Blockchain Technology in Waste Management

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Implementing blockchain technology in waste management is a novel approach to environmental sustainability and accountability challenges in our modern world. Blockchain, a technology that enables decentralized and immutable ledgers, is being re-imagined as a tool to revolutionize waste management. This innovative approach aims to improve waste management transparency, traceability, and efficiency, resulting in significant environmental and economic benefits.

Keywords: blockchain technology ; waste management ; smart contracts in waste systems ; blockchain in recycling

1. Introduction

Waste management's disposal chain is a complex system involving many stakeholders. Typical waste transfers involve citizens and industries; municipalities; outsourced entities that collect and manage the bins; different centers that deal with collection, disposal, and recycling; and producers of recycled waste materials that put new products on the market [1].

The monitoring and recording of waste collection data plays a crucial role in ensuring compliance with applicable laws and regulations. It also has the potential to provide valuable insights that could influence future legislation and ultimately prevent the inefficient disposal of waste through methods such as landfilling or incineration. However, the process of tracking waste and monitoring ownership to generate these important data are inherently complicated. Challenges can arise from a variety of sources, such as products breaking down into smaller components, existing laws such as extended producer responsibility, which requires manufacturers to dispose of the subsequent waste from their products, and the problem of the abandonment of ownership through littering or dumping. Tracking waste and monitoring its owners currently requires more pragmatic solutions than those currently in widespread use [2].

Waste management systems can be changed by using the advantages of blockchain technology, which is a decentralized system for immutably recording data [3]. In this context, blockchain technology has emerged as a transformative force, offering new approaches to improve the efficiency and sustainability of waste management [4]. From secure and transparent transaction records to facilitating waste recycling, the opportunities the blockchain offers are both profound and far-reaching.

The main advantages of implementing blockchain technology are that it can guarantee safety and authenticity, verify that products are environmentally friendly, and help reduce resource consumption and improve recycling performance [5]. Blockchain can potentially affect the supply chain and enable quick and efficient information exchange between parties [6]. Adopting a blockchain can be a game changer for the supply chain, removing the traditional system's flaws and inefficiencies.

2. Characteristics of Blockchain Technology

The prevailing data processing systems are mainly based on centralized architectures within organizational units or cloud technology [7]. When a business process requires interaction between multiple entities, communication solutions are added to enable these interactions through specific communication mechanisms. However, centralization also has drawbacks, such as potential points of failure, vulnerability to cyberattacks, and data inconsistency [8]. This approach can drive up costs and complicate systems. Participants must rely on trusted intermediaries to act as arbiters and approve transactions or verify the origin and accuracy of data.

Blockchain is a system based on a database network that allows all participants to record, disseminate, and store information effectively, securely, and equally [9]. Moreover, it is a system that operates without a central administrator or manager, in which all data history is available at all times and in which information, once stored, cannot be changed. In other words, it is a system designed so that the information stored and transmitted over the network has a high level of credibility and security, and network participants have transparent access to a common, trusted source of information [10].

A blockchain database can be defined as a sequence of data blocks that are tightly linked (**Figure 1**). Each block contains elements such as data, a block identifier (hash), and the identifier of the previous block [11]. Any change in data in a block is immediately detected due to inconsistencies in the structure of the entire chain. The chain's integrity is constantly monitored by all network users [12].

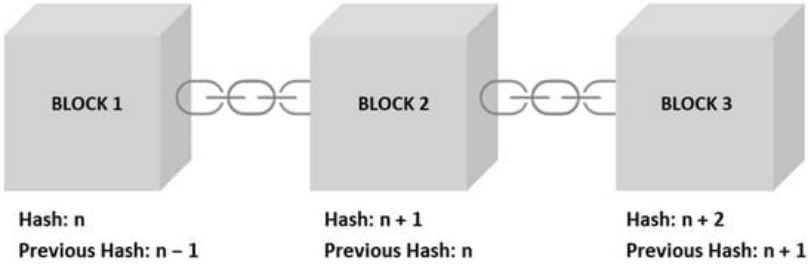

Figure 1. Scheme of a sequence of data blocks in blockchain technology.

In an operational sense, the blockchain is a distributed multi-user database managed by a network of computers operating according to a specific blockchain protocol [13]. Each network node has its own copy of the database, operates it with equal rights, and can initiate and verify changes. Everyone has access to the database, but no one controls it, and consensus enforced by the protocol makes all changes. The main features of the blockchain are its immutability and transparency. Network participants immediately detect and reject any attempt to interfere with previously stored data [14].

Finally, it is important to emphasize that the distributed environment means that each participant owns a complete copy of the blockchain (**Figure 2**). This makes the system resistant to failures and attempts to centralize control. All changes are made based on consensus among network participants. Thus, the blockchain provides a reliable and transparent source of truth for all participants [15].

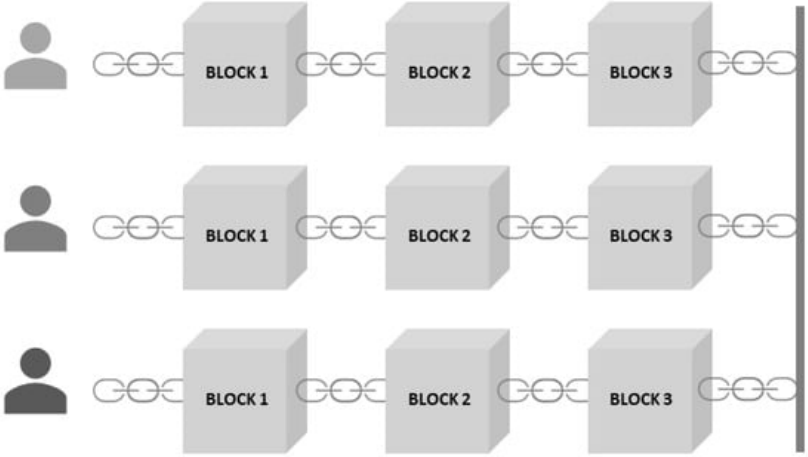

Figure 2. The environment of blockchain technology.

3. Types of Blockchain Technology

Blockchain technology can be used for public registers available to the general public. Although encryption techniques may protect certain data in this registry, its origin is verifiable from available records. To inspect this data, there are tools such as a blockchain explorer or dedicated data extraction and analysis software [16].

When choosing blockchain technology for a specific application, it is crucial to determine the appropriate blockchain type. There are three basic types:

- Public Blockchain: This is characterized by an open structure that anyone can connect to. It operates in a decentralized and autonomous manner, not subject to the control of any central entity. Decisions regarding its development are made democratically by the user community.

- Private Blockchain: This is a dedicated solution, most often created for a specific organization or consortium of enterprises. Access is strictly limited, and the network is managed under the supervision of a designated unit or group.

- Hybrid Blockchain: This combines features of both types above. It is a specific form of a private blockchain with a defined management policy. However, some parts of it can use the public network infrastructure, for example, to make

settlements between participants.

Although originally created as the basis for cryptocurrencies, blockchain technology has the potential to revolutionize many sectors of the economy. By ensuring data transparency and immutability, the blockchain can help trace the origin of products, which is particularly important in the food, clothing, and pharmaceutical industries. For example, in the healthcare space, the blockchain can store and share patients' medical data while ensuring their privacy and security. In the energy sector, this technology can support the development of so-called microgrids, enable more effective energy exchange between users, and support the entire process related to a circular economy [17]. The unique properties of blockchain technology mean that it can play a key role in shaping the future of many sectors of the economy

4. Smart Contracts

A key element of blockchain technology is smart contracts, which sometimes digitally mirror real-world contracts. Smart contracts contain codes for agreements between parties, monitor terms, and perform embedded functions. Smart contracts replace traditional legal third parties with network consensus. They can increase efficiency and reduce transaction costs because they automatically execute when certain conditions are met and maintain digital records of rules and business logic. Smart contracts can also be used for supply-chain process management and reengineering [18]. These contracts are created jointly by participants in a network. They serve the purpose of facilitating peer-to-peer transactions or remittances, as described by Wang et al. [19]. After a transaction is completed, a corresponding block is generated and distributed across the network nodes. Online merchants involved in the process can verify the transaction details to ensure the integrity of the transaction data. Smart contracts function as programmable code that can be executed automatically and as active participants. They can respond immediately to the information received and carefully record and retain the value of the transaction.

Smart contracts adhere rigorously to predefined rules through the consistent monitoring of trigger conditions. They execute the corresponding code when conditions are met and record the generated data onto the blockchain. In energy transactions, smart contracts play a pivotal role in receiving and processing transaction information. They can temporarily hold energy assets from buyers and sellers during transactions and carry out operations based on pre-established transaction rules agreed upon by the involved parties. Serving as fundamental and integral components of regional energy trading models, smart contracts are poised to remain a prominent subject of interest in both blockchain and energy research [20].

In waste management, smart contracts could play many key roles, such as automatic verification and rewards. If a waste management system offers rewards for recycling, a smart contract could automatically verify that a particular person is separating waste correctly and provide them with appropriate rewards [21]. Smart contracts could also trace the origins of waste, helping to identify and eliminate sources of pollution. They could provide transparency in the recycling process, ensuring that waste goes to the appropriate treatment sites and is not disposed of in unauthorized locations [22]. To help accomplish this, wastes produced in various locations (e.g., factories, households, restaurants) can be "tagged" on the blockchain system with a unique identifier. This identifier is immutable and can be assigned to a specific waste source. As the waste passes through various stages—from production to transport to processing—these activities are recorded on the blockchain. Additionally, to optimize the entire process, a smart contract could be integrated with other systems, such as fleet management systems for waste collection vehicles, allowing route optimization and more effective resource management [23].

5. Implementation of Blockchain Technology in Waste Management

In combination with the Internet of Things (IoT), the blockchain can bring many benefits. The IoT consists of physical devices, ranging from simple sensors and cameras to advanced machines and devices, that communicate with each other via the Internet; this allows the collection, analysis, and exchange of data in real time [24]. The main advantage of IoT is the ability to automate and optimize processes, which leads to increased efficiency, reduced costs, and improved quality of life [25]. Examples of IoT applications include smart homes, health monitoring, advanced production systems, and vehicle fleet management. Thanks to IoT, devices can collect data in real time and make decisions automatically. The blockchain, in turn, ensures the security and immutability of this data, which is crucial for many applications such as supply chain monitoring [26], asset management [27], or product certification [28].

The blockchain can be used as a communication bus to enable the creation of digital services and products and provide the necessary tools to create solutions. There are many blockchain solutions on the market that can be used in various scenarios. For example, IoTeX combines fast, secure blockchain technology with the IoT [29]. VeChain blockchain

specializes in enterprise-class solutions. Thanks to its stability and integration possibilities, it is used to build solutions based on the supply chain and data integrity [30]. SkeyNetwork blockchain provides technology that connects IoT devices to the blockchain. SkeyNetwork's Non-Fungible Tokens (NFTs) are proof of ownership due to smart objects in a network having their unique token.

Applying blockchain technology to waste management can be observed as part of the development of smart cities. These cities embody a conceptual urban development model based on the utilization of human, collective, and technological capital to enhance development and prosperity in urban agglomerations [31]. Despite the widespread use of technology in smart cities, they can have problems with waste management [32]. These cities generate domestic, commercial, medical, agricultural, and industrial waste. This waste can be classified into various categories, including liquid and solid household waste, medical waste, hazardous waste, recyclables, green waste, and electronic waste (e-waste). It is often sent to landfills, waste recycling facilities, composters, and waste-to-energy generation plants [33]. Including traceability and tracking capabilities is of great value in validating the legitimacy of data on waste collection, processing, and transportation in smart cities. These features enable real-time monitoring of the location and condition of waste throughout its journey, i.e., from collection to sorting, transportation, treatment, and disposal or recycling. Unlike current centralized waste data management systems that are vulnerable to intentional or accidental tampering, these tracking capabilities improve the integrity of the process [17]. Traceability is invaluable in facilitating identifying, storing, and comprehensively managing data on activities and outcomes within waste management processes. Key data points typically recorded during waste disposal include details such as waste type, volume, pickup location, route information, updated transit times, and details about the people involved in each waste disposal phase. Thus, blockchain technology has great potential to replace the slow manual systems used in waste management in many smart cities [34].

One of the ways that the blockchain can improve waste management is by creating digital asset tokens (e.g., security tokens) associated with smart cities' waste for tracking and tracing purposes [35]. These tokens play a pivotal role in tracking recycled waste materials. They significantly assist government agencies in reducing waste management costs and streamlining business operations. Traceability ensures that waste generated in smart cities is managed by established waste management guidelines to protect the environment from pollution. It also enables users to monitor the lifecycle of smart city waste efficiently [36].

Blockchain technology can identify the specific type of healthcare waste processed at recycling facilities and then reused to manufacture medical devices and equipment [37]. The increased transparency in asset traceability enabled by the blockchain increases the value of the waste supply chain. It minimizes the costs associated with waste management processes such as collection, sorting, transportation, and processing [38].

Industries can use the blockchain to identify the origin and transportation route of food scraps and waste to recycling facilities for fertilizer production [39]. Using these data, they can build new fertilizer production facilities near waste sources to reduce transportation costs.

The blockchain's tracking capability allows users to record the location of trucks transporting smart city waste in real-time, providing additional information such as optimal routes and waste weight [40]. These data on the location of waste shipments ensure that trucks drive in accordance with designated garbage collection points. This is especially important when waste comes from different areas and communities. To increase human safety, the blockchain can use sensors attached to garbage bags to verify that hazardous waste remains separate from non-hazardous waste during transport [41].

The blockchain's transparency and immutability make it useful for tracking the amount of waste shipped, received, and recycled at recycling facilities, detailing the credentials and actions of waste handlers, and recording where waste is stored during the separation, sorting, recycling, or disposal process. This identifier can be assigned to a specific waste source. As waste passes through various stages—from production to transportation to processing—all these activities are recorded in the blockchain [42]. Such an identifier for waste in the blockchain system could take different forms depending on the needs and specificity of a particular system. It could take the form of a QR code or a special Radio Frequency Identification/Near Field Communication (RFID/NFC) chip. Using a two-dimensional code, which can be easily scanned with a smartphone or a special reader, it is possible to store large amounts of information and easily print it on various materials. A QR code can be placed on product packaging that, when scanned, directs the user to a blockchain record with information about the origin of the waste [43]. Regarding RFID/NFC, items can be tracked remotely using radio waves [44]. The tracking process is automatic, the solution is weatherproof, and the data can be stored directly on the chip and connected to the blockchain as an NFT token. The choice of a particular identifier depends on many factors, such as the

type of waste, available infrastructure, cost, and security requirements. Different identification technologies can also be combined, depending on the needs of a particular waste management system.

A product-tracking ecosystem requires a combination of advanced technologies with well-designed processes and extensive collaboration between all supply chain stakeholders [45]. Using the above solution to ensure transparency in the recycling process is a key element for sustainable waste management [41]. Modern societies are increasingly emphasizing the responsible use of resources, and transparency of recycling processes is one of the most important tools for gaining the trust of consumers and stakeholders.

An example of a solution implemented in some cities in Poland is the ability to monitor the filling levels and collection of trash containers. Waste24, a waste collection company, is working to achieve adequate recycling rates and make the whole waste collection process smoother. For this purpose, it uses a blockchain in software for municipal services and individual waste generators which improves the process of waste management by increasing the transparency of the whole process; this is reflected in tools such as the Waste Database. The combination of its proprietary software solution with the blockchain supports transparent waste management, as all information about each participant in the waste cycle is recorded in real-time. This allows one to accurately document what is happening to the waste that is produced at any given time.

Waste24 focuses on waste disposal automation, which is a particular problem especially for large waste producers and enterprises with many branches. In the case of the latter, waste collection is a factor that greatly affects costs. A blockchain in waste management improves control over the expenses incurred for each waste collection [36]. Waste24.net software is integrated with container fill sensors, informing users about any overflows. By using blockchain solutions as a communication bus, communication barriers eliminated due to time play an important role in the work of waste collection companies. Waste must be collected within a relatively short window, so garbage trucks do not obstruct other cars from moving on the streets. An indirect result of the work on a blockchain in waste management is the “Digital Key” application, whose task is to open gates and garbage shelters. This innovation significantly shortens garbage truck stops in front of properties and improves traffic throughout the city. All Waste 24 solutions are based on the use of the SkeyNetwork blockchain ecosystem. Thanks to the integration of intelligent IoT sensors, the Waste.net system, and the SkeyNetwork blockchain, it is possible to constantly check how much free space remains in the garbage bin of a given company, which not only makes garbage collection more efficient, but also to reduces costs.

The above example shows that the modern market requires companies not only to manage the supply chain effectively, but also to pay attention to sustainable development and ecological responsibility. In this context, technologies such as IoT and the blockchain are becoming increasingly attractive to enterprises seeking innovations in supply chain management.

With increasing environmental awareness and an emphasis on sustainable business practices, real-time, closed-loop monitoring will likely become the standard across many industries. As technology advances and the price of IoT sensors declines, the opportunities for closed-loop applications will expand, bringing benefits to both businesses and the environment.

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 [46]. 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 implementing waste management services. Since waste management involves organizations with competing interests, blockchain technology can offer unlimited benefits to waste handlers.

Many waste materials’ service life and reliability vary and depend on the composition and working environment of such equipment/products/materials. At the end of the life of such materials, they should be recycled or disposed of responsibly at approved waste recycling facilities. For example, many waste mobile phones contain expensive lithium and cobalt materials that could be reused to manufacture new products after mobile phones are discontinued [47].

Based on the food supply-chain system defined by Khan et al. [48], the process can be redefined for a waste management system:

(1)Provider: In the context of waste management, this stage involves providing information regarding the origin of waste, including details about the crops, the use of pesticides and fertilizers, and the machinery involved. All transactions related to this stage are recorded on the blockchain.

(2)Producer: In waste management, this phase focuses on gathering information about the waste-producing entity, which may be a farm or a similar establishment. It includes details about the farming practices, cultivation process, and weather conditions. This information is documented for transparency and accountability.

(3)Processing: In waste management, this stage pertains to the processing facility where waste is handled. It includes details about the facility itself, the equipment used, and the specific processing methods employed. Transactions with waste producers and suppliers are logged on the blockchain for traceability.

(4)Distribution: This phase involves managing the transportation and distribution of waste. It encompasses information about shipping, routes taken, storage conditions, and transit times at each stage of transportation. All transactions involving waste suppliers and traders are recorded on the blockchain to ensure transparency and accountability.

(5)Retailer: In the waste management context, this stage involves providing information about the waste item, including its quality, quantity, expiry date, storage conditions, and shelf life. These data are crucial for the proper handling and disposal of the waste.

(6)Consumer: This final stage allows the end consumer to access detailed information about the waste item using a QR code on their mobile device. This information includes the journey of the waste item from its source to the retailer, providing transparency and building consumer confidence in the waste management process.

Therefore, reliable channeling of waste materials can lead to an environmentally friendly and safe smart city. Producers of solid waste, such as scrap metal, car tires, and smartphones, are usually required to monitor these materials after they have reached the end of their useful life [49]. Technologies can help ensure that waste from all materials sold is collected at waste treatment centers. The lifespan of each solid material device and the overall supply in the market can ensure that the waste of all solid materials sold is collected at waste treatment centers. Producers can collect waste through registered retailers, designated collection sites, or authorized dismantlers/recyclers. Residential waste channelization refers to the collection and processing of waste at a designated waste treatment center. Centralized waste channelization solutions are costly and less trustworthy [50]. In addition, such solutions cannot provide a reliable traceability of waste channelization. Some challenges for centralized systems are complete control over waste collection data, sensor credibility, fault tolerance requirements, and low robustness due to non-replicable data.

References

1. Baralla, G.; Pinna, A.; Tonelli, R.; Marchesi, M. Waste Management: A Comprehensive State of the Art about the Rise of Blockchain Technology. Comput. Ind. 2023, 145, 103812.
2. Taylor, P.; Steenmans, K.; Steenmans, I. Blockchain Technology for Sustainable Waste Management. Front. Political Sci. 2020, 2, 590923.
3. Akram, S.V.; Alshamrani, S.S.; Singh, R.; Rashid, M.; Gehlot, A.; Alghamdi, A.S.; Prashar, D. Blockchain Enabled Automatic Reward System in Solid Waste Management. Secur. Commun. Netw. 2021, 2021, 6952121.
4. Esmaeilian, B.; Sarkis, J.; Lewis, K.; Behdad, S. Blockchain for the Future of Sustainable Supply Chain Management in Industry 4.0. Resour. Conserv. Recycl. 2020, 163, 105064.
5. Centobelli, P.; Cerchione, R.; Del Vecchio, P.; Oropallo, E.; Secundo, G. Blockchain Technology for Bridging Trust, Traceability and Transparency in Circular Supply Chain. Inf. Manag. 2022, 59, 103508.
6. Das Turjo, M.; Khan, M.M.; Kaur, M.; Zaguia, A. Smart Supply Chain Management Using the Blockchain and Smart Contract. Sci. Program. 2021, 2021, 6092792.
7. Li, W.; Wu, J.; Cao, J.; Chen, N.; Zhang, Q.; Buyya, R. Blockchain-Based Trust Management in Cloud Computing Systems: A Taxonomy, Review and Future Directions. J. Cloud Comput. 2021, 10, 35.
8. Zhao, W. On Blockchain: Design Principle, Building Blocks, Core Innovations, and Misconceptions. IEEE Syst. Man. Cybern. Mag. 2022, 8, 6–14.
9. Wang, Q.; Su, M. Integrating Blockchain Technology into the Energy Sector—From Theory of Blockchain to Research and Application of Energy Blockchain. Comput. Sci. Rev. 2020, 37, 100275.
10. Andoni, M.; Robu, V.; Flynn, D.; Abram, S.; Geach, D.; Jenkins, D.; McCallum, P.; Peacock, A. Blockchain Technology in the Energy Sector: A Systematic Review of Challenges and Opportunities. Renew. Sustain. Energy Rev. 2019, 100, 143–174.

11. Wu, J.; Tran, N.K. Application of Blockchain Technology in Sustainable Energy Systems: An Overview. Sustainability 2018, 10, 3067.
12. Al-Farsi, S.; Rathore, M.M.; Bakiras, S. Security of Blockchain-Based Supply Chain Management Systems: Challenges and Opportunities. Appl. Sci. 2021, 11, 5585.
13. Wang, H.; Cen, Y.; Li, X. Blockchain Router: A Cross-Chain Communication Protocol. In Proceedings of the 6th International Conference on Informatics, Environment, Energy and Applications, Jeju, Republic of Korea, 29–31 March 2017; Part F128273. pp. 94–97.
14. Rejeb, A.; Zailani, S.; Rejeb, K.; Treiblmaier, H.; Keogh, J.G. Modeling Enablers for Blockchain Adoption in the Circular Economy. Sustain. Futures 2022, 4, 100095.
15. Bhubalan, K.; Tamothran, A.M.; Kee, S.H.; Foong, S.Y.; Lam, S.S.; Ganeson, K.; Vigneswari, S.; Amirul, A.A.; Ramakrishna, S. Leveraging Blockchain Concepts as Watermarkers of Plastics for Sustainable Waste Management in Progressing Circular Economy. Environ. Res. 2022, 213, 113631.
16. Paul, P.; Aithal, P.S.; Saavedra, R.; Ghosh, S. Blockchain Technology and Its Types—A Short Review. Int. J. Appl. Sci. Eng. 2021, 9, 189–200.
17. Bao, J.; He, D.; Luo, M.; Choo, K.-K.R. A Survey of Blockchain Applications in the Energy Sector. IEEE Syst. J. 2020, 15, 3370–3381.
18. Kouhizadeh, M.; Sarkis, J.; Zhu, Q. At the Nexus of Blockchain Technology, the Circular Economy, and Product Deletion. Appl. Sci. 2019, 9, 1712.
19. Wang, S.; Ouyang, L.; Yuan, Y.; Ni, X.; Han, X.; Wang, F.Y. Blockchain-Enabled Smart Contracts: Architecture, Applications, and Future Trends. IEEE Trans. Syst. Man. Cybern. Syst. 2019, 49, 2266–2277.
20. Wang, Q.; Li, R.; Zhan, L. Blockchain Technology in the Energy Sector: From Basic Research to Real World Applications. Comput. Sci. Rev. 2021, 39, 100362.
21. Sen Gupta, Y.; Mukherjee, S.; Dutta, R.; Bhattacharya, S. A Blockchain-Based Approach Using Smart Contracts to Develop a Smart Waste Management System. Int. J. Environ. Sci. Technol. 2022, 19, 7833–7856.
22. Li, J.; Kassem, M. Applications of distributed ledger technology (DLT) and Blockchain-enabled smart contracts in construction. Autom. Constr. 2021, 132, 103955.
23. França, A.S.L.; Amato Neto, J.; Gonçalves, R.F.; Almeida, C.M.V.B. Proposing the Use of Blockchain to Improve the Solid Waste Management in Small Municipalities. J. Clean. Prod. 2020, 244, 118529.
24. Rathore, M.M.; Paul, A.; Hong, W.H.; Seo, H.C.; Awan, I.; Saeed, S. Exploiting IoT and Big Data Analytics: Defining Smart Digital City Using Real-Time Urban Data. Sustain. Cities Soc. 2018, 40, 600–610.
25. Almalki, F.A.; Alsamhi, S.H.; Sahal, R.; Hassan, J.; Hawbani, A.; Rajput, N.S.; Saif, A.; Morgan, J.; Breslin, J. Green IoT for Eco-Friendly and Sustainable Smart Cities: Future Directions and Opportunities. Mob. Netw. Appl. 2021, 28, 178–202.
26. Cole, R.; Stevenson, M.; Aitken, J. Blockchain Technology: Implications for Operations and Supply Chain Management. Supply Chain Manag. 2019, 24, 469–483.
27. Truong, V.T.; Le, L.; Niyato, D. Blockchain Meets Metaverse and Digital Asset Management: A Comprehensive Survey. IEEE Access 2023, 11, 26258–26288.
28. Chang, P.Y.; Hwang, M.S.; Yang, C.C. A Blockchain-Based Traceable Certification System. Adv. Intell. Syst. Comput. 2018, 733, 363–369.
29. Pieroni, A.; Scarpato, N.; Felli, L. Blockchain and IoT Convergence—A Systematic Survey on Technologies, Protocols and Security. Appl. Sci. 2020, 10, 6749.
30. Song, J.; Zhang, P.; Alkubati, M.; Bao, Y.; Yu, G. Research Advances on Blockchain-as-a-Service: Architectures, Applications and Challenges. Digit. Commun. Netw. 2022, 8, 466–475.
31. Angelidou, M. Smart City Policies: A Spatial Approach. Cities 2014, 41, S3–S11.
32. Esmaeilian, B.; Wang, B.; Lewis, K.; Duarte, F.; Ratti, C.; Behdad, S. The Future of Waste Management in Smart and Sustainable Cities: A Review and Concept Paper. Waste Manag. 2018, 81, 177–195.
33. Sarangi, P.K.; Srivastava, R.K.; Singh, A.K.; Sahoo, U.K.; Prus, P.; Sass, R. Municipal-Based Biowaste Conversion for Developing and Promoting Renewable Energy in Smart Cities. Sustainability 2023, 15, 12737.
34. Alnahari, M.S.; Ariaratnam, S.T. The Application of Blockchain Technology to Smart City Infrastructure. Smart Cities 2022, 5, 979–993.

35. Esposito, C.; Ficco, M.; Gupta, B.B. Blockchain-Based Authentication and Authorization for Smart City Applications. Inf. Process Manag. 2021, 58, 102468.
36. Gopalakrishnan, P.K.; Hall, J.; Behdad, S. Cost Analysis and Optimization of Blockchain-Based Solid Waste Management Traceability System. Waste Manag. 2021, 120, 594–607.
37. Le, H.T.; Le Quoc, K.; Nguyen, T.A.; Dang, K.T.; Vo, H.K.; Luong, H.H.; Le Van, H.; Gia, K.H.; Van Cao Phu, L.; Nguyen Truong Quoc, D.; et al. Medical-Waste Chain: A Medical Waste Collection, Classification and Treatment Management by Blockchain Technology. Computers 2022, 11, 113.
38. Park, A.; Li, H. The Effect of Blockchain Technology on Supply Chain Sustainability Performances. Sustainability 2021, 13, 1726.
39. Hassoun, A.; Carpena Rodríguez, M.; Önal, B.; Pakseresht, A.; Kaliji, S.A.; Xhakollari, V. How Blockchain Facilitates the Transition toward Circular Economy in the Food Chain? Sustainability 2022, 14, 11754.
40. Gopalakrishnan, P.K.; Hall, J.; Behdad, S. A Blockchain-Based Traceability System for Waste Management in Smart Cities. In Proceedings of the ASME Design Engineering Technical Conference, Virtual, Online, 17–19 August 2020; Volume 6.
41. Pelonero, L.; Fornaia, A.; Tramontana, E. A Blockchain Handling Data in a Waste Recycling Scenario and Fostering Participation. In Proceedings of the 2nd International Conference on Blockchain Computing and Applications, BCCA 2020, Antalya, Turkey, 2–5 November 2020; pp. 129–134.
42. Song, G.; Lu, Y.; Feng, H.; Lin, H.; Zheng, Y. An Implementation Framework of Blockchain-Based Hazardous Waste Transfer Management System. Environ. Sci. Pollut. Res. 2022, 29, 36147–36160.
43. Hrouga, M.; Sbihi, A.; Chavallard, M. The Potentials of Combining Blockchain Technology and Internet of Things for Digital Reverse Supply Chain: A Case Study. J. Clean. Prod. 2022, 337, 130609.
44. Glouche, Y.; Sinha, A.; Couderc, P. A Smart Waste Management with Self-Describing Complex Objects. Int. J. Adv. Intell. Syst. 2015, 8, 1–16.
45. Mohsen, B.M. Developments of Digital Technologies Related to Supply Chain Management. Procedia Comput. Sci. 2023, 220, 788–795.
46. Sahoo, S.; Mukherjee, A.; Halder, R. A Unified Blockchain-Based Platform for Global e-Waste Management. Int. J. Web Inf. Syst. 2021, 17, 449–479.
47. Gu, F.; Summers, P.A.; Hall, P. Recovering Materials from Waste Mobile Phones: Recent Technological Developments. J. Clean. Prod. 2019, 237, 117657.
48. Khan, H.H.; Malik, M.N.; Konečná, Z.; Chofreh, A.G.; Goni, F.A.; Klemeš, J.J. Blockchain Technology for Agricultural Supply Chains during the COVID-19 Pandemic: Benefits and Cleaner Solutions. J. Clean. Prod. 2022, 347, 131268.
49. Jacobs, C.; Soulliere, K.; Sawyer-Beaulieu, S.; Sabzwari, A.; Tam, E.; Jacobs, C.; Soulliere, K.; Sawyer-Beaulieu, S.; Sabzwari, A.; Tam, E. Challenges to the Circular Economy: Recovering Wastes from Simple versus Complex Products. Sustainability 2022, 14, 2576.
50. Singh, S.; Chhabra, R.; Arora, J. A Systematic Review of Waste Management Solutions Using Machine Learning, Internet of Things and Blockchain Technologies: State-of-Art, Methodologies, and Challenges. Arch. Comput. Methods Eng. 2023, 1–22.