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Waste management: a comprehensive state of the art about the rise of blockchain technology★

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ABSTRACT

In the last century, the increased urbanization and population growth produced a dramatic increase in waste production, causing serious problems for the environment and human health like never before. Currently, correct waste management represents a serious challenge that can be faced through the use of new technologies. Blockchain technology is a disruptive and emerging ICT solution. Because of its ability to ensure transparency, data immutability, and consensus among stakeholders involved, this shared distributed data structure has grown in popularity in a variety of industrial sectors, including finance, health, and supply chain. The purpose of this study is to analyze the current state of the art in the use of blockchain technology in the waste management sector with a focus on the literature state of the art and on ongoing or soon to be launched industrial project cases. This paper investigates blockchain-based waste management systems; their benefits for the circular economy and in terms of social, environmental, economic, and health dimensions; as well as limitations and drawbacks that could prevent the use of blockchain in the waste sector.

1. Introduction

The increased urbanization and population growth have made the problem of waste management a concrete and worldwide issue, especially in large inhabited centers. The Basel Convention defined Waste as "substances or objects which are disposed of or are intended to be disposed of or are required to be disposed of by the provisions of national law" (UNEP, 2011). The environmental contamination due to waste mismanagement, caused by open dumping and open burning, is a severe issue, especially in low-income countries (Ferronato and Torretta, 2019). Depending on the country, different management practices can be adopted and a good waste classification is essential for management efficiency (Wen et al., 2014). Waste management with its disposal chain is a very complex system that involves many stakeholders. Typical waste transfers involve: i) citizens and industries; ii) municipalities; iii) outsourced entities that collect and manage the bins; iv) different centers that deal with the collection, disposal, and recycling; v) producers of recycled waste materials that put new products on the market. Starting from the last transfer, it is possible to start over from the citizen and industries that use the product, closing the loop. The circular economy (CE) model establishes the rules for closing the loop, providing a production and consumption model that aims to reduce waste to landfill, by reprocessing goods and materials at the end of their life cycle. To create a CE, the complete materials' traceability at each stage, from their source to their use to their disposal, is crucial (Shojaei et al., 2021), as well as adopting new methods to design and operate manufacturing processes to reduce waste (Aivaliotis et al., 2021).

Unfortunately, due to the large number of actors involved in the waste management process, information tracking is often compromised. Indeed, most of the time, data sharing is missing, and their synchronization is made difficult due to different collection systems and adopted policies by the various actors along the chain. Furthermore, the synchronization of information, if any, can often take place with considerable delay (Preethi and Radhakrishan, 2019; Laouar et al., 2019). Due to the lack of waste traceability technologies, in most cases, the information is collected manually by the operators, for example, on paper notes, and then digitized in centralized systems. Data can be subject to errors, sometimes voluntarily, given the lack of real-time synchronization (Ahmad et al., 2021a). Because of the complexities of this context, the use of information and communications technology (ICT) appears to be the most promising and effective way to properly monitor and control waste management and recycling.

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The recent blockchain technology stands out among the options due to its distinct features that allow it to be used to create shared, transparent, reliable, tamper-proof electronic archives as well as automatic control and monitoring systems. This paper focuses on this technology with the goal of determining how and how much this technology is used by researchers and business realities to implement waste management systems and to solve waste management problems.

A blockchain is a growing collection of structured and chained digital records called blocks, conceived the first time to realize the Bitcoin payment system (Nakamoto, 2019). Each block is a collection of transactions, linked to the previous one using cryptographic algorithms to form a chain that cannot be modified retroactively unless the entire structure is changed. A blockchain is stored and governed within the blockchain network's nodes, which share the same information (hence the name Distributed Ledger Technology) and establish consensus rules aimed at preventing abuse and attacks. Blockchains 2.0 (the most prominent example being Ethereum) enable the use of transactions to record structured data and execute computer programs known as smart contracts within the blockchain (Buterin et al., 2014; Savelyev, 2017). A blockchain-based information system allows the system's users to be distinguished via cryptography, allows the implementation via Smart Contracts of permission mechanisms for individual actors, allows the implementation of control logic on the data, and allows all actors to access from any node on the network the same shared data that is always updated, correct, traceable, and tamper-proof. It is unsurprising that blockchain technology is spreading in a variety of industrial and commercial sectors, particularly supply chain management and monitoring (Baralla et al., 2019; Toyoda et al., 2017).

The research presented in this paper assumes that blockchain technology can also provide numerous benefits to waste management, such as waste traceability at all stages of exchange; fraud prevention mechanisms; a more effective strategy against the illegal landfill market; and a timely incentive for virtuous behavior. Furthermore, it may enable the effective implementation of the CE by precisely monitoring not only the reverse chain (waste management up to raw material regeneration) but also the phases of the forward chain from production to consumption, with the goal of reducing virgin material consumption and monitoring product reuse. The use of this technology in waste management is a recent application and the understanding of the actual impact of this technology in waste management is worthy of investigation and the focus of this study of the state-of-the-art.

This work describes blockchain technology applications in each phase of waste management; identifies and analyzes research contributions, discussing proposed solutions for blockchain-based waste management through a literature review; identifies and describes real software projects that implement blockchain-based information system for waste management; and discusses the findings in terms of impact dimensions and drawbacks that may prevent the use of blockchain technology.

The paper is structured as follows: Section 2 presents the applications and advantages of blockchain technology in each macro-phase of the waste management process, from a perspective of circular economy.

Section 3 reports the method and the results of the literature review on the use of blockchain technology in waste management. Section 4 examines twenty-two projects aiming at the development of an information system for waste management that have declared to use blockchain technology. Section 5 discusses positive impacts on environmental, economic, social, and health dimensions by applying the CE principles supported by the use of DLTs. Lastly, section 6 draws conclusions.

2. Blockchain technology in Waste Management and Circular Economy

Waste management is the set of activities that enable the systematic organization of waste collection and treatment in the so-called *reverse chain*. However, the waste management system can use information from the so-called *forward chain*, thus including the phases of production and consumption of products (Liu et al., 2020). Any waste management system is unique because it is influenced by a plethora of factors such as numerous and diverse stakeholders, waste type, disposal policy, country involved, law and regulations. Nevertheless, there are some common issues that are currently a challenge to address. Preethi and Radhakrishan (2019) in their work identified some major challenges to be addressed in the waste management cycle including *Lack of Technology in tracking waste flow*, *Lack of Accountability*, *Lack of awareness and enforcement*. Likewise, Laouar et al. (2019) identified seven big problems to manage the waste, among them *Cheating and manipulation*, *Loss and wrong of information*, *Lack of control*. Generally, each of the phases concerning waste management is currently managed by different companies. Each of these has its own dedicated database and software. For this reason, the data is neither shared nor synchronized, so it is difficult to monitor how much waste was generated by consumers and how much actually arrived at the designated centers.

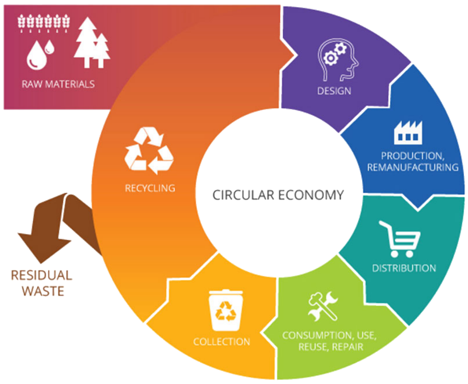

Figure 1: Representation of the Circular Economy (EU-Commission, 2020)

The benefits of a blockchain-based waste management system will be discussed further below, both in terms of the circular economy and the individual stages of this process.

2.1. Circular economy and blockchain technology

The use of blockchain can sustain the entire waste management system and enable the CE, side by side with other technologies such as the Internet of Things (IoT), Cloud Computing, Geographic Information Systems, and the application of Operations Research algorithms. Data recorded on the blockchain is immutable; it is shared among all the participants; and to be recorded, it must be validated by the network. In a blockchain-based waste management system, each system user has a blockchain account (consisting of their private key and public address) and has been granted permission to access or send transactions in order to use specific system features. The system logic of a blockchain-based waste management system can be implemented within the blockchain via smart contracts. A smart contract is a programmable blockchain account that interacts automatically with other blockchain accounts. Its code is always running inside the blockchain, waiting for a specific event or series of events to occur (Savelyev, 2017). For example, based on the data stored in the blockchain, a smart contract can be deployed to monitor a user's behavior over time and automatically activate reward or penalty policies. Appropriate smart contracts can also be deployed to correctly control access restrictions and allows to configure nodes and users read/write rights, assuring data access as well as user privacy in private or permissioned blockchains (Xiao et al., 2020; Ferrag and Shu, 2021).

The market of global waste and recycling was evaluated at about 55.1 billion U.S. dollars in 2020 and, in 2028, it is projected to be worth 90 billion (Tiseo, 2022). But the World Bank estimated that only 19% of waste is currently treated for recycling and composting (Kaza et al., 2018). The United Nations' Sustainable Development Goals, or SDGs, seek to "substantially reduce waste generation through prevention, reduction, recycling, and reuse" (target 12.5) by 2030 (United-Nations, 2020). Many industrialized countries are enacting regulations and laws to reduce waste mismanagement and prevent waste by implementing CE principles. In March 2020, the European Commission adopted the new Circular Economy Action Plan (CEAP) as part of the new agenda to support sustainable growth in order to achieve the climate neutrality target by 2050. The action plan applies to the entire life cycle of products by targeting design, promoting CE processes and encouraging sustainable consumption to ensure the prevention of waste and the use of resources in the economy for as long as possible, attempting to minimize residual waste (EU-Commission, 2020). Figure 1 depicts the phases that characterize the CEAP model.

Blockchain technology can allow supply chains and waste management systems to be aligned with the CE paradigm, as it allows the traceability of key data (such as the monitoring of the use of raw materials in production) and the implementation of automatic control mechanisms. These applications make production more efficient and cleaner and improve communication between stakeholders (Upadhyay et al., 2021; Park and Li, 2021), also by addressing information anomalies and providing uniform data to the entire network (Böckel et al., 2021). Shojaei et al. (2021) summarize the different advantages deriving from the use of the blockchain infrastructure to support the CE as: trust and untying from a third party; cost sharing among participants; availability due to its decentralized nature; transparency and security.

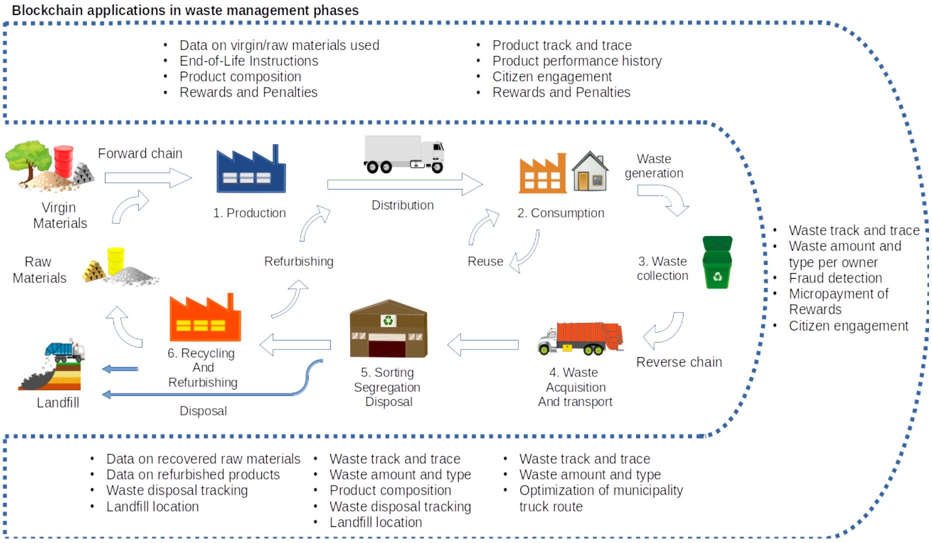

Figure 2: Representation of the macro phases of a waste management system (from 1 to 6) and the related applications of the blockchain technology, in a Circular Economy model

2.2. Blockchain-based waste management systems

Waste management is a complex activity that includes a succession of phases and sees the participation of of numerous actors (or entities). It is possible to identify six macro-phases of waste management: 1. Production; 2. Consumption; 3. Waste collection; 4. Waste acquisition and transport; 5. Sorting, segregation, and disposition; 6. Recycling and Refurbishing. Among a blockchain-based waste management system actors are the following: the Producer (for example, a manufacturing company), the Consumer (for example, a citizen, an industry, or a hospital), the Waste Collector, the Eco center, the Recycling Center, as well as the Government Environmental Inspectors and the Local Authority. The introduction of blockchain technology involves a change in the roles and responsibilities of each actor in the waste management system. The system includes all of the actors' tools and devices, such as IoT devices (such as QR code readers, scales, and RFID), GIS-based systems, and supplementary storage and computing systems.

Figure 2 represents the six phases and their interconnections, and represents blockchain technology and its applications as a shared information channel for the system. Figure 3 represents the main actors, and represent the components of a blockchain-based waste management system. An explanation of the contribution of using the blockchain will now be discussed for each phase.

1. Production. The production phase can be considered a key point for waste prevention. A producer accesses the blockchain system and records data on the composition of its products and the use of virgin materials through a specific smart contract. In the case of large documents (such as end-of-life instructions), the producer stores them in an external system and uses the blockchain to link and certify them. The Producer lists the blockchain addresses of system members who can access production data (e.g., the Government Inspector) or end-of-life instructions (e.g., industrial consumers or reverse chain operators) via a specific smart contract that implements the access rules.

The producer also accesses the life cycle data of its products, generated in the later stages of the process, and use them in decision-making processes. A government inspector uses blockchain data in view of the EPR law's adoption, introducing automatic rewards or penalties based on a specific smart contract code.

2. Consumption. A consumer reads the composition and history of a product (new or reused) before purchasing it and then makes a blockchain transaction to record the change of product ownership. Depending on the type of product, useful information for monitoring its status can be automatically recorded (anonymously or on a voluntary basis). For example, for an industrial machine, information such as performance, type of use, or degree of wear can be recorded. Local authorities and government inspectors access consumption data to predict the amount of waste that will be generated, and to implement citizen engagement policies such as token-based incentives for product reuse.

3. Waste collection. The consumer places the consumed product into the appropriate receptacle or delivers it for disposal. Currently, most advanced countries uses RFID devices in *smart bins* to automatically acquire waste collection data. But this information is typically sent to a centralized server system, and information is not shared across the

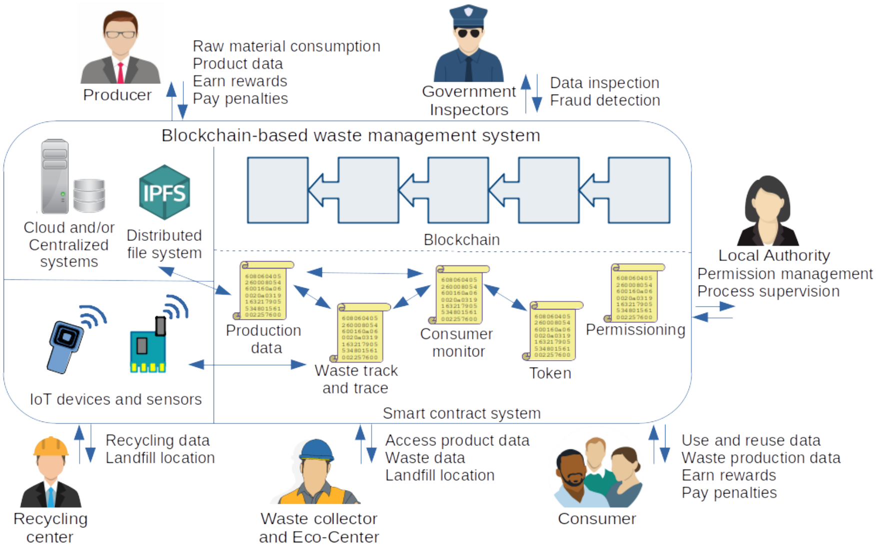

Figure 3: Representation of the main components and actors of a blockchain-based waste management system

waste management chain. In a blockchain-based system, the IoT sensors and RFID devices installed inside the smart bins automatically generate and transmit details on the type and quantity of waste produced by each consumer, via a transaction to a specific smart contract. Government inspectors read blockchain data to track waste and implement anti-fraud strategies. The local authority implements a smart contract-based reward system to encourage citizen engagement (such as micropayments, token issuance as money to spend in the local economy, or tax reduction). The actors of the subsequent phases access the data of the collection phase for an optimal organization of disposal activities.

4. Waste acquisition and transport. This phase is the beginning of the so-called *reverse chain*. In this phase, the blockchain-based system allows the waste collectors to automatically acquire and certificate the measurements of the weights and types of waste transported, i.e., detected by IoT scales installed on the transport vehicles, as well as the route taken by the trucks and detected by GPS devices. Smart contracts automatically compare and verify expected and actual waste data without the need for human intervention, which can lead to errors, sometimes voluntarily. To optimize collection routes and times, the waste collector employs blockchain data in off-chain route optimization software.

5. Sorting, Segregation, Disposal. In this phase, the waste material is in the Eco center and managed to be sorted, segregated and prepared for designated treatment (recycling, refurbishing, waste-to-energy, or disposal by landfill). The eco center reads blockchain data about products composition and waste amount from previous phases to operate efficiently and securely, and write into a specific smart contract the amount and type of waste treated, the exact locations of landfills and the quantity and type of discarded material. Governments access eco centers data to fight waste mismanagement, and to prevent issues such as uncontrolled open dump sites and environmental contamination.

6. Recycling and refurbishing. During this phase, the recycling center make transactions to a specific smart contract to share among the system stakeholders the data regarding the amount and quality of its production of recycled raw material. It also updates product history in the case of product refurbishing, and records the amount and type of residual waste disposal (to be managed as described in the previous phase).

3. Literature Review

The literature review is organized into phases. The first phase is dedicated to choosing the archives and defining the search queries. The second phase is dedicated to the definition and application of exclusion criteria. The third phase is the classification and analysis of scientific contributions. This phase focuses on research papers that explicitly describe the blockchain system used. See the discussion section for further information on the problems faced and their resolution.

Table 1
Number of literature resources included and excluded after phase two

Category	Number
Relevant to the research topic	48
Description of a relevant project	3
Borderline	15
Excluded because not relevant to the research topic	47
Excluded because not Online Available	3
Total	116

3.1. Method

To conduct a review of the scientific literature on the use of blockchain technology in the waste management industry, sources from valuable scientific archives were first selected, including Scopus, Web of Science, and Google Scholar. Research not rigorously reviewed from ResearchGate or Arxiv was also analyzed. Data sources was queried in May 2021, by using structured search strings such as: {Waste and recycling and blockchain}, {plastic waste blockchain}, {rural wastes blockchain technology}, {smart waste management system and "blockchain technology"}.

A total of 116 papers were found, issued between 2017 and 2021. More than half of the papers are published between 2020 and 2021, which suggests a sign of growing interest in blockchain technology in the waste management sector. As a second phase, the results of the literature were evaluated based on the abstract to exclude out of topic works. In this phase, 47 papers were excluded. Three papers that are not available online were also excluded. Papers that are not primarily focused on BC but present the technology as promising for waste management while providing relevant information were considered "borderline." Fifteen borderline papers were discovered. In addition, three references about actual relevant projects were discovered: Merbel Design (Regout et al., 2019), PlasticBank (Katz, 2019), PlasticTwist (Koscina et al., 2019). Table 1 summarizes the results of the second step of our analysis.

Thus, the set of research works included in our analysis consisted of 66 papers, including 36 journal articles, 17 conference papers, and 13 other documents. The next steps of this literature analysis were structured to cover as much information as possible about the concrete use of blockchain technology in the considered domain. Therefore, it investigates technical details such as the type of blockchain used, the waste typology and phases of waste management considered, the protocol used, programming languages used, the type and access modality of information, the emission of tokens, and the integration with other technologies. The third step of the literature review's findings are discussed in the paragraphs that follow. Three sections comprise the literature review's findings, including: blockchain usage, token emission, and integration with IoT sensors.

Section 5 provides a further discussion about the results of the literature review.

3.2. Blockchain usage

The majority of the analyzed papers present blockchain technology as a new and promising ICT able to disrupt the waste management sector, but they do not provide technical information about its implementation or platform used. Indeed, among sixty-six analyzed papers, only sixteen provide technical details about the proposed blockchain platform. This suggests that technical research into the applications of blockchain technology in waste management is in its early stages. More papers talk about a blockchain-based system to monitor waste, discussing advantages, disadvantages, and costs of the use of a public, private, or hybrid blockchain but without technical details (Latif et al., 2019; Gopalakrishnan et al., 2021). For each of the sixteen papers that provide technical details, the usage of blockchain in the waste management process was investigated. In particular, the phases involved in the process were identified and mapped with the phases reported in Section 2 and Figure 2. Furthermore, particular attention has been paid to the data that the authors of the papers intend to store on the blockchain, as well as on the waste typology, and the country concerned where specified. Table 2 shows the results of this analysis. On the basis of the phases involved, it is possible to notice that six papers use the blockchain on the entire chain, from phase 1 to phase 6, embracing the circular economy model. Although oriented to the correct recycling of materials, three papers involve the use of the blockchain starting from the waste generation but not involving the production phase. Five papers applied the blockchain to phases 2 and 3, Consumption and Collection, focusing on concepts such as citizen engagement, sensitizing the local community to correct waste disposal in return for a reward. Finally, one paper deals with the waste chain to ensure proper disposal in the landfill by tracing and tracking the product from the production phase to its end phase (from phase 1 to phase

5). The waste typology treated in the latter case includes medical supplies and equipment for COVID-19 Ahmad et al. (2021a).

Among papers that specify their proposed blockchain platform, Ethereum was found to be the most commonly used. However, the papers which suggest the use of alternative blockchains such as Hyperledger (Koscina et al., 2019; Liu et al., 2020, 2021) or Polkadot (Scott et al., 2021). Authors describe a comparison with the Ethereum blockchain, underlining and motivating their choice to address the problems of data privacy and transaction costs, but also latency and throughput. Permissioned blockchain may be able to satisfy the needs of a waste management system for privacy and cost savings (Schmelz et al., 2019; Koscina et al., 2019), (Liu et al., 2021).

The papers examined consider the use of a system of interconnected smart contracts, mostly written in Solidity (Sahoo and Halder, 2020; Dua et al., 2020), which allow interaction between stakeholders to make the process more efficient (Gupta and Bedi, 2018; Utomo et al., 2020), and the creation of automatic reward and penalty systems (Lamichhane et al., 2017; Dasaklis et al., 2020). Several papers focus on defining the actors of the blockchain-based system, their roles, and the use of strategies to involve citizens (Scott et al., 2021; Dua et al., 2020; Pelonero et al., 2020; Koscina et al., 2019; Utomo et al., 2020). The proposed architectures include multiple subsystems to ensure efficient and cost-saving use of the blockchain and proper utilization of computational and storage resources (Laouar et al., 2019; França et al., 2020). They are designed according to the principle of on-chain or off-chain (Liu et al., 2020), which entails identifying which system components will be implemented within the blockchain and which will be implemented outside of it. The off-chain components include the external storage systems to record large amounts of data (Wang et al., 2019; Dasaklis et al., 2020) or distributed databases such as the Interplanetary File System (IPFS) (Sahoo and Halder, 2020). This allows one to save in the blockchain only essential information for the waste management system, or preserve existent waste tracking systems (Schmelz et al., 2019) while using the blockchain as a communication and validation infrastructure.

3.3. Token emission

Among the analyzed works, some papers, although they do not provide technical details about the platform to be used, suggest the use of blockchain for waste management as a tool able to cause correct waste disposal in the face of a digital reward (Akter, 2021; Kassou et al., 2021). Consumers play a decisive role in the proper functioning of the blockchain-based waste management system. People's involvement in the system would increase in the face of an incentive for correctly managing products at the end of their life cycle (Preethi and Radhakrishan, 2019). Local or central governments may use a reward mechanism to encourage people to manage and transfer their waste in a sustainable way, either by transferring ownership or disposing of it properly (Taylor et al., 2020), or to motivate stakeholders to adopt and join the blockchain-based system (Kamilaris et al., 2019). At the time of purchase, a deposit mechanism system can be used to incentivise people to do proper recycling. Indeed, the deposit will be refunded when the product reaches a recycling yard (Lawrenz et al., 2020). The amount of the deposit and the payment of the refunds are recorded in the blockchain via transactions. The use of tokens is also proposed in the poor or unbanked regions to allow people to receive a reward without the need for a bank account (Bartoletti et al., 2018) or to help people out of poverty. Digital coupons or cryptocurrencies are introduced to trade agricultural waste in rural areas such as in Changzhi City, China (Zhang, 2019). Waste disposal is converted into clean energy or agricultural by-products such as fertilizer or animal feed (Makkar et al., 2020). In the case of a commercial product, tokens can be used as a reward to incentivise consumers to returns goods to the supply chain (Kouhizadeh et al., 2019; Sahoo and Halder, 2020; Gopalakrishnan et al., 2020; Scott et al., 2021) supporting therefore the CE (Sandhiya and Ramakrishna, 2020). Finally, the use of tokens is discussed in (Katz, 2019) as part of the PlasticBank project with a dual purpose to fight plastic pollution and support economic development in a poor region, and in (Koscina et al., 2019) under the PlasticTwist project as described in the previous subsection.

3.4. Blockchain and IoT

According to Esmaeilian et al. (2018) studies that address IoT applied to waste management systems can be classified into four categories: i) Development of data acquisition and sensor-based technologies; ii) Development of communication technologies and data transmission infrastructure; iii) Test the capabilities of IoT systems in field experiments; iv) Truck routing and scheduling for waste collection operations. As shown in Table 2 several works deal with IoT devices combined with blockchain technology. According to the aforementioned classification, the papers that address the use of IoT belong to the first and last categories. The use of "smart" IoT delivery points, connected both to the blockchain system and the mobile apps of the different users involved, allows tracking product flow and

Table 2
The list of sources analyzed in phase three and the result of the analysis.

Reference	Waste Tipology	Blockchain Platform	Phase involved	Other technologies	Blockchain data record	Geographical position
(Liu et al., 2020)	Waste in general	Hyperledger Fabric	1-2-3-4-5-6	IoT, RFID, GPS	Product design and composition. Product Life cycle history including ownership and re-manufacturing/refurbishing. Waste tracking at each phase updated from each stakeholder involved from waste generation to recycling and reuse.	Generic
(Gupta and Bedi, 2018)	Electronic waste	Ethereum	1-2-3-4-5-6	IoT, Smart Barcode	Product composition. Complete waste tracking at each phase updated from each stakeholder involved from waste generation to recycling and reuse. Rewards	India
(Sahoo and Halder, 2020)	Electronic waste	Ethereum	1-2-3-4-5-6	Future integration with IoT and AI	Product registration. Ownership history. Incentives on the base of waste conferred	Generic
(Dua et al., 2020)	Electronic Waste	Ethereum	1-2-3-4-5-6	5G	Product composition. Complete Waste tracking at each phase updated from each stakeholder involved from waste generation to recycling and reuse. Ownership history. Rewards or penalities	India
(Dasaklis et al., 2020)	Electronic Waste	Ethereum	1-2-3-4-5-6	-	Product composition (PR). Product Life cycle hystory including ownership and remanufacturing/refurbishing	Generic
(Wang et al., 2019)	Power batteries	Ethereum	1-2-3-4-5-6	RFID, BMS	Product composition. Complete Waste tracking at each phase updated from each stakeholder involved from waste generation to recycling and reuse. Ownership history	Generic
(Ahmad et al., 2021b)	Medical supplies and equipment	Ethereum	1-2-3-4-5	-	Stakeholder registration. Amount of product ordered and delivered. Ownership history. Tracing and track of waste until disposal	Generic
(Scott et al., 2021)	Solid waste	Polkadot	2-3-4-5-6	-	Stakeholder registration Complete Waste tracking at each phase updated from each stakeholder involved from waste generation to recycling and reuse. Ownership history. Rewards or penalties	Generic
(Laouar et al., 2019)	Waste in general	Ethereum	3-4-5-6	Future integration with IoT and AI	Amount and type of waste collected. Tracing and track of waste. Ownership history	Generic
(Schmelz et al., 2019)	Waste in general	Ethereum/ Private Blockchain	3-4-5-6	GPS	Amount, tracing and tracking of waste	Europe
(Liu et al., 2021)	Plastic	Hyperledger Fabric / Ethereum	1-2-3-6	-	Product composition and registration. Rewards on the basis of quality of plastic involved	Generic
(Lamichhane et al., 2017)	Waste in general	Ethereum	2-3	IoT, Smart bins	Micropayments reward on the base of waste produced	Generic
(Pelonero et al., 2020)	Waste in general	Ethereum	2-3	IoT, Smart bins, Cloud computing	Amount and type of conferred waste. Micropayments reward on the base of waste conferred.	Generic
(Utomo et al., 2020)	Waste in general	Ethereum	2-3	IoT, Smart bins	Micropayments reward on the base of waste conferred in public bins.	Japan
(França et al., 2020)	Waste in general	Ethereum	2-3	Cloud Computing	Reward on the base of waste conferred in waste collection centre (Green coin). Amount of waste conferred from consumer to Waste collection centre.	Sao Paulo, Brazil
(Koscina et al., 2019)	Plastic	Hyperledger Fabric	2-3	-	Reward on the base of waste conferred. Amount of waste conferred from consumer.	Generic

measuring each agent's contribution to waste management (Sekhri, 2018). IoT devices can provide data on product energy consumption during its entire life cycle. Consequently, engineers or product designers can revise the production process to save energy. At the same time, consumers can be informed of the product's environmental impact to adapt their behaviour (Zhang et al., 2020). Similarly, smart bins (Zhang, 2019; Akter, 2021), or smart bags (Pelonero et al., 2020) connected to a blockchain system identify the waste collector by means of a mobile app, which instantly receives a reward at the time of collection. Smart bins with IoT devices are also used in medical contexts to monitor water waste and sanitary waste in terms of quantity, tracking and disposal (Kassou et al., 2021). Furthermore, the use of IoT in waste bins is suggested to measure waste levels (Rotună et al., 2019; Sham et al., 2020b; Thada et al., 2019), to identify the waste type, to automatically sort and segregate it (Sahoo and Halder, 2020) and to debit fees to users linked to the garbage weight (Lamichhane et al., 2017; Utomo et al., 2020). Sandhiya and Ramakrishna (2020) developed a knowledge base for the IoT-enabled smart bins with the aim of reducing the conceptual ambiguities often found in the plastic industry. They also used the digital twin concept to retrieve data, stored within a blockchain, about the original weight of the product which is disposed of within the smart bin. Data coming from Industrial IoT devices (IIoT), and stored within a blockchain system, is proposed to record water consumption, industrial wastewater generation, and wastewater treatment (Hakak et al., 2020). Data from IoT devices could also be used to optimize the routing of collection trucks (Zhang, 2019; Latif et al., 2019; Ahmad et al., 2021a; Sandhiya and Ramakrishna, 2020), i.e. a Smart Bins is picked up only if its volume is over 80%. Communication between IoT devices and blockchain can be done by a direct connection or through a gateway. In the first option, IoT devices are configured and programmed to compose and sign blockchain transactions (via its private key) to transmit acquired data to the blockchain. The actual communication protocol is determined by the type of blockchain. Transaction data from IoT devices must conform to the smart contract functions charged with receiving IoT data (Kim et al., 2019). Alternatively, an off-chain component of the system can be configured as a gateway to collect and process raw data from devices and send it to the blockchain in the form of a transaction (Liu et al., 2020). In this second option, existing devices can be re-used in a new blockchain-based waste management system. A smart contract could be also programmed to determine whether or not an IoT device is an authorized member of the system; otherwise, transactions will be rejected.

Given the security and privacy problems, the use of IoT could lead to a reluctance to use it. Integration within a blockchain system provides an ideal solution to that issues (Lamichhane et al., 2017; Ferrag and Shu, 2021), obtained also by hiding sensitive data, i.e., by using one-use-only ids on-chain and linking them to a person off-chain (Pelonero et al., 2020).

4. Projects Overview

This section presents blockchain-based projects on waste management. The project investigation was carried out in two phases. The first is the search for information and the identification of projects; the second is the classification and analysis of individual projects.

4.1. Method

Phase one started with previous literature research. During this phase, information about real-world initiatives such as government funding projects, start-up, initial coin offering (ICO), and private trials in small communities was pinpointed. Then, using search engines, project software repositories such as GitHub, and ICO listing websites, relevant projects were found on the Internet. In total, 22 projects were found.

In phase two, for each project its purpose was evaluated, as well as the type of waste managed, its status, the blockchain technology used, and the waste management phases involved according to Figure 2, the issuance of tokens and the integration of other technologies. An evolution scale consisting of the following steps has been developed to assess the state of the projects Under study - Scaling up - Prototype - Pilot - In use.

4.2. Results

Table 3 summarizes the findings of the analysis. It can be seen that all the projects are quite recent between 2017 and 2020. Some of these began a few years earlier (Provenance, 2013; PlasticBank, 2013), but it is only recently that they introduced blockchain technology. According to collected data, it can be noticed that a significant part of initiatives is focused in Europe 56% followed by North America 14%, and only a small percentage concerns developing countries. A good portion of projects are global, but some local projects claim to export their experience worldwide. The majority of the projects have their websites offline. This suggests the closure of the initiative or its failure. Among that, according to online available data, Recereum (Recereum, 2017) closed to evolve with the W2V project (W2V, 2019). Instead, about the Vastum (Anthesis, 2019) project, the latest information dates back to 2019 when the company declared the conclusion of the first phase (focused on proof of concepts). As explained by the company (VeChain, 2020), given the early technology, the use of a decentralized database does not provide better solutions than a centralized database.

Of the active projects, only 9% are In Use whereas 22% are Pilot projects and 13% have developed a prototype. The remaining proposals are still in the very early stages. This suggests that the interest in blockchain technology in the waste management sector is growing, although it is just at the beginning.

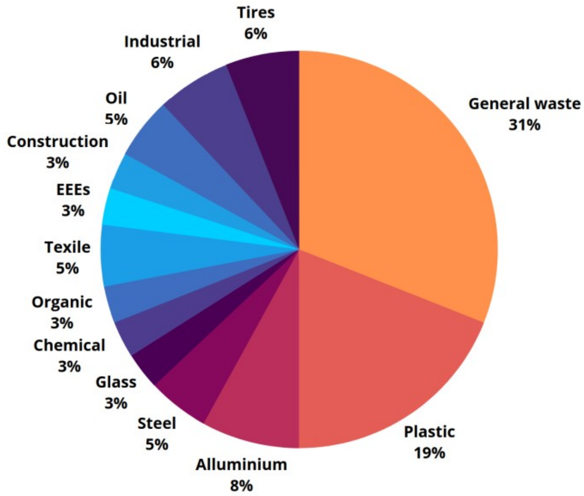

Figure 4: Typology of waste on examined projects

When analyzing blockchain platforms claimed by projects, Ethereum and Hyperledger Fabric are the most commonly used. However, among the seven projects which declare to use Ethereum, only three are operatives, the remaining seem to be inactive, as shown in Table 3. Four projects do not declare the type of blockchain. Two of these have their website offline, which means they are probably failed. HFZA (Emirates News Agency, 2019) is Under Study. Vastum (Anthesis, 2019) during the first phase, now closed, seems to prefer the use of a centralized database.

More than half of the projects have declared to introduce its own token or cryptocurrency, regardless of the type of blockchain, permissionless or permissioned. So, in summary, by considering active projects, the use of a blockchain permissioned system (9 projects) is preferred to public blockchain solutions (5 projects).

In terms of integration with other technologies, Table 3 shows that only a few projects have considered system integration with Artificial Intelligence or IoT device technology. In addition, some of those projects have been stopped.

As for waste typology, as shown in Figure 4, it can be noticed that 19% of the projects deal with plastic waste, but the majority of project, 31% do not focus on a specific waste typology. Considering the phases identified in Figure 2, the waste disposal chain changes considerably according to the type of waste treated. If a real project does not refer to any specific type of waste, it can be a wake-up call of non-concreteness, and it smells of hype and failure. Analyzing the waste management phases where the blockchain is used, only 6 projects out of 22 appear to be oriented towards the CE, with technology being used in all phases. However, none of these are in use. Based on our research, only two projects appear to be in use; both involve citizens in the recovery of abandoned garbage in exchange for a reward obtained via a blockchain platform.

5. Discussion

Our study shows that waste management through the use of blockchain technology is a complex issue that researchers and practitioner are tackling from different points of view and with different blockchain technologies, also emphasizing specific aspects or issues.

Cross-cutting consequences have been elicited in three dimensions: economic, social, and environmental, with health added, in order to grasp the positive values or impacts of using blockchain technology for proper waste management.

5.1. Economic

A product at the end of its life has an economic value if it is totally or partially reusable. The waste value depends on a correct separation at source, or on the application of concepts such as CE or sharing economy, and so it depends on which stages of the process are monitored and managed by the system (Chik and Makurin, 2020; Esmaeilian et al., 2018; Lamichhane et al., 2017). A blockchain-based waste management system, prioritizing information sharing in the chain, allows for better value recovery. Knowledge of the product's history shared within the system, such as its

Table 3
List of Blockchain-Based Waste Management Projects

Project/ Ref	**Type of Waste**	**Status**	Blockchain Platform	Token	Integration	**Blockchain Advantages**	Phase involved
Circularise (2019)	PET	Prototype	Cirbase	Circoin	-	Raw material passports to plastic and any other materials produced	1-2-3-4-5-6
CISE (2019)	General	Under study	Quorum	-	-	Support circular economy	1-2-3-4-5-6
Provenance (2013)	Food/Textile	Scaling up	Hyperledger Fabric	-	-	Trace product history	1-2-3-4-5-6
Vastum (Anthesis, 2019)	General	Closed	-	-	-	Recording all waste movements from producer to its final destination and fate	1-2-3-4-5-6
EME (2020)	Excess materials	Pilots	Hyperledger Fabric	-	AI, RDF	Track the journey of the assets across its lifecycle	1-2-3-4-5-6
Traca (International, 2020)	General	Pilot	Activeledger	-	-	Tracing and tracking life cycle of recycled materials.	1-2-3-4-5-6
Chemchain (2017)	Chemicals	Scaling up	Hyperledger Fabric	ChemChain	-	Keep track of hazardous chemicals along the value chain	1-2-3-4-5
Oilsc (2016)	Oil	Prototype	Ethereum	OGSC	-	Tracing oil and gas supply chain	1-2-3-4-5
RecycleGO (2016)	Plastic, metals	Pilot	Hyperledger & ASTERI	-	Multiple BC	Reduce plastic waste, tracking recycling activity	2-3-4-5-6
Swachhcoin (2016)	Households and industries	Website offline	Ethereum	RCR	AI, Big Data, IoT	Transform waste inputs into useful outputs of high economic value	2-3-4-5-6
KleanLoop (2019)	General	Under Study	Hyperledger Fabric	KleanCoin	AI, IoT	Transparent waste trading recycling data optimization	2-3-4-5-6
EWP (Flinders, 2018)	General	Pilot	Ethereum	-	-	Monitoring the cross-border European waste transportation process and cost	3-4-5-6
RecycleToCoin (2017)	PET	Website offline	Ethereum	BCDC	-	Citizen engagement, reward for a correct waste disposal	2-3
Wasteledger (2018)	General	Website offline	-	-	AI, IoT	Tracking waste movements across the entire chain	3-4-5
PlasticTwist (2018)	Plastic	Pilots	Hyperledger Fabric	PlasticToken	SG	Support multiple actors for the "Plastic as an asset" model	1-2-3
Recereum (2017)	Solid waste	Closed	Ethereum	Swachh	-	Citizen engagement, reward for a correct waste disposal	2-3
W2V (2019)	PET	Scaling up	VeChain	W2V	-	Citizen engagement, reward for a correct waste disposal	2-3
PlasticBank (2013)	PET	In use	Hyperledger Fabric	SPCC	-	Collect and sell ocean littered plastic, citizen engagement	2-3
OpenLitterMap (2018)	General	In use	Ethereum	LitterCoin	AI, SG	Token rewarded for littered waste geo-information	3
Data-tritus (arepgroup, 2017)	General	Website offline	-	-	-	Collecting data about station bins.	3
4New (2018)	Waste to energy	Website offline	Ethereum	KWATT	-	Tracing the entire chain from collection of waste to generation of electricity to sale	-
HFZA Waste Permit Portal (Emirates News Agency, 2019)	General	Under study	-	-	-	Facilitate operations, increase trust among stakeholders, reduce valuable time and resources.	-

life cycle (Latif et al., 2019) or raw materials used, can aid in the correct recycling of its components, recovering their economic value (Dasaklis et al., 2020; Dindarian and Chakravarthy, 2019; Sahoo and Halder, 2020). In particular, Tozanlı et al. (2020) has proposed using blockchain technology an IoT devices to securely acquire and store data about e-products in the form of *digital twins*, and monitor their entire life-cycle, including the disposal and recycling phases.

Reliable blockchain data on the availability, quantity, and quality of recycled materials can motivate manufacturers to use more retrieved feedstock (Chidepatil et al., 2020; Liu et al., 2021), whether they are precious materials from e-waste (e.g. gold, platinum, and silver) (Dindarian and Chakravarthy, 2019; Chen and Ogunseitan, 2021), (Wang et al., 2019; Dhungana and Szpytko, 2019), or also materials from batteries (Wang et al., 2019; Dhungana and Szpytko, 2019), plastic boxes (Sekhri, 2018), or agricultural waste (Zhang, 2019; Makkar et al., 2020). Under ideal conditions, waste returns back to the producer who manages it through their recycle centers. (Gupta and Bedi, 2018). Producers are thus interested in the shared data on products' life cycles, which they can use in their decision-making processes to improve existing products or design new ones from waste. (Kouhizadeh et al., 2019; Zhang et al., 2020; Ajwani-Ramchandani et al., 2021b). The system's smart contracts can be deployed to model and monitor particular information such as the ownership, responsibility, and quality assurance of *products as a service* throughout their entire life cycle (Faber and Jonker, 2019). The use of a blockchain system can also create new job opportunities by unifying this vast unorganized sector (Dua et al., 2020).

5.2. Social

A well-implemented blockchain-based waste management system could involve and motivate producers and consumers to adopt practices aimed at the reuse and recycling of waste (França et al., 2020) and at the use of sustainable products (Zhang et al., 2020; Liu et al., 2021) for safeguarding of natural resources. Most of the highlighted impacts of the blockchain application heavily rely on the direct participation of citizens and companies that produce waste. Getting a reward, they are encouraged to correct waste disposal, recycling, reusing, and even spread awareness(Preethi and Radhakrishan, 2019; Ahmad et al., 2021a; Ajwani-Ramchandani et al., 2021a). Users could be rewarded on the basis of quality and type of waste they produce, i.e. use of recyclable products (Lamichhane et al., 2017). Blockchain smart contracts can support economic incentive with the issuance of tokens as discussed in Section 3.3. Collected data can be also used to monitor citizens' habits and could help municipalities decide appropriate strategies (Pelonero et al., 2020). Producers that apply transparent recycling policies can also improve their social image and reputation (Wang et al., 2019), with a consequent benefit to their sales. For this application, Morrow and Zarrebini (2019) suggested the use of blockchain technology, associated with IoT devices, to support recycling, waste reduction and to create social good. Updated blockchain data on current ownership of reconditioned or reused goods allows the tracing of any social responsibilities, such as those related to proper disposal (Taylor et al., 2020) or provides legal evidence of liability in the case of hazardous waste accidents (Song et al., 2022). In this context, the blockchain can guarantee real-time waste monitoring by introducing the issuance of penalties to stakeholders who do not ensure safety-compliant operations (Dua et al., 2020).

5.3. Environmental

The citizens' motivation towards correct waste disposal leads to a reduction of illegal dumping (also called fly-tipping) with a consequent benefit for the environment (França et al., 2020; Sham et al., 2020a). The access to blockchain shared information about the composition of products or about their life-cycle, both in the case of complete disposal and in the case of partial recycling, can lead to correct waste management, minimizing the environmental impact (Zhang et al., 2020; Dindarian and Chakravarthy, 2019; Wang et al., 2019; Sahoo and Halder, 2020; Dasaklis et al., 2020; Lamichhane et al., 2017). Furthermore, these type of data can lead to uniquely identify the owner of a product by contrasting the illegal disposal (Lawrenz et al., 2020). The blockchain, allows government or local authorities to monitor the sector by including contrast actions of the black market (Sahoo and Halder, 2020) and environmental crimes (Ongena et al., 2018; França et al., 2020; Schmelz et al., 2019; Laouar et al., 2019). For example, industrial wastewater or hazardous materials in e-waste such as lead, mercury, arsenic, or cadmium, if not correctly identified, separated, and disposed of, can cause severe problems for the environment and health (Hakak et al., 2020). IoT devices can also be used to monitor if a hazardous waste transport truck is overloaded. This data can be analyzed automatically by smart contracts to contrast the overload issue from the source (Song et al., 2022).

5.4. Health

One of the objectives of blockchain-based waste management systems is the monitoring of landfilling of waste. This allows to reduce uncontrolled landfills and prevent prevent fly-tipping by entailing the reduction of diseases such as Dengue, Zika, Chikungunya (França et al., 2020) that afflict people who work in so-called informal recycling, present in countries in way of development. Blockchain technology can help governments recoup the informal waste economy, making it in full compliance with the law (Wilson et al., 2006; Sekhri, 2018). Transparent waste information ensured by the blockchain, such as hazardous raw material composition, can aid in safe disposal (Dindarian and Chakravarthy, 2019) or in a correct product evaluation and recovery (Wang et al., 2019). In farmlands, for instance, correct waste delivery by farmers will eliminate the need to segregate them by hand during the treatment by avoiding worker health risks within the disposal center (Zhang, 2019). During the COVID-19 pandemic, the World Health Organization (WHO) recently declared that COVID-positive users must carefully collect their waste to prevent the virus from spreading. In this sense, waste tracked by a blockchain system can be useful for this purpose (Ahmad et al., 2021a; Nandi et al., 2021; Ahmad et al., 2021b). The correct waste segregation of sanitary waste or, in general, products that do not lend themselves to a CE approach is, therefore, necessary to avoid or mitigate health and environmental risks (Kassou et al., 2021), especially in a developing countries context (Ajwani-Ramchandani et al., 2021a,b).

6. Conclusion

The analysis conducted by this paper investigated the use of blockchain technology applied to waste management with the aim of examining advantages, trends, and the state of the art in the use of that technology in this industry. The research has focused both on the literature review and on the examination of recently launched real projects.

In the first partthe paper presents a simplified model containing the main macro-phases for the waste management process that, according to the CE paradigm, include product production and consumption. For each phase, potential blockchain applications were specified in terms of stakeholders involved, data records, integration with other technologies, and potential advantages over traditional methods.

According to the findings of the literature review, blockchain is proposed to solve common issues of current waste management systems and as an enabling technology for the circular economy. By exploiting its intrinsic characteristics, blockchain can guarantee transparency, immutability, traceability, and sharing of data among system stakeholders. The use of blockchain technology can support proper waste management by eliciting positive impacts on the economy, environment, society, and people's health. It can also support citizen engagement by means of economic incentives with the issuance of cryptocurrencies or tokens. In addition, to contrast waste dumping, tokens can be used to support the local economy and help people out of poverty. However, despite the much-vaunted advantages of the use of blockchain technology, only 16 out of 65 papers provide technical details about their system or about the implementation, suggesting the literature interest is just at the beginning. In the same way, regarding the type of treated waste or the geographic areas involved, in most of the papers, both are not specified and are quite general. This suggests, once again, how the use of this technology is still in the phase of study.

The project's overview analyzes 22 different initiatives by investigating the typology of waste, geographical areas involved, blockchain platform used, and waste management phases involved. Unlike the literature review, most of the projects are specifically applied to a well-defined category of waste and are almost all localized. This is due to the concreteness of the projects, which, to be applied to real cases, must necessarily focus on a specific category with a well-defined disposal chain. However, considering the current status of projects, it is possible to notice that about 30% seem to be closed or failed because their websites are offline and no updated information can be found on the web. Furthermore, only 13% have developed a prototype and only 9% are in use. The information and conclusions found for the projects' overview are in line with those in the literature. The reduced number of papers providing system technical details and the low percentage of projects in use or in a prototype phase suggests the adoption process is still long, but certainly there is a promising interest. The interest in blockchain technology is primarily focused on waste recycling or partial recovery, with only a small number of research works or projects devoted to the CE, revealing how this sector must evolve in order to produce long-term solutions, such as through eco-design.

Despite the hype, it should be noted that blockchain technology is still in its early stages, with some critical issues, particularly for public blockchains, that must be addressed, including scalability, data privacy, high energy consumption, and low throughput. The analyzed blockchain applications in waste management identify these problems and propose solutions based on permissioned or private blockchains and on the use of multiple blockchains, providing for the use of off-chain systems for calculation operations and storage of large data. The solutions are strictly linked to the specific application context and are thus studied based on the type of waste and number of process phases considered, the types of actors involved, the geographical location, and backward compatibility with off-chain existing IT systems. The differences between solutions highlight the heterogeneity of proposals. Any blockchain-based waste management system must be specifically designed, and its costs, which may be a barrier to adoption, must be estimated (including costs for system setup and migration, network maintenance, and staff training). In real world applications, the design should involve and begin with the will of many stakeholders, particularly governments and local authorities, especially if the CE paradigm is to be pursued. Therefore, a strong political or entrepreneurial will is needed. Currently, another obstacle to the adoption of blockchain in waste management is the lack of knowledge about its potential benefits and its applications. Perception of the technology is often influenced by the bad reputation of cryptocurrencies such as Bitcoin, especially when hindered by governments. Moreover, the number of people who are familiar with blockchain technology is limited to a niche group of innovators. On the contrary, depending on country policies or donors, blockchain adoption can attract funding for projects or startups (i.e., the ICO phenomenon). Also, the lack of law and regulation constitutes a barrier for adoption in the waste management field. However, due to the high interest in the technology and to the wide programming communities behind it, limitations may be quickly overcome.

On the basis of this analysis, it is possible to state that the adoption of blockchain, in the near future, can trigger a revolution in the waste management sector by supporting the CE paradigm, but at the same time, a radical change is needed, a change of perspective in terms of sustainable product design, cooperation between disciplines, increase of awareness, and the introduction of new professionals, which can facilitate a future vision towards gradually eliminating the concept of waste.

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