blockchain-assisted voting-based system [54], [80], the swarm can decide about a particular item in the waste based on a set of parameters such as shape, color, and texture. The rules defined in the smart contracts can calculate the sum of the opinions of the robots and declare the opinion of the majority as the final decision. Blockchain can minimize the waste segregation time, improves waste handling efficiency, and present an audit-able way to issue incentives to the owners of the robots involved in the waste segregation process. A consortium or federated blockchain platform for registering endorsers, validators, and committers from different organizations can be established to implement this use case. In contrast to private blockchain platforms, multiple organizations govern a consortium platform.

H. ACCOUNTABILITY OF WASTE MANAGEMENT OPERATIONS

The waste in smart cities produced by hospitals, smart industries, homes, and smart grid systems is often collected and managed by private companies, community owners, or designated representatives of the state. The waste management strategies such as recycling, recovery, prevention, and reuse involve diverse stakeholders effectively and sustainably utilizing waste management-related resources such as waste landfill [75], [81]. The involved stakeholders in the waste management process identify waste material to be recycled using their RFID tags [82]. The actions of the stakeholders involved in managing waste in smart cities should comply with the waste management laws to govern the storage, treatment, shipment, recycling, and disposal of all types of waste. The existing systems responsible to manage waste in smart cities are inefficient in holding individuals or organizations accountable for their services that have caused a delay or loss of waste at any stage. Through blockchain technology, the involved stakeholders such as producers, shippers, consumers, and waste handler can be placed into a single network

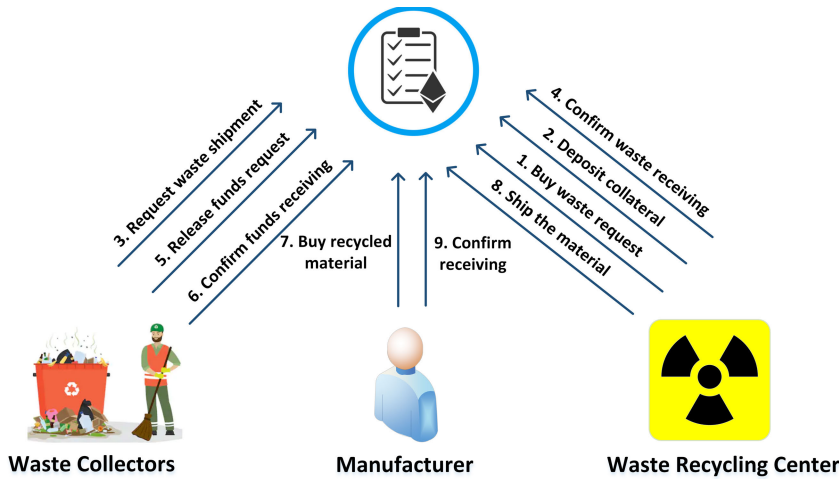


FIGURE 4. Interaction between waste collectors and the waste recycling center using a blockchain-based smart contract.

of connected nodes, thus, making data and transactions visible and transparent to the authorized parties.

Trust, decentralization, enhanced security, and data privacy are desired features of blockchain technology in the waste management industry. Despite the strong cryptographic backing to the blockchain, it is still difficult to fully protect the blockchain from external attacks. The accountability feature identifies who is responsible for a particular action within the blockchain network. For instance, the dishonest miners of the Ethereum blockchain platform can approve an invalid transaction for monetary benefit. The accountability feature of blockchain can identify such dishonest miners to force financial penalties on them. Further, there are many use case scenarios that require accountability of the user's actions involved in waste management to assure compliance with rules for a cleaner and safer city. Through blockchain, the authorities can verify that the hazardous industrial waste is unloaded at the designated recycling location. It can further assist in verifying the lost waste by comparing the volume of shipped and received waste at the disposal center, establish provenance data about the household waste, calculate and present the percentage of incinerated and disposed of waste, and verify the recycling capability of a plant and the actual waste recycled for plannings, based on the analysis of the waste-related data stored on blockchain [30]. Through transaction transparency and data traceability features, it can identify the impossible fast transportation and unnecessary fuel consumption during waste shipment. It can also assist the authorities to trace the waste shipped to illegal dumping sites to avoid waste landfill taxes. Finally, the blockchain can identify that the industrial water in a particular industry has been given wastewater treatment or not [83].

Table 2 compares the existing blockchain-based solutions related to waste management. The solutions mainly focus on waste shipment tracking, waste-related fraud identification, transparent waste sorting, and accountability of stakeholder's actions. They are based on highly proficient models to motivate citizens to channelize their waste by issuing rewards

and penalties. Also, some of the existing studies focus on electronic, general, solid, agricultural, and industrial waste to provide incentives to citizens to channelize their waste. Despite the tremendous progress made by the emerging technologies in theory and practice in smart cities' waste management, considerable uncertainties still exist about the value of visibility and transparency in the supply chain and logistics operations of waste handlers. The existing solutions for waste management have mainly focused on end-to-end visibility of supply chain operations related to waste shipment and incentive sharing with the stakeholders for e-waste collection. It has been analyzed that the existing solutions have overlooked the importance of data privacy because the majority of the solutions have considered the Ethereum platform for implementation. Furthermore, the developed applications for waste management in smart cities highly count on sensors responsible to sense, collect, and share waste-related data on the blockchain. The platform chosen by existing studies is incapable to manage such large-sized data produced by the sensors. Finally, very limited studies exist that have focused on wastewater treatment, which is a hot research topic nowadays.

III. RESEARCH PROJECTS AND CASE STUDIES

This section presents insightful discussions on the recent blockchain-based projects and case studies that mainly focus on digitizing waste management operations within smart cities.

A. RECERREUM

Recently, many countries have formulated legislation about domestic waste management in urban areas. Many governments have proposed monetary incentives or punishments to motivate citizens to channelize their domestic waste, thereby increasing the waste recycling rate. The main barriers to the success of existing centralized-based waste management include waste-related information modification, technological externalities, high search and transaction costs due to

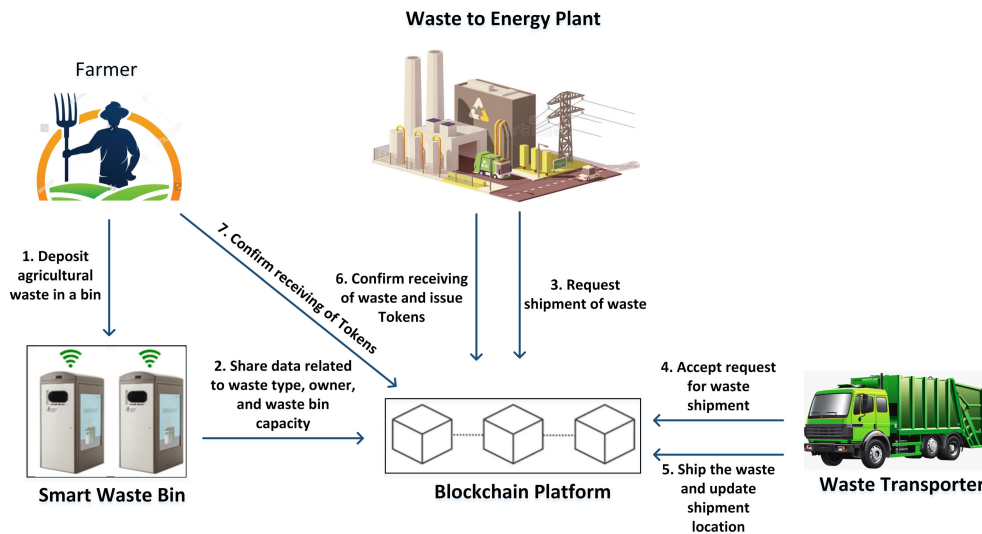


FIGURE 5. Highlighting the actions of stakeholders using a blockchain-based system to generate energy from the agricultural waste.

highly disintegrated waste channelization centers, and consumer perceptions about waste management responsibilities. Recerream (RCM) is an Ethereum-based framework which gives monetary benefits to citizens as a reward to sort the domestic waste at waste source [57]. It aims that the citizens should be able to make money from every recycled bottle, battery, or piece of electronic equipment in a transparent and effective manner. The RCM coins can be deposited in the wallet of the citizens on depositing waste at a designated center such as bottles vending machine, stations collecting recyclables, and waste collection centers. These coins can be used by the citizens for making payments against their electricity bills or any other services. The blockchain in RCM has many applications such as smart contracts based verification of the waste deposited, fast and automated payment settlement, and supply chain operations [57], [86], [87]. The supply chain feature enables users to verify and trace the waste submitted by them. It can further assist in discovering the products manufactured by the waste submitted by the citizens. The Recerream project is based on the ERC-20 token and greatly secures the financial transactions between the waste-handling participants. The private registration service of the Recerream platform assures that this platform is accessible to authorized users only, thereby increasing the data reliability. The waste segregation cost of the recycling units decreases along with a significant increase in the waste recycling rate as the Recerream follows waste sorting at the waste source. However, the scalability issue can affect the adaptability of Recerream. Besides, the defense control module, which aims at safeguarding the system against several attacks such as DDoS has not been implemented by the Recerream project.

B. SWACHCOIN

Swachcoin has leveraged multiple cutting-edge technologies to effectively manage residuals and industrial waste for

converting it into useful products. Similarly to the Recerream platform, it has also implemented Ethereum-based smart contracts to calculate and transfer incentives to citizens for channelizing their waste. The key modules of the Swachcoin system include Swachh Adaptive Intelligence (SwATEL), Swachh Internet of Things (SwIOT), Swachh Bins (SwBIN), Swachh Big Data (SwATA), and Swachh Decentralised Application (SwAPP) [58], [59]. Among others, SwATEL is responsible for making the waste management equipment intelligent to increase their operational efficiency, thereby increasing the system productivity. The SwBIN module is capable of automatically segregate the waste based on its type, color, and dimension. The SwIOT enables to remotely control and manage the waste bins. The SwATA module is responsible for analyzing the waste management data to optimize routes of trucks to minimize fuel consumption rates. The SwAPP refers to an interface that offers unique features to the users such as user wallet, token credit system, truck location tracking, SwBIN waste level status, and unique user identification. Swachcoin offers both token-based and flat-based means to present incentives to the users for channelizing their waste properly. The blockchain part of Swachcoin records the transaction data on the public Ethereum platform. It also stores other data such as machine logs and prescriptive analytic reports on the blockchain for easy auditing and high transparency [58], [88]. In contrast to the Recerream platform, Swachcoin has employed multiple technologies to efficiently handle the waste and transfer incentives to the customers. The Ethereum-based smart contracts have ensured that the waste management activities comply with the waste handling rules. Swachh tokens called Swachhcoins can be used by industry and domestic households to purchase recycled products at discount rates. Furthermore, through the SWAPP application, the network users transfer and track donations given by the community members to assist the citizens to clean the environment.

TABLE 2. Comparison of the existing blockchain-based solutions proposed for waste management in smart cities.

Article	Waste Type	Objectives	Services	Rewards Penalty	Solution	Platform
[10]	Electronic Waste	To efficiently manage electronic waste using an Ethereum blockchain platform in 5G- enabled environment	Asset Tracking	Rewards	Framework	Ethereum
[47]	Electronic Waste	To investigate the role of blockchain for waste handling in compliance with rules stated in waste management act	Waste Shipment Tracking, Auditability	Rewards Penalty	Framework	Ethereum
[30]	General Waste	To track and monitor the flow of waste across the borders in a transparent way	Waste Shipment Tracking, Auditability	N/A	Prototype	Ethereum
[84]	General Waste	To connect all participants and track the waste by assuring waste data reporting on a single platform	Waste Tracking, Auditability	N/A	Prototype	N/A
[33]	Medical Waste	To assure that medical waste is handled in compliance with safety rules	Waste Shipment Tracking, Auditability, Transparency	Penalty	Prototype	Ethereum
[85]	Solid Waste	Employing a blockchain-based system for life cycle assessment of solid materials	Waste Tracking, Policy Implications	N/A	Framework	N/A
[32]	Agricultural Waste	To provide incentives to the farmers against agricultural waste in waste-to-energy project	Waste to Energy, Auditability	Rewards	Framework	NA
[35]	Domestic Waste	To efficiently manage the garbage through a blockchain-based system	Waste Frauds, Smart Bins Monitoring	Penalty	Theoretical	N/A
[31]	Solid Waste	To develop an Ethereum-based system to securely transfer tokens to users as a reward of participating in waste management activities	Waste Sorting, Transparency	Rewards	Framework	Ethereum
[34]	Electronic Waste	To implement a blockchain-based system that can trace the assets throughout their life cycle	Smartphone Tracking	Rewards	Prototype	Ethereum
[51]	General Waste	To highlight the processes/participants involved in waste management activities using a blockchain-based system	Waste Documentation, Waste Shipment Tracking	N/A	Theoretical	N/A
[83]	Industrial Waste	To present a conceptual architecture of a system employing blockchain technology for the industrial wastewater management	Water Waste Monitoring, Automation	N/A	Theoretical	N/A

Swachchoin being implemented on the Ethereum platform is incapable of solving the blockchain scalability issue.

C. PLASTIC BANK

Plastic Bank is a multi-technology-based project run by a Canada-based company. It has recently established several waste collection centers in the Philippines, Haiti, and Indonesia. It aims to enable waste collectors to sell the collected waste at a locally designated center at a competent rate [89], [90]. It offers incentives to the waste collectors as a reward for cleaning the ocean based on the type and weight of the waste collected. Subsequently, it sells the recycled waste to the manufacturers to manufacture new products. The role of blockchain technology in Plastic Bank is to register entities and immutability record each recycling activity for making the waste recycling process highly secure, trusted, auditable, and transparent. The plastic bank has considered IBM’s blockchain platform, known as Hyperledger Fabric, hosted on a private network managed by cognition foundry [68], [91], [92]. Blockchain technology assists automating the transfer of the cryptocurrency tokens to the wallet of the recycler following successful recycling. The payments to the recyclers can be tracked, hence blockchain can eliminate the risk of data loss or theft. It also allows exchanging cryptocurrency tokens against the local currency. The registered organizations on this network can use the earned cryptocurrency tokens to pay tuition fees, get medical insurance, and pay basic utilities. It has provided a smartphone-based application

that is linked to the blockchain-based wallet, and it assists recyclers or waste collectors in managing their cryptocurrencies [89]–[92]. The plastic bank has proposed a security-rich and highly scalable reward management system which uses a blockchain platform hosted on the BM LinuxONE Servers on IBM Cloud. The traceability feature of the Plastic bank project enables the authorities to assure that the tokens are immediately provided to legitimate users only. The Plastic bank platform has introduced a crypto token which is currently equivalent to one US cent. Through the GPS mapping system implemented in the Plastic bank, data verification can be conducted very quickly to assure that the collected plastic belongs to the ocean. As the Plastic bank is hosted on a private blockchain platform, hence, it is vulnerable to attacks by adversaries due to limited network decentralization.

D. RecycleGo AND EMPOWER

RecycleGO has collaborated with DeepDive Technologies group to bring about trust in the supply chain business of recycling materials. It has employed a Hyperledger Fabric platform to verify, track, trace, and report activities in recycling supply chain business processes. It connects the participants such as buyers, suppliers, shippers, recyclers, and other supply chain actors to the recycling services using smart contracts deployed on blockchain to increase the visibility for better decision making. It can assist to track the plastic bottles throughout their lifetime; from its manufacturing to collection and conversion back to the raw material for manufacturing

new products. Apart from the supply chain operations, it also assists the haulers of recyclables to follow the optimal route as they are integrated with the fleet management and route optimization system. The key hauling services offered by RecycleGo include routing efficiency, dispatch messaging service, containers' location tracking, and instant pickup confirmation service [60], [93], [94]. The blockchain-based smart contracts have enabled RecycleGO to optimize the recycling operations and verify the carbon offset and supply chain operations. The analysis of immutable data stored on the blockchain can assist the authorities in making sustainable waste management plans. Finally, the efficient sharing of potentially secure data related to plastic bottles increases the collaboration opportunities among the recycling participants. The implemented system has increased the visibility of the user's operations and data in the waste supply chain. However, the data privacy of citizens has been overlooked in the RecycleGO platform. Empower is a Plastic Bank-type blockchain-based startup that allows citizens to sell plastic waste in exchange for tokens (1 kg plastic waste = 1 EMP); the earned tokens are securely awarded and can be exchanged against the money or used to pay for waste clean-up in other locations. The main processes or entities considered by the Empower project in the value chain include waste pickers/collectors, collection centers, waste aggregators, recycling facilities, manufacturers, and products. Empower aims to develop a global waste deposit and tracking system that should allow the users to trace and track waste in a transparent way. Since the blockchain-based data is immutable, therefore, it is secure against any type of corruption. The traceability feature of Empower platform enables the authorities to assure that during the cleaning and processing of plastics at the waste recycling center, the EU regulations and certified methods are followed closely. The empower gives an accurate and verifiable real-time estimate of the volume of plastic waste collected from the cities. Empower aims to use the Zafepace blockchain platform to trace and track the end-of-life of the plastics [68], [95]–[97].

E. TROVENTUM AND AGORA TECH LAB (ATL) PROJECT

Troventum is a sustainable development digital project that aims to interconnect every participant of the waste supply chain through a trusted and decentralized platform. It facilitates the waste management participants such as producers, procurers, recyclers, product manufacturers, shippers, and retailers to perform their business activities in a secure, trusted, and auditable way. The potential participants of the platform include waste generators, retailers, collectors, recyclers, and manufacturers. The modules of Troventum that facilitate the operations of stakeholders including waste generators, retailers, collectors, recyclers, and manufacturers include TROVENTUM.BONUS, TROVENTUM.BONUS, RECYCLER OS and TROVENTUM.TRADE, RECYCLER OS, and TROVENTUM.TRADE and TROVENTUM.CARGO, respectively. Troventum consists of several modules and has been

implemented on the Ethereum blockchain platform. The users are offered cryptocurrency tokens as a reward for engaging in waste collection, sorting, and channelization. Troventum OS module of Troventum refers to a suite of software that offers bonuses to the people collecting and selling domestic waste. The Recycler OS module enables waste recyclers to keep an immutable record of transactions related to receiving and recycling various types of waste. The *Troventum.Coin* module allows the product manufacturer to buy raw materials generated from the recycled waste from the suppliers/recyclers. *Troventum.Trad* streamlines the raw material shipment process between the raw material suppliers and product manufacturer [67]–[69]. Agora Tech Lab (ATL) aims to leverage a customized blockchain platform to securely transfer tokens as a reward to encourage citizens to keep the environment pollution-free by channelizing their waste. ATL is a Rotterdam-based organization that integrates waste management systems to the blockchain platform to immutably store the waste management-related transactions on it. The tokens received by the waste collectors can be used for personal government services [68]. By using the Ethereum platform, ATL has revealed a wallet to enable the citizens to receive and send tokens after evaluating waste collection-related activities. The smart contracts in the proposed system enable citizens to report and collect the waste. The collected waste is tracked through a blockchain-based smart contract during its shipment to the waste recycling facilities. The smart contract designated for reward management immediately transfers tokens to the waste collector.

Discussion: The aforementioned research projects employed blockchain technology to secure the transactions related to waste management operations in smart cities. Though, these research projects have successfully secured the waste management services including plastic bottles traceability, incentives issuing to the citizens as a reward for participating in waste management activities, controlling the waste bins remotely, and penalizing the companies for illegal dumping/shipment of the waste. But, the performance of these applications can be greatly affected by the blockchain network latency, transaction throughput and cost, and capacity or capabilities of the IoT devices. Blockchain network latency represents the time required to add the new block of transactions in the chain; whereas throughput is the number of transactions executed in a unit of time. For instance, Bitcoin requires up to ten minutes to confirm a transaction and it provides a maximum throughput of seven transactions per second [98]. The performance of waste management applications such as robots-assisted waste sorting and segregation can be profoundly affected by the high block creation time of the underlying blockchain platform. Therefore, private blockchain platforms are often preferred for such applications as they are faster and takes less time to confirm a transaction. Every transaction on the blockchain requires certain computational resources during execution; hence the owner of the transaction is required to pay a fee in the form of cryptocurrency for the mining process. The

high transaction cost can greatly affect the adaptability of blockchain technology to waste management applications in smart cities. The Ethereum blockchain platform requires the entities transacting on the Ethereum network to pay transaction fees as gas in Ethers to incentivize the miners to successfully process the transactions.

The waste management services are enabled using the IoT devices that are deployed in smart cities for data collection and resource monitoring. Several types of IoT devices, nodes, and sensors such as connected devices, waste monitoring equipment, wastewater quality sensors, cameras, lights, and meters are used to collect and analyze waste management-related data. The IoT devices are resource constraints by design and cannot execute inherently complex cryptographic functions and consensus algorithms as implemented by the majority of the blockchain platforms. Hence, such devices are designated as lightweight nodes (i.e., Ethereum clients) and connected to the gateways through the API interface. Gateways can work as a full node and has full access to the global state of the ledger. Gateways retrieve the data from the blockchain as requested by the lightweight IoT devices. The integration of IoT with the blockchain via trusted gateways can compromise the decentralization feature of blockchain technology.

Most of the developed research projects for waste management in smart cities have leveraged private and public blockchain platforms to automate business operations in waste management. The private blockchain platforms used for waste management applications in smart cities are permissioned and mostly owned by a single organization, cheap in terms of transactions execution cost and infrastructure requirements, highly energy-efficient due to limited system participants, and requires high trust among the participants involved in waste management operations. Further, private blockchain platforms are scalable and ensure high system throughput, which as a result enriches the experience of stakeholders involved in waste management services. In contrast, the public blockchain platforms used for waste management applications are accessible publicly by everyone and costly in terms of transactions execution cost. Further, public blockchain platforms are less energy-efficient and scalable and do not require trust among the participants involved in waste management operations.

In summary, this research has demonstrated the potential of blockchain-based systems by presenting their key benefits/features in three exemplary use case scenarios related to waste management in smart cities. Based on the high importance of these use case scenarios, we have chosen them as an example. They are very useful to develop and follow policies related to efficient waste management. These systems are presented to highlight the system components, stakeholders, and information flow direction for a particular use case scenario. Further, these exemplary presented blockchain-based systems can act as a base and guideline for other use cases on how they can be employed with minimal modifications. The majority of the discussed projects such as Reccerum,

RecycleGo, and Swachain have focused on incentive management for plastic waste collection and sustainable circular economy. The exemplary systems presented in Section II have focused on the audit and traceability of the operations of the stakeholders involved in waste segregation, agricultural waste-based energy generation, and recycled materials order management. The exemplary systems are not completely compatible with the systems discussed in this section because of the differences in the implementation goals. For instance, the majority of the existing research projects have focused on the transferring of cryptocurrency tokens to the waste providers in a secure way using Ethereum and Hyperledger Fabric platforms.

It is worth mentioning that many of the systems presented in this section are already completed and deployed by the companies. Our presented exemplary systems aim to present a high-level design of a blockchain-based system to highlight system users and components. The visual structure presented by such systems can be helpful to organize the information and work on it effectively. The systems presented in this section are platform-dependent; whereas, our presented exemplary systems have not focused on the implementation policy. In summary, there is a limited relationship between the existing systems and the presented exemplary systems.

IV. OPEN RESEARCH CHALLENGES

In this section, we discuss several open research challenges that hinder the successful adoption of blockchain technology into smart cities for waste management.

A. WASTE MANAGEMENT SMART CONTRACTS VULNERABILITIES

The blockchain-based systems leveraged to manage waste in smart cities employ smart contracts to execute events and functions. Examples of such smart contracts include IoT-based waste bins monitoring, real-time waste shipment tracking, waste fraud detection, and stopping the illegal waste landfills. Solidity language is used to develop Ethereum smart contracts for waste management in smart cities. Being just another version of the software that runs on a distributed and permissionless network, the Ethereum smart contracts for waste management are prone to several security issues. Smart contracts are immutably stored on the blockchain that presents various pros and cons. Smart contracts are rated safe against any modification by hackers; but, they cannot be modified by the developers to meet the new business requirements after their deployment. For instance, after the successful deployment of the waste shipment handler smart contract on the blockchain, the municipality authority cannot revise the terms and conditions related to the waste shipment (third party waste shipment service) as agreed by the participating entities due to smart contracts irreversibility characteristic. The waste shipment handler smart contract implements the rules about waste delivery, tracking, and payment handling. The hackers attempt to manipulate the execution of the smart contracts using loopholes present in waste management smart

contracts to execute it in favor of their activities (e.g., stealing the virtual currencies) [83], [98], [99]. The common vulnerabilities in smart contracts for waste management are classified into operational, security, developmental, and functional categories [100]. The common vulnerabilities in waste management smart contracts that are often exploited by hackers include reentrance attacks, integer overflow, denial of service attacks, and remote code execution. Hence, it is essential to rigorously test the smart contracts for waste management before their deployment using highly proficient security analysis tools such as Smartcheck, ReGuard, OYENTE, Mythril, Securify, GASPER, to name a few [83], [98].

Another challenge related to smart contracts usage for waste management is the limited throughput and storage capacity of existing blockchain platforms. The existing IoT-based solutions for smart cities waste management employ sensors to collect, segregate, and process the collected waste. Since the deployed sensors for waste management applications are more in quantity, hence these sensors generate a large amount of real-time data to store on the blockchain [29], [47], [98]. The existing blockchain-based solutions depend on smart contracts to manage such data. However, it is challenging for the existing smart contracts to manage such a large amount of data effectively. More specifically, the quality of service (QoS) for the waste management applications can be significantly affected due to extended transaction execution and waiting time caused by large-sized data traffic (Public platforms) [101]. Existing public blockchain platforms are incompetent and non-scalable to handle such a massive amount of data. For instance, the Ethereum blockchain platform is not scalable as it employs a PoW consensus algorithm. The upcoming version of the Ethereum platform aimed at using PoS to increase the throughput of the system [54], [98], [101]. The privacy assurance challenge to the existing public blockchain platforms also affects the use of smart contracts for waste management in smart cities. Another challenge faced by blockchain-based smart contracts for waste management is the irreversibility of smart contracts after their deployment. As a result, organizations find it tough to change the business policies once smart contracts are deployed.

B. STORAGE REQUIREMENTS AND WASTE DATA QUALITY

The business processes involved in waste monitoring, collection, segregation, transportation, and disposal generate a large amount of data. Such data could be in various forms such as videos, images, or documents that assure the waste management activities complying with local and global environmental protection and human safety laws. Examples of gathered data include the type of waste collected, real-time location of the shipped waste, recycling/landfill sites, and transportation route followed by waste transporting trucks [30]. Such data comes from several hundred thousand sensors deployed in smart cities to monitor the waste continuously, and storing it on the blockchain. Every node in the blockchain network stores a copy of this data, thus it leads to

a shortage of blockchain storage capacity. The performance of blockchain technology is high when it stores and processes the data of small-scale businesses. However, the performance of blockchain is severely affected by large-scale business applications. The decentralized storage systems such as IPFS, Filecoin, and Storj.io store large-sized waste-related data in an efficient way [98], [102]. The integration of blockchain with such systems can overcome the limitations of blockchain technology. A decentralized storage system (e.g., IPFS) generates an irreversible hash of the stored data. Such hashes can be immutably recorded on the blockchain to assure that the data stored on the decentralized storage system has not been modified [54]. Also, blockchain-based systems can limit the size of data stored on blockchain by leveraging off-chain communication channels.

The waste management applications for waste collection, sorting, recycling, and disposal in smart cities require that the data recorded on the blockchain should be absolutely correct. For instance, the waste resource management service requires that the data recorded on the blockchain should be in the correct form as incorrect data can lead to wrong decision-making regarding waste resource planning. However, it is challenging for existing waste management systems to prevent wrong data input stored permanently on the blockchain. As a result, the incorrect source data causes blockchain data to be polluted (i.e., garbage in garbage out). Novel solutions must be proposed for waste management applications to efficiently handle data quality problems. One possible solution could be to implement strict control mechanisms to assure correct data. More specifically, municipality stakeholders should be allowed to impose control on waste management data. The municipality should be set responsible for the development, maintenance, and adaptation of blockchain architectures and infrastructures to minimize blockchain data pollution.

C. DEVELOPMENT OF SCALABLE APPLICATIONS FOR WASTE MANAGEMENT

The stakeholders involved in waste management in smart cities require high quality-of-services (QoS) while using blockchain-based services. Many waste management applications in smart cities such as robot-assisted waste segregation and sorting generate large, complex, and high precision sensor data at high speed. As a result, it becomes challenging for the underlying platforms to quickly and reliably process such data. Additionally, among many metrics, transaction throughput, type of IoT devices, the storage capacity of blockchain, the latency of the transaction's execution, and transactions cost highly impact the QoS of blockchain-based waste management applications. Considering the decentralized and self-governing nature of blockchain technology, it is difficult to optimize such parameters while ensuring high transaction execution transparency, security, and privacy [103]. Bitcoin platform's throughput is up to seven transactions per second. It has been reported in various studies that the throughput of the Ethereum 1.0 platform is 16 to 20 transactions per second; whereas, Ethereum 2.0 promises

a throughput of 100,000 transactions per second [33], [54], [104]. The existing solutions proposed for the development of scalable waste management applications are mainly classified into two layers.

The layer 1 solutions for waste management in smart cities concentrate on improving the on-chain blockchain features such as consensus algorithm, block size, and structure of the ledger. However, each solution has its associated problems. For instance, the approach extending a block size can maximize the system throughput; but, it extends the block propagation time. The extended blockchain propagation time can cause multiple blockchain forks. On the other hand, layer 2 solutions have focused on shifting the complex operations to off-chain, thereby minimizing the burden on on-chain blockchain resources to improve its throughput [105]. Among many solutions, Bitcoin-cashing, block compressing, lightweight and fast consensus algorithms, and sharding has focused on maximizing the throughput of the blockchain-based systems. Side-chain and cross-chain approaches are some examples of layer-2 solutions that can assist in maximizing the throughput of the existing platforms [23], [33], [104], [105].

D. RESILIENCE AGAINST ATTACKS

The participating stakeholders in the waste management processes can intentionally upload an unnecessarily large amount of textual and image data to the blockchain by generating attacks for monetary benefits, cyberwarfare, or any other personal reasons. The attacks can assist the adversaries to get access to the wallet of the user or extend the block's creation time to minimize system throughput. The attacks on the blockchain result in transaction malleability, security breaches, limited privacy, data redundancy, and regularity non-compliance [106]. Many solutions exist that effectively mitigate denial of service (DoS) or distributed denial of service (DDoS) attacks on blockchain. In [107], authors have proposed an Ethereum-based smart contract that enables the participating organizations in identifying and reporting the white or blacklisted IP addresses to mitigate DDoS attacks. It assures that traffic from the white list of IP addresses is forwarded to the blockchain; whereas, the traffic from the blacklisted IP addresses is filtered and ignored. The software-defined networking (SDN) enabled blockchain-based architecture discussed in [108] has mitigated the DDoS attacks on blockchain by introducing another security layer to the system proposed in [107] using bloom filter.

An IoT-integrated blockchain architecture that has implemented a registration smart contract to mitigate DDoS attacks has been presented in [109]. Many of the systems proposed for mitigating the DDoS attacks have followed the Ethereum blockchain platform. Such solutions are incompetent considering the scalability challenges of the Ethereum platform. The accuracy of blockchain-based waste management data can lead to make better decisions (e.g., waste collection activities, etc.). Blockchain can protect the waste-related data from modification by the adversaries by storing the hash of the

previous block to the current block. Blockchain technology does not deal well with the accuracy of data generated by IoT sensors. This can be achieved to some extent by integrating blockchain with multiple technologies including artificial intelligence (AI) techniques, deep and federated learning, and secure device metadata binding mechanisms [72]. Also, by proposing blockchain-based reputation systems, the adversarial entities in the waste management network can be identified and blacklisted [110].

E. INTEROPERABILITY AND INTEGRATION WITH THE LEGACY SYSTEMS

The waste management industry involves several technologies, devices, sensors, components, and organizations that work closely to handle the issues related to waste collection, segregation, and disposal in smart cities. The innovative blockchain technology aims at solving trust and operational transparency-related issues of the existing legacy systems (discussed in section II). Blockchain is only one piece of the technologies used by the highly complex, unpredictable, and challenging waste management industry. Therefore, blockchain needs to be well integrated with the existing waste management systems to efficiently control and manage the operations of stakeholders in the supply chain of smart cities waste. Also, the stakeholders (i.e., waste generators, collectors, shippers, and recyclers) involved in the waste management of smart cities have competing interests among themselves, and they belong to different organizations. Further, such organizations could have deployed heterogeneous blockchain platforms to perform their business activities. The high coordination and communication among the participating stakeholders in the waste management industry require a smooth, timely, and fast execution of transactions related to waste management. The interoperability feature enables waste management organizations that use heterogeneous blockchain platforms to interact and share data among themselves uninterruptedly, seamlessly, securely, and efficiently without any intervention by the end-users. Hence, despite the diversity in the supported languages, interfaces, consensus protocols, and hashing algorithms, blockchain platforms implement technical and semantic interoperability to allow the participating stakeholders in waste management operations to perform cross-chain transactions [54], [111].

For instance, atomic swaps allow trustful cryptocurrency exchange by enabling the waste-handling players to transfer certain tokens from the Bitcoin platform to the Ethereum platform. Komodo's BarterDex tool has used atomic swaps to exchange cryptocurrencies in a decentralized network [112]. The approach mentioned in PolkaDot has implemented a designated blockchain platform that can work as a relay node to provide blockchain interoperability support [111]. One of the key requirements of the stakeholders involved in waste management activities is the security and privacy of data and transactions when interacting with another platform's user. Hence, future interoperability-supported blockchain platforms should be highly secure, fast, and

privacy-preserving to meet the requirements of involved stakeholders.

F. PRIVACY PROTECTION OF WASTE MANAGEMENT DATA AND PARTICIPANTS ANONYMITY

Guaranteeing data privacy and entity anonymity by the underlying blockchain-based platforms are the key requirements of stakeholders managing waste in smart cities. By design, blockchain is a distributed database that manages the data and transactions related to waste management in smart cities into a hierarchical chain of blocks. The security of waste management-related data and transactions is assured through cryptography hash functions and decentralized consensus protocols. The key features of existing blockchain platforms preserving the security and privacy of data include integrity, confidentiality, and anonymity of users' identity through digital signatures, system, data, and transaction availability through decentralization, and unlinkability of transactions to calculate the true identity of a user [14], [33], [113]. Ethereum provides the pseudonymous identity of the users as it presents a disguised identity for the user to preserve data privacy. The blockchain platforms leverages the hash of the user's public key to enable users to interact with the system.

The use of such identifiers hides the identity of the users. However, successful inference attacks on the blockchain can create the linkage among a user's transactions to reveal the identities of users. More specifically, the public blockchain platforms are vulnerable to inference attacks as transactions, pseudonymous addresses, and other user data are publicly available. Private blockchain platforms run in a controlled environment. Thus, they are more secure than public blockchain platforms. Private blockchain platforms such as Hyperledger Fabric and Hyperledger Besu [22], [99] can preserve the privacy of waste management data through private channels and Orion private transactions manager, respectively. Considering the data privacy requirements of the waste management applications, private blockchain platforms are preferred for waste collection, sorting, and recycling in smart cities. Further, a private blockchain platform ensures that transactions are anonymous to the public.

G. INCENTIVES MANAGEMENT AND SLOW BLOCKCHAIN ADOPTION

The sensing and data transmission capabilities of IoT-based sensors have enabled officials to closely monitor the waste bins' status. Such data is useful to optimize routes of trucks shipping the waste to recycling centers. Blockchain technology has shown a great role to bring trust, security, fairness, operational transparency, and audit features to existing affairs of waste management handling in smart cities. It can assist the authorities to verify that the hazardous waste is properly disinfected before it is disposed of at a recycling center to minimize the chances of disease spreading [38], [47], [75]. The disposed of material at the recycling center can be sold to the manufacturers to manufacture new products. Thus, the increase in the rate of waste recycling

can effectively strengthen the circular economy of waste materials. Stakeholders such as customers, rigors, segregation personnel, transporters, and waste recyclers are involved in the waste management of smart cities. These stakeholders require to closely coordinate and cooperate to perform waste management-related activities efficiently. Blockchain has the potential to assist the stakeholders involved in the supply chain of waste management operations to communicate in a trusted, secure, and verifiable way. The adoption of blockchain technology requires close cooperation and coordination of stakeholders to minimize waste handling related frauds, data manipulations, and illegal waste dumping. Also, it requires changing of current operational and business model of the participating stakeholders. The stakeholders often expect incentives for deploying or adopting blockchain-based technologies. Hence a fair incentive scheme must be proposed to motivate the organizations to cooperate for the successful adaptation of the blockchain technology. Despite the many advantages of blockchain technology and the availability of several open-source projects for waste management as highlighted in Section III, blockchain adoption in the waste management industry is in its infancy.

Several technological, institutional, and organizational factors influence the adoption of blockchain in the waste management industry. Although the traditional systems are considered as cheap, fast, and highly flexible compared to blockchain-based waste management solutions, they are vulnerable to several security threats by intruders and fall short in providing data transparency, privacy, visibility, and fault tolerance features. The availability of a specific blockchain tool that can fully digitize the services of the waste management industry can influence its adoption [7], [8]. In addition, the infrastructural facilities that detail various facilities such as waste transportation network, traffic control and management, fine-grained and transparent incentives and penalties models, and real-time waste monitoring (using IoT devices [114]–[116]) are required for the successful adoption of the blockchain platform in the waste management industry. Currently, laws and regulations for blockchain are not mature enough, thereby affecting its adaptability in the waste management industry. Finally, organizational factors such as training facilities, top management support, perceived cost of investment, and available human resources greatly influence the adoption of blockchain into waste management within smart cities [7], [62], [99].

V. CONCLUDING REMARKS AND RECOMMENDATIONS

In this article, we have discussed how blockchain technology can be leveraged for managing waste within smart cities in a manner that is decentralized, tamper-proof, transparent, traceable and trackable, auditable, secure, and trustworthy. We explored the key opportunities offered by blockchain technology for managing various activities and actions related to the collection, shipment, segregation, disposal, and recycling of waste in smart cities. We presented a blockchain-based framework for waste management to

highlight system components, participants along with their role definition, and data flow among system components. We provided insightful discussions on the recent blockchain-based research projects and case studies to highlight the practicability of blockchain in the waste management of smart cities. We identified and discussed several challenges remaining to be addressed to unlock the full potential of blockchain in terms of waste management within smart cities. Our concluding remarks along with key recommendations include:

- The transparency and immutability features of blockchain can assist in tracing and tracking the amount and type of waste collected in a community, the details about waste collectors, the location from where it was collected, and the current shipment location and final destination of the collected waste.
- The fault tolerance and data tamper-proofing properties enable blockchain to efficiently manage scarce waste management resources, identify frauds related to illegal waste disposal and landfilling, and issue penalties to an individual/industry involved in hazardous waste spreading.
- The parameters such as system throughput, transaction execution latency, data volume, competing interests of the concerned participants, bugs and vulnerabilities in smart contracts, and available gas and size of the block can significantly affect the performance of blockchain-based solutions developed to manage waste.
- Segregating waste within smart cities through highly autonomous robots can assist in minimizing human interference for health safety purposes. Blockchain technology can enable such robots to make effective decisions based on highly trusted, secure, transparent, and verifiable data.
- Employing a public blockchain platform for digitizing waste management services in smart cities faces many challenges related to preserving data and transaction privacy. Ensuring compliance with General data protection regulation laws for data privacy can increase the adaptability of public blockchain platforms in smart cities.
- In the future, we aim to propose and implement a Hyperledger Fabric-based system that will calculate the reputation of each registered waste recycling unit based on its environmentally friendly waste disposal policies.

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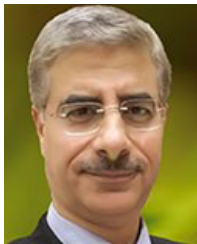
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