blockchains

Review

Blockchain on Sustainable Environmental Measures: A Review

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Abstract: Blockchain has emerged as a solution for ensuring accurate and truthful environmental variable monitoring needed for the management of pollutants and natural resources. The immutability property of blockchain helps protect the measured data on pollution and natural resources to enable truthful reporting and effective management and control of polluting agents. However, specifics on what to measure, how to use blockchain, and highlighting which blockchain frameworks have been adopted need to be explored to fill the research gaps. Therefore, we review existing works on the use of blockchain for monitoring and managing environmental variables in this paper. Specifically, we examine existing blockchain applications on greenhouse gas emissions, solid and plastic waste, food waste, food security, water usage, and the circular economy and identify what motivates the adoption of blockchain, features sought, used blockchain frameworks and consensus algorithms, and the adopted supporting technologies to complement data sensing and reporting. We conclude the review by identifying practical works that provide implementation details for rapid adoption and remaining challenges that merit future research.

Keywords: environmental sustainability; blockchain; pollution monitoring; plastic waste; solid waste; greenhouse gas emissions; food waste and security; water management; wastewater; circular economy

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1. Introduction

Environmental sustainability faces significant challenges due to escalating pollution from our daily activities and production practices [1]. Factors such as unsustainable utilization of natural resources and inadequate waste management exacerbate global warming, resulting in more frequent extreme weather events such as droughts, floods, shifts in climate patterns, and rising sea levels, leading to land loss [2].

Numerous countries and regions worldwide are mobilizing to combat climate change, striving to curb emissions and limit global warming to 1.5 degrees Celsius as outlined in the Paris Agreement [3]. While halting pollution is an aspirational long-term goal, it is currently impractical, as many economies rely on industrialization and diverse human activities. Striking a balance in managing pollutants and their production emerges as a pragmatic solution [4]. However, accurately measuring, monitoring, and reporting waste generation and resource usage present significant challenges, especially given the presence of stakeholders with conflicting interests within the management chain. In such circumstances, ensuring data fidelity becomes a considerable concern [5].

To address these challenges, an electronic recording system with features such as data availability, transparency, and protection against manipulation is crucial. Blockchain technology has emerged as a promising solution to these challenges. By employing a distributed and parallel data ledger, blockchain ensures data immutability, making it resistant to Byzantine attacks [6]. However, blockchain offers more than just immutability. Its distributed record-keeping approach and the use of a consensus algorithm contribute to its trustworthiness and resiliency, meeting the needs of users and policymakers seeking to protect data associated with environmental variables to achieve actual results on protecting the environment and bounding climate change. But there are many possible applications, environmental variables, and polluters on where blockchain may be applied, and some have been recently addressed in the literature. Therefore, it is necessary to know the applications and objectives of these research works and their motivations to use blockchain to identify existing research gaps.

In this paper, we review existing research that applies blockchain technology to enhance trust in the recording, sensing, and management of variables affecting environmental sustainability. These variables are greenhouse gas (GHG) emissions, solid waste, plastic, food, water, and a new circular economy that targets to reduce, reuse, and repurpose used materials to reduce their environmental impact. These works represent interdisciplinary approaches that leverage environmental, social, financial, and engineering solutions. We have excluded applications of blockchain technology in energy and chemical waste management [7] due to the broad scope of the former and the localized nature of the latter.

The contribution of this paper is the addressing of the following questions: (1) What are the motivations for using blockchain technology in the management of GHG emissions, solid and plastic waste, food waste, water usage, and circular economy? (2) What specific features of blockchain are sought in existing research? (3) What gaps exist in current research that warrant further investigation?

Through exhaustive literature research, we address these questions, uncover intersections, and outline remaining challenges from the reviewed literature. Our analysis aims to offer guidance for future research endeavors in this rapidly evolving field. We categorize the blockchain frameworks utilized in each topic, their respective consensus mechanisms, the supporting technologies for data collection, and the persistent challenges across the reviewed works.

The remainder of this review is organized as follows. Section 2 presents some basics of blockchain and consensus algorithms reported in the reviewed work and overviews the blockchain features that make blockchain a technology of interest to support the monitoring of variables for environmental sustainability. Section 3 presents existing applications of blockchain for the management of GHG emissions (with a specially dedicated section to carbon), solid, plastic, food waste, water, and circular economy. Each environmental variable reviewed in this section is structured and can be read as a standalone section without losing context. Section 4 presents future challenges and Section 5 presents our conclusions. Figure 1 shows a snapshot of the topics covered in this review.

Figure 1. Content and organization of this paper: Applications of blockchain for the management of GHG emissions, carbon, solid waste, plastic waste, water management, food waste, and circular economy.

2. Blockchain

Blockchain is a decentralized and distributed digital ledger that keeps data immutable to safeguard both data and the record-keeping process [8]. Blockchain operates across a peer-to-peer (P2P) network of nodes, called miners or validators, that interplay a consensus algorithm to certify data as truthful. Data are recorded after consensus is affirmatively verified. The distributed ledger is organized as blocks of verified transactions. These blocks are linked as a chain to provide historical immutable records. With the combination of distributed operations of the consensus algorithm and cryptographic schemes, blockchain makes it difficult for adversaries to tamper with the information stored in the distributed ledger.

Based on the access permissions, blockchains can be categorized into public, private, and consortium frameworks. A *public blockchain* allows any user to join, read the blockchain's content, submit transactions, verify content correctness, and participate in the consensus algorithm. Well-known examples of public blockchains are Bitcoin [8], NXT [9], and Ethereum [10]. A *private blockchain* uses a sole entity for granting permission for users to join the network, and write or send transactions to the blockchain. Examples of private blockchains are Hyperledger Fabric, Ripple, and Eris [11]. A *consortium blockchain* uses a consortium to grant access to each participant [12].

2.1. Blockchain Frameworks

There are numerous blockchain frameworks. Here, we briefly introduce those used in the reviewed literature for environmental data recording.

A *blockchain framework* is a set of tools that enables the development of blockchain-based applications. The frameworks support the function of consensus mechanisms, smart contracts, cryptographic functions, and Application Programming Interfaces (APIs) to build decentralized applications (dApps) or blockchain-based solutions. Popular blockchain frameworks include Ethereum [10] and Hyperledger [13]. The following are brief introduction to blockchains detected in the reviewed works within the scope of this review.

- *Bitcoin* is well-known blockchain for payment exchange and cryptocurrency generation [8]. This public blockchain handles between 4.6 and 7 transactions per second, making it hardly scalable.
- *Ethereum* is a programmable P2P network that enables users to build and deploy decentralized applications [10].
- *Hyperledger* is an open-source blockchain platform hosted by the Linux Foundation's Hyperledger project designed to meet confidentiality, privacy, and scalability requirements while maintaining a global collaboration between finance, banking, supply chains, manufacturing, and technology [13].
- *Corda* is designed for enterprise environment, highlighting data privacy, security, and compliance [14]. Corda shares data on a need-to-know basis because parties may be competitors who want to keep business relationships and details secret from one another. Participants must first obtain a digital certificate before joining the network [15–17].
- *Algorand* is a blockchain platform that claims to be secure, decentralized, and scalable while reducing energy consumption. It uses a consensus algorithm called pure proof-of-stake (PPoS) that enables large participation and prevents forks for enhanced security [18].

Table 1 categorizes the frameworks adopted based on the consensus algorithm used, whether they are fully or partially decentralized, and the throughput in terms of the number of transactions per second. These values are reported by the individual papers and the framework platforms.

Table 1. Performance comparison of blockchain frameworks.

Name	Consensus	Decentralized	Transaction Rate (tps)
Algorand [18,19]	PPoS, Algorand Consensus	public	1100
Bitcoin [8]	PoW	public	4.6, max 7
Ethereum [10]	PoW	public	15
Hyperledger-Iroha [20]	YAC	open source and private	depends on network
Hyperledger-Fabric [13]	PBFT, Raft or Kafka	private	3500
Hyperledger-Sawtooth [21]	PBFT or Proof of Elapsed Time (PoET)	open source and private	depends on network
Corda [14,16]	Pluggable Consensus	private	200

2.2. Consensus Algorithms

A *consensus algorithm* is a protocol used by the nodes of a blockchain network to ensure consistency among the distributed ledgers [11]. Various consensus algorithms have been considered for environmental monitoring. Here, we briefly introduce those widely adopted ones in the reviewed works.

- *Proof of Work (PoW)* is a consensus algorithm used in Bitcoin, and later also used in Ethereum [11]. In this scheme, nodes called miners or validators compete to solve a computationally challenging puzzle to decide who leads the addition of the latest block in the valid blockchain. The miner who resolves the puzzle first is the selected miner who adds the new block in the blockchain.
- *Proof of Useful Work (PoUW)* is similar to PoW; however, it requires that the work is not just computational but also useful in some real-world applications [22,23].
- *Proof of Stake (PoS)* uses the level of a stake that each validator (called forgers) puts forward to as another variable to select the block committing node (instead of resolving a puzzle) [9,24].
- *Delegated Proof of Stake (DPoS)* resolve "the rich getting richer" problem presenting in PoS by also considering votes from the nodes in the network [25].
- *Proof of Stake Time (PoST)* solves the problem of "the coin-age". Beside the stake, validators must demonstrate consistent participation and contribution over time to be chosen to create new blocks.
- *Practical Byzantine Fault Tolerance (PBFT)* is a consensus algorithm proposed to solve the Byzantine Generals Problem and optimizes for low overhead time to solve problems associated with already available Byzantine Fault Tolerance solutions [25].
- Three consensus used with Hyperledger are: *Raft* [26] and *Kafka* [27], which are crash fault-tolerant, and *YetAnotherConsensus*, as used by Iroha [20,28]. Raft and Kafka use a leader–follower mechanism to improve transmission efficiency and rotated the leader role to ensure fault tolerance.
- *Proof-of-trust (PoT)* is a consensus algorithm that selects validators based on the participants' trust values. PoT has a centralized reputation-based approach to reach a consensus and avoids low throughput and high resource consumption. By separating participants' powers in the consensus process, PoT promotes fairness and security [29].
- *Proof of Vote (PoV)* is a consensus protocol based on a voting mechanism and consortium blockchain. PoV separates voting rights and executive rights. The consensus mimics the voting campaign by designing four types of network participants: commissioner, butler, butler candidates, and ordinary participants [30].

2.3. Blockchain Features in Environmental Monitoring

Blockchain provides features such as data security, transparency, and trust, enhancing efficiency across diverse industries and applications for recording and management systems. Some blockchain features are inherent attributes, like data immutability, and others are enabled by the use of smart contracts in a blockchain. For example, a smart contract can be deployed on a blockchain to facilitate the establishment of environmental policy and ensure enforcement. Figure 2 shows the blockchain features mostly sought after in environmental management and monitoring applications. These features are described as follows:

- **Immutability (IM)** is the feature that transactions (data) stored in the blockchain cannot be tampered with. Once data are recorded in the blockchain, it cannot be changed. This measure guarantees the integrity of the data within the blockchain, as attempts to modify it are highly infeasible.
- **Anonymity (AN)** is the attribute of a system where participants' and stakeholders' information is protected and kept private.
- A **Smart contract (SC)** is a self-executing trusted code that runs on a blockchain network without needing a trusted or centralized node [31]. Blockchain clients issue transactions to trigger smart contracts to perform functions on the blockchain.

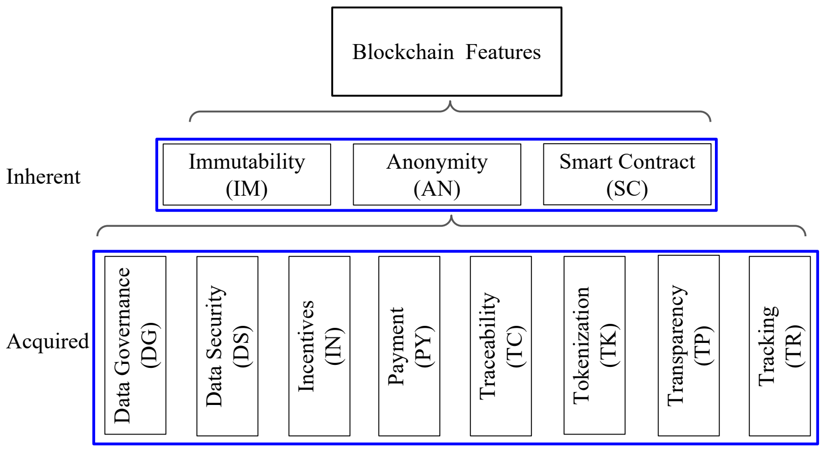

Figure 2. Blockchain features in environmental monitoring: inherent ones and acquired ones, identified in this paper.

Other acquired features that are enabled by blockchain include the following:

- **Data Governance (DG)** defines how data are shared and who or what processes have access to the recorded data.
- **Data Security (DS)** is the property of a system that makes data immune to a specific attack. These data are the transaction content.
- **Incentives (IN)** are the mechanisms designed to encourage user participation. These incentives encompass both rewards and penalties within the system. Rewards are employed to promote favorable behavior and adherence to the established rules defined by smart contracts, while penalties serve to discourage unfavorable behaviors.
- **Payments (PY)** is the process of *transferring* cryptocurrencies or tokens between blockchain clients' accounts in exchange for goods or services.
- **Traceability (TC)** is the ability to access chronological information of a client, a physical or digital object, or a process through recorded transactions. Traceability allows users to follow the history of an object. Provenance, as a specialized application of tracking, uses traceability to identify the origin of the subject.
- **Tokenization (TK)** is the representation of a universal value of physical or digital assets, or ownership rights on a blockchain network. Tokens can be exchanged or generated in a blockchain as a result of a smart contract.
- **Transparency (TP)** is the property that allows users to access information recorded in the blockchain for verification. Users may look into this feature to access historical data.
- **Tracking (TR)** is the feature of blockchain that allows access to the data regarding the current location or status of objects or processes.

Table 2 outlines the terminologies and abbreviations for features of blockchain used in this paper. In the following analysis, we highlight the commonly targeted features in the existing literature.

Table 2. Features of blockchain sought by reviewed approaches.

Terminology	Abbreviation
Anonymity	AN
Immutability	IM
Smart contracts	SC
Data Governance	DG
Data Security	DS
Incentives	IN
Payments	PY
Traceability	TC
Tokenization	TK
Transparency	TP
Tracking	TR

3. Blockchain-Based Management of Critical Elements for Sustainability

The critical elements for sustainability identified in this paper are greenhouse gas and carbon emissions, solid and plastic waste, food, water, and circular economy. Because blockchain is used as a ledger, we look into the motivations of using blockchain and the features sought, and identify which blockchain framework are adopted. We also identify the technology used to support data acquisition and monitoring. At the end of the section, we identify the challenges left for future research.

Research Methods. The followed research method was an exhaustive search for publications where blockchain is used to monitor the environmental variables addressed in this paper, and identify the motivations of using blockchain, threats, features, frameworks, consensus algorithms, and the supporting technologies. The searched databases were Science Direct (Elsevier) and IEEE Xplore that archive conference and journal papers. We greatly used Google Scholar, which directed the search to many other publishers and databases. We also made a general search on the Internet and retrieved information from sites on products and projects on the focus themes. The search produced about 300 publications, and about 200 were considered to have enough original information to be reported. The others are references to basic or associated information for completness. Different from other works, the uniqueness of this review is the identification of the motivations for using blockchain on environmental sustainability. Each environmental variable addressed here are independent from the others and so that each topic in this review can be read independently. The results of the analysis are greatly summarized by the provided tables.

3.1. Greenhouse Gas Emissions

GHG are those that contribute to the warming of the Earth's atmosphere. These gases include carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulfur hexafluoride (SF_6), and nitrogen trifluoride (NF_3) [32,33]. Other important GHG emissions are particulate matter PM2.5, PM5, and PM10 and volatile organic compounds [32].

Monitoring the generation of GHG emissions is recognized as a critical need. Industries and households that utilize combustion in various capacities are significant sources of GHG emissions that also require monitoring.

In this section, we examine existing research on monitoring and recording GHG emissions data, identifying the objectives that drive the implementation of blockchain technology, and the target GHG emission. Figure 3 highlights the detected objectives in the use of blockchain applications for GHG emissions. We also provide insights into blockchain and other supporting technologies. These supporting technologies are those used to sense, collect, transmit, or store data in combination with blockchain. The supporting technologies are various and aim to provide additional information on strategies to address an interface between blockchain and the environment/users. Table 3 summarizes the information gathered from the reviewed literature.

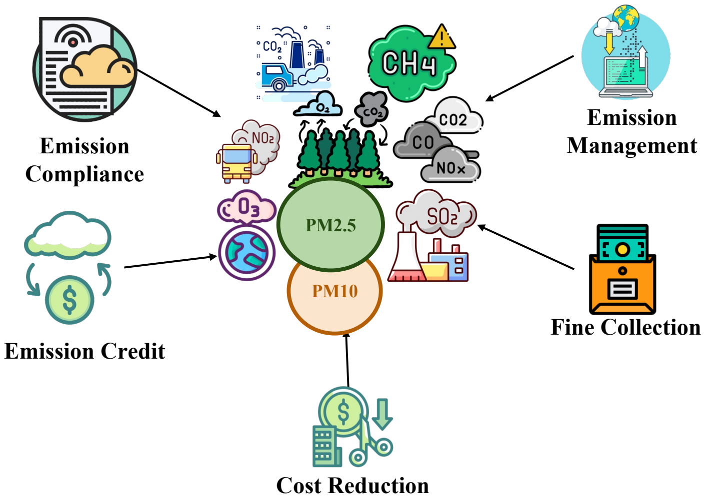

Figure 3. Objectives of blockchain applications for the management of GHG emissions.

Table 3. Blockchain applications for the management of GHG emissions.

Objectives	Emissions	Blockchain Features	Framework	Supporting Technologies	Challenges
Check compliance [34–37]	CO [35], NO_2, SO_2 [34–36], N_2O	SC, TP	Ethereum [36], Hyperledger [34, 37]	IPFS [35], data compression [36]	Scalability
Facilitate management [38–41]	CH_4 [40,41], H_2, NO_2, SO_2, NH_3 [38], PM2.5 [39]	TC, TP	Ethereum [39]	5G [38], Cloud and edge computing [38], crowdsourcing [39]	Scalability [39]
Manage emission credit [42]	NO_2, O_3, PM2.5, PM10	IN	IB-AQMS blockchain/PoW	N.A.	Smart contract conditions check
Collect fines [43]	NO_2, PM2.5	TP	N.A.	N.A.	Tracking, scalability
Reduce cost [44]	NO_2, O_3, PM2.5, PM10		Ethereum	IPFS	Cost, IPFS reliability

3.1.1. Objectives

Five distinct objectives have been identified using blockchain to mitigate the impact of GHG emissions: (a) monitoring for compliance with policy limits, (b) managing emissions by polluters, (c) utilizing emission credits, (d) reducing costs, and (e) managing fine collection.

- **Check compliance:** It is generally believed that curbing GHG emissions depends on compliance policy, agreements, and allowances [34,36–38,45]. The main concern is to keep sensed data accurate [38] so compliance can be verified [34]. It is important for some policies to also record humidity and temperature data to justify environmental variations [36] that can be associated with specific policy agreements [37].
- **Facilitate management:** Management of emissions share similarities with compliance except that it can help emitters as well [39]. Such activity may involve monitoring and quantification of the GHG (as seen for methane) [40,41].

- **Manage emission credit:** In this scenario, producers of GHG emissions may be granted credits or allowances for emission, and blockchain could serve as a reliable mechanism for verifying compliance [42].
- **Collect fines:** The process of fine collection necessitates an efficient system to monitor and track payments made by environmental policy offenders [43]. The adoption of blockchain technology in this context ensures the implementation of a secure payment system.
- **Reduce cost:** It was also explored to use blockchain for recording various GHG emissions to reduce cost [44]. One strategy was to reduce the cost of storage and for that they resorted to using Inter-Planetary File System (IPFS). However, the use of IPFS also requires looking into reliability and data durability [46].

3.1.2. Blockchain Features

Transparency [34–41,43], traceability [38–41], and integrity [42], facilitated by the immutability property of blockchain, are key motivations for employing blockchain in monitoring and measuring GHG emissions. These properties are sought by studies on compliance verification, management facilitation, and fine collection. However, achieving transparency often requires additional functionalities to grant different stakeholders access to the recorded data.

3.1.3. Blockchain Frameworks

The most commonly reported blockchain framework for recording GHG emissions is Ethereum [36,44]. Other frameworks, such as IBM-AQMS [42] and Hyperledger [34], have also been adopted. However, the reported studies did not provide information about the rationale behind their choice of framework nor the sought features.

3.1.4. Supporting Technologies

Given the expansive nature of monitoring GHG emissions, crowdsourcing approaches have been considered [39]. Additionally, technologies such as 5G have been utilized to transmit data directly to blockchain repositories, minimizing data exposure [38]. Some studies have explored the use of IPFS to store recorded data in large public off-chain databases, offering enhanced security protection [35,44]. Furthermore, data compression techniques have been employed to reduce storage requirements [36].

3.1.5. Challenges

The plethora of works focusing on recording and monitoring GHG emissions converge on scalability as a major challenge [36,39]. Managing numerous sensors required for accurate evaluations of GHG generation in large urban areas poses difficulties in centralized management. One proposed approach involves outsourcing the monitoring of such emissions [39], although implementing a methodology to crowdsource while maintaining data immutability presents significant challenges. Nevertheless, this approach could extend sensing coverage to large areas. The scalability required not only affects the blockchain itself but also off-chain storage and the used storage in general [44].

Other challenges include implementing actionable smart contracts to monitor changes and compliance with emission limits for emissions credit management [42]. Scalable tracking for fine collection management of nonconforming emitters is another challenge. The cost of blockchain implementation is an important factor that one must consider for actual implementations and it is, therefore, a topic that needs further study. Other GHGs that are yet to be considered for monitoring with blockchain technology are HFCs, PFCs, SF_6, and NF_3. Furthermore, the reviewed literature focuses more on proposing systems that may not have yet been implemented and tested. Therefore, there is an evident gap in developing systems that prioritize the implementation of blockchain and observing its performance under real testing scenarios.

3.2. Carbon Management

As the primary and popular global warming contributor, monitoring of carbon has attracted significant attention, with the objective of regulating, monitoring, decreasing, and eventually recapturing such emissions [47]. To mitigate climate change, global initiatives by governments, industries, and organizations have focused on monitoring and regulating carbon emissions [48–52]. However, measuring, monitoring, and reporting of carbon management lacks public trust because most human activity produces carbon and the required reporting and verifying task might conflict with economy benefits [53,54]. In Table 4, we summarize the objectives, the blockchain systems, and technologies reported in the literature.

Table 4. Blockchain-based systems for carbon emission management.

Objective	Sector	Blockchain Features	Framework (Consensus)	Supporting Technologies	Challenges
Monitor carbon	Building and construction [55,56]	SC, IN, TC, TP	Hyperledger Fabric (Kafka) [55], Hyperledger Fabric [56]	Database [56], sensor	Raw data fraud [56]
	Environment [57]	TC, TP	N/A	Sensor	Scalability
	Food industry [58]	TR	Carbon Footprint Chain (Raft-like)	N/A	N/A
Trade carbon	General public [59]	SC, DS, PY, TK, TP	Not specified (PoR)	AI	Scalability, data privacy, implementation cost
	Corporate [53,54,60–69]	SC, DG, IN, PY, TC, TK, TP	FISCO BCOS (PBFT) [60], Multi-level blockchain [53], Hyperledger Fabric (DPoR) [61], Hyperledger Fabric (Solo) [62], Multichain [63], Bitcoin [64], Hyperledger Fabric (Kafka) [68]	Sensor [53,60], reputation system [61,63]	N/A
	Transportation [70–73]	SC, DG, IN, PY, TC, TK, TP	Hyperledger Fabric (PBFT) [70], Hyperledger Iroha (YAC) [71], Ethereum [73]	VANETs [70]	Data privacy, environmental impacts of blockchain, scalability [72]
	Energy [74,75]	SC, IN, PY, TC, TK, TP	Hyperledger (Kafka) [74], Ethereum [75]	Priority and reputation system [74]	N/A
	Marine ecosystem [76]	SC, DG, TC, TK, TP	N/A	N/A	N/A
	Building and construction [77]	SC, DG, IN, TC, TK, TP	N/A	N/A	Raw data fraud
	Fashion industry [78]	TP	N/A	N/A	N/A
Capture and store carbon	Industry [79]	DS, IN, TK, TP	Not specified (PoUW)	Sensor	N/A

3.2.1. Objectives

We categorize the reported objectives into carbon monitoring [55–57], carbon trading [53,54,59–78], and carbon capture and storage (CCS) [79], as shown in Figure 4. Table 4 summarizes the various identified objectives and the features of the adopted blockchains to achieve those objectives. Carbon monitoring is primarily focused on measurement, reporting, and verification (MRV) of sensed data [80]. Carbon trading, while treating these emissions as tradable commodities, is an emerging objective.

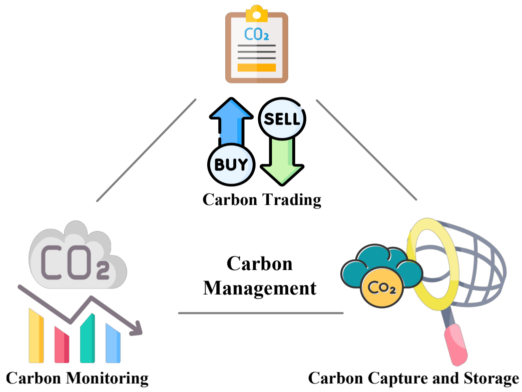

Figure 4. Objectives of blockchain applications for carbon management.

- **Carbon monitoring:** The building and construction sector is one of the largest contributors to GHG [81]. Here, making data transparent to stakeholders and preserving data integrity [55,57], especially among service providers [58], to support trust among various stakeholders [56], have been major objectives in data monitoring projects.
- **Carbon trading:** In carbon trading among individuals and companies [53,54,59–69], transaction verification [59], data integrity [60], and maintaining security and efficiency of the trading system [61], where transactions are influenced by both the offer price and the reputation value of emitting enterprises, are main concerns. Transportation systems are another large contributor of carbon [70–73]. Blockchain-based systems enable the transportation emission trading with trust between individuals [71] and vehicles [70,73]. In the energy sector, blockchain is being proposed to trace the source of carbon, enabling transparency in carbon trading [74,75]. Various conceptual blockchain frameworks for emission trading to ensure transparency have also been proposed for marine and coastal ecosystems [76], the building sector [77], and the fashion apparel industry [78].
- **Carbon capture and storage:** For CCS, Bachman et al. [79] introduced a new native token on a blockchain that uses Proof-of-Useful-Work (PoUW) as the consensus mechanism to incentivize carbon removal. With this incentive mechanism, CCS facilities compete with each other for the amount of captured and stored carbon emissions.

3.2.2. Blockchain Features

The most demanded use of blockchains in carbon emission management is smart contracts, as it provides the mechanism to keep records in a blockchain. Transparency [53–57,59–65,69–79] and traceability [53–57,60–65,67,69–77] are also amongst the most sought-after features in this topic. Incentive management [53–56,60–65,70–75,77,79], tracking [53,54,59–65,70–77,79], and data governance [53,54,60–65,70–73,76,77] are also considered.

3.2.3. Blockchain Framework

The adopted blockchains for carbon management are: Hyperledger Fabric [55,56,61,62,68,70,74], Ethereum [73,75], CFC [58], FISCO BCOS [60], Multichain [63], Bitcoin [64], and Hyperledger Iroha [71]. Hyperledger Fabric is the most widely adopted blockchain, owing to its flexibility to adopt different consensus algorithms. Some applications that also target scalability, and thus, high transaction throughput, use raft-like consensus algorithms, such as in food-industry applications [58].

3.2.4. Supporting Technologies

The use of sensors and numerous IoTs motivates the adoption of a database to store the data obtained to achieve fast access time and low cost per record stored [56]. Aligned with the objective to reduce data exposure, the protocol design for having sensors directly reports data to the blockchain, and thus, minimizing human intervention has been reported to be of large interest [53]. To govern the carbon trading system, artificial intelligence (AI) is employed to detect carbon emissions anomalies [59]. The use of vehicular ad hoc networks (VANETs) has been explored to enable direct trading between vehicles that contribute to the generation of carbon [70]. Other approaches to incentivize the reduction of carbon emissions require a reputation system that allows carbon contributors to compare their emission levels [61,63,74].

3.2.5. Challenges

Although holding significant promise in reducing carbon emissions, blockchain-based carbon management systems may encounter issues such as data privacy, scalability, cost, and the risk of raw data fraud during the emission data collection process. The inherent transparency of blockchain technology ensures symmetrical information sharing among stakeholders, but it also raises concerns regarding the handling of confidential information. Scalability becomes a growing concern as more participants or sensors are integrated into the carbon management system, potentially impacting its performance. Additionally, the energy consumption of blockchain technology raises concerns about its carbon footprint and its implications for carbon emissions. Collecting emission data are inherently exposed to raw data fraud, especially those systems that require human intervention. Autonomous communication and management are also needed solutions.

3.3. Solid Waste Management

Solid waste is the materials generated from daily human activities, movable, and permanently discarded [82]. They are categorized into municipal, electronic, medical, agricultural, and hazardous waste, depending on the source of generation. Most of the solid waste ends up in landfills, and it significantly impacts the environment and human health by contaminating the soil and groundwater and generating methane and carbon dioxide during decomposition [83]. As shown in Figure 5, the phases of effective solid waste management (SWM) typically are: generation, segregation, collection, transportation, treatment, and disposal in an environmentally friendly manner. To perform this task effectively, solid waste may need to be tracked using well-recorded immutable data using blockchain. The following objectives highlight the foreseen challenges.

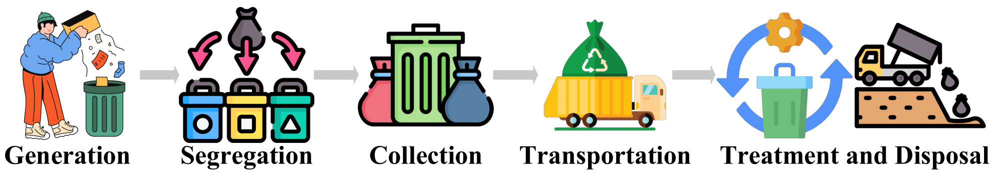

Figure 5. Stages of solid waste management for the application of blockchain.

3.3.1. Objectives

Table 5 shows a summary of the objectives of using blockchain in SWM along with the type of waste, the reported blockchain features, adopted framework and consensus, supporting technologies, and its remaining challenges.

- **Incentivize waste segregation:** Waste segregation is more effective at the source. Therefore, a system to reward cryptocurrency to those individuals or groups who segregate solid waste is a major incentive mechanism [84].
- **Incentivize waste collection:** This is the most popular objective in SWM. Systems to manage the recording of proper disposal of solid waste and the distribution of rewards are of major interest [85–88]. Other approaches include a penalty to those

who do not comply with disposal policy. Proper discarding often means to return such disposed materials to a retailer or dealer, so that rewards are assigned. Rewards are in the form of tradable tokens [89] or cryptocurrency [87].

- **Monitor waste transportation:** Illegal dumping and dumping hazardous waste are major concerns in the reviewed applications. For the latter concern, reducing information asymmetry between contributors of solid waste and waste manager is needed [90]. Real-time monitoring of waste transportation can also help reduce these two concerns [91].
- **Improve solid waste management:** There are a few works that consider the general management of solid waste as a target. These approaches aim to support waste tracking [92], especially for medical waste [93,94].

3.3.2. Blockchain Features

In summary, smart contracts, transparency, and tracking are widely sought-after blockchain features to address the challenges of information asymmetry in SWM. Data governance [92,95–97] is of interest for improving municipal waste management to control access to the record. Data security is adopted by monitoring municipal waste transportation [91] and improving medical waste management [93,94]. Incentivization is adopted for waste segregation and collection as well as improving municipal waste management [84,87,88,92,95–97]. Traceability is reported in approaches for incentivizing waste segregation [84], monitoring hazardous waste transportation [90], and improving municipal waste management [93,94].

Table 5. Blockchain applications for solid waste management.

Objective	Waste Type	Blockchain Features	Framework (Consensus)	Supporting Technologies	Challenges
Incentivize waste segregation [84]	Municipal	SC, IN, TC, TP	Ethereum	IoT, QR code	N/A
Incentivize waste collection [85–89]	Electronic [85,86]	SC, IN, TP, TR	Ethereum	IoT, sensors, barcodes, browser extensions	Incentivization [85], Security [86]
	Agricultural [89]	TP	N/A	QR Code, IoT	Scalability
	Municipal [87,88]	SC, IN, TR	Ethereum [87]	Fog computing, GPS, RFID [88], IoT [88]	Implementation and tokenization [87,88]
Monitor waste transportation [90, 91]	Hazardous [90]	SC, TC, TP, TR	N/A	IoT, GPS	Validate input data, data ownership, lack of regulation
	Municipal [91]	DS, TP, TR	N/A	UHF, VANETs, IoT, Geo-fencing techniques	N/A
Improve solid waste management [92–97]	Municipal [92,95–97]	SC, DG, IN, TC, TP, TR	Ethereum (PoW) [95], Ethereum [92,97]	QR code [92], IoT [97]	Resilience in adopting blockchain technology [96], scalability [92]
	Medical [93,94]	SC, DS, TC, TP, TR	Ethereum [93], Hyperledger Fabric [94]	IPFS [93]	Data privacy, lack of regulation, smart contract vulnerabilities, scalability [93], data validation [94]

3.3.3. Blockchain Frameworks and Consensus Algorithms

Among the reviewed papers for SWM, Ethereum [84–87,92,93,95,97] and Hyperledger Fabric [94] emerge as popular frameworks. The reported consensus algorithm includes PoW [95].

3.3.4. Supporting Technologies

Various technologies, such as IoT [84,88–90,97], GPS [88], QR codes [84,89,92], and RFID [88], are crucial in collecting data throughout the waste segregation, collection, transportation, treatment, and disposal processes. These technologies are often integrated into smart waste bins or waste trucks. On the computational side, a decentralized storage system, IPFS, is also used for off-chain data logging [93]. Ultra-high frequency (UHF) and VANETs are used to efficiently retrieve sensor data over extended distances. UHF tags and readers are used to identify waste bins while VANETs enable the location detection of them [91]. Geo-fencing techniques are also employed for effective waste monitoring and timely collection from dump spots [91].

Computing infrastructure and applications are identified for the collection, recording, sharing of data, and managing of IoT devices and for hosting services. These applications include fog [88], cloud [87], and edge computing [89].

3.3.5. Challenges

Some challenges commonly identified with blockchain technology are also identified in blockchain-based SWM systems. They are the implementation and monetary value determination of the cryptocurrency [87,88], data sharing boundary [90,93], scalability [89,92], lack of regulation on blockchain technology [90], resilience in adopting blockchain technology [96], and smart contract vulnerabilities [93]. Data standards and how to validate data from off-chain storage to blockchain are needed to ensure interoperability among the systems [90,94].

3.4. Plastic Management

Plastics represent a major source of pollution to the environment, and are already permeating into most of the food chain and into animals and people [98–100]. Plastic is a key contributor to the municipal solid waste. However, because of its vast impact on the environment, we give it its own section.

Municipalities manage plastic waste through incineration, disposal to landfills, recycling, or exporting to other countries/regions [101]. Some of these options are not helpful as they just move plastic waste from one place to another through exportation or contaminate in other forms as GHG generated by incineration.

3.4.1. Objectives

As shown in Table 6, the objectives of blockchain-based approaches for plastic-waste management include incentivizing plastic collection, plastic feedstock tracing, and plastic trading. Figure 6 shows these objectives described in the following.

- **Incentivize plastic collection:** Plastic collection is a prime management task for the others and one that depends on incentivizing individuals to discard and collect plastics [102]. Traceability can help to motivate proper plastic disposal by increasing consumer liability [103], while tokenization helps with rewarding those individuals who properly dispose plastic waste [104]. Another strategy to facilitate plastic waste collection is to crowdsource the location of the plastic waste with reliably geo-tagged public photographs so that collectors can locate it [105] and by connecting collectors with plastic collecting companies [106].
- **Trace plastic feedstock:** Plastics and microplastics in the ocean have recently claimed significant attention. Publicity has also generated plans to incentivize plastic collectors to recover such plastics from the ocean. But monetary incentives also motivate abuse (e.g., claim ground plastics as ocean plastics). Therefore, blockchain finds its use

in incentivization [107], plastic segregation [108,109], and plastic traceability [110]. Data management is another supporting task in plastic collection, specially targeting raw recyclable plastics that currently considered of high value [111,112]. There is especial interest in applications that target textile products made from recycled plastics collected from land and ocean [111].

- **Support plastic trading:** The recyclability index (RI) of plastics indicates how much plastic can be recycled and the value of plastic is driven by it [113]. Recyclable plastic can be traded and that benefits from trading and accounting systems using blockchain [114,115].

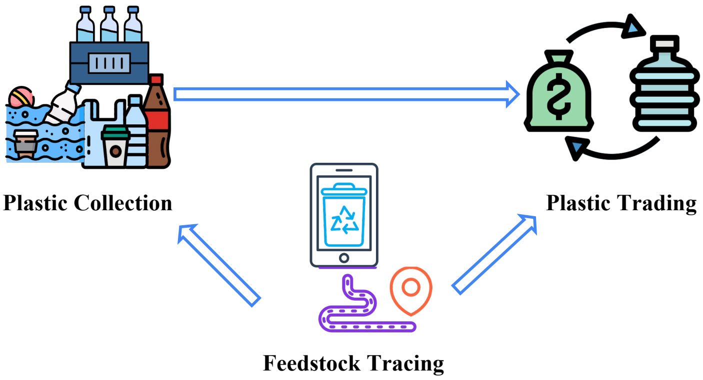

Figure 6. Objectives sought in the management of plastic with existing blockchain-based systems.

Table 6. Blockchain applications for plastic waste management.

Objective	Plastic Type	Blockchain Features	Framework (Consensus)	Supporting Technologies	Challenges
Incentivize plastic collection [102–106]	Plastic bottle [102]	IN	Multichain/Fine-grain permission	Digital badge, mobile app	Data security [104]
	Urban plastic [103–106]	SC,IN	Hybrid blockchain [103], Hyberledger Besu [106], IOTA (Fast probabilistic consensus) [104]	Digital badge, mobile app, IoT devices [103,104,106]	
	Coastal plastic and plastic packaging [105]	IN	Ethereum	Mobile app, crowdsourcing geo-tagged image, relational database, cloud computing	
Trace plastic feedstock [107–111]	Ocean Plastic	TC	N/A	N/A	
	Recycled plastic [108,109,111]	SC, IN, TC, TP	Consortium blockchain [109]	Digital badge [111], IoT devices, AI [108]	
Support plastic trading [112–115]	Plastic products [112,113]	SC, IN, TC, TP, TR	Consortium blockchain [113], Hyperledger Fabric + Ethereum (PBFT + PoW) [112]	N/A	Scalability [112,113]
	Plastic waste [114,115]	SC, IN, TC, TP, TR	Ethereum [114], EVM [115]	DApp	

3.4.2. Blockchain Features

Incentivization is the most sought-after blockchain feature for plastic management, which is triggered mostly for plastic waste collection. This feature is leveraged by the use of smart contracts [111]. Traceability and tracking are mostly used for feedstock tracing and trading while transparency is reported for tracing recycled plastics and supporting plastic trading to provide the source information [111,113,115]. Tracking is also considered to help consumers approach plastic recycling organizations [106,114].

3.4.3. Blockchain Framework

Hyperledger fabric and Ethereum are the most adopted frameworks. However, many of the blockchain solutions for plastic management adopt a multi-chain approach that uses a combination of multiple blockchains to handle credit transferring and recording tracing [112,113,115], IOTA [104], or a consortium blockchain [109].

3.4.4. Consensus Algorithms

The most popular consensus algorithm in plastic waste management is PBFT, while PoW and PoS are also considered in system implementations. Expectedly, many of the piloted systems lead by commercial organizations use proprietary consensus in their systems and little can be found about them.

3.4.5. Supporting Technologies

Incentivization mostly drives the adoption of digital badges, digital assets, and wallets as credit systems to incentivize plastic collection and trading. Database, image processing, smartphone apps, cloud computing, and IoT devices are often adopted in collecting, segregating, tracking plastic waste, and in providing information to improve system efficiency.

3.4.6. Challenges

A few of the pilot blockchain solutions for plastic management have exposed several issues including data security [116], scalability of the system because of the selected consensus algorithm [117], privacy concerns [118], and energy efficiency of the blockchain framework.

3.5. Food Waste Management

Food waste comprises not only the discarded food itself, but also the energy, water, and resources expended during its production, transportation, and packaging, significantly amplifying the carbon footprint of the food supply chain [119]. As a response, recent research has increasingly turned to blockchain technology to enhance the efficiency of food supply chains, reduce food waste, and ensure food safety and security.

3.5.1. Objectives

The objectives of using blockchain in the food supply chain are to (a) reduce food waste, (b) ensure food safety and security, and (c) improve the efficiency of the food supply chain. These objectives, shown in Figure 7 and summarized in Table 7, are discussed in the following.

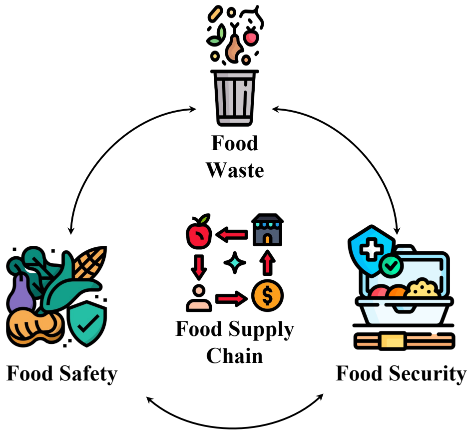

Figure 7. Objectives of blockchain applications for food management.

Table 7. Blockchain applications for food waste management.

Objective	Blockchain Features	Framework	Supporting Technologies	Challenges
Reduce food waste [120–124]	SC, DS, TC, TP	Hyperledger Fabric [120], SmartNoshWaste [121], Hyperledger Sawtooth [123], OriginChain [124]	QR code [120,121,123], RFID [120], Cloud Computing [121]	Scalability
Ensure food safety [125–132]	TC, TP, TR	Trusted Trade Blockchain Network Cloud Platform (TTBNCP) [129], NavIC [131], Not specified [127,128], IBM Hyperledger Framework [125,126, 130]	IoT [129], RFID [128], IPFS [131,132]	Scalability, data security
Ensure food security [133–137]	TC, TP, TR	Not specified	IoT [135], RFID [133], ML [134], PDS [136]	Scalability
Improve food supply chain [138–142]	SC, TC, TP	Modified blockchain [138], (PBFT) [141]	IoT [138], RFID [138], MAS [140]	Scalability, transparency

- **Reduce food waste:** The proposed blockchain-based solutions to manage food waste leverage the management of data across the supply chain for product tracking and origin tracing. The approaches include mobile app platforms for preventing food fraud, enhancing transparency in dairy product provenance, and expediting food contamination source identification [120]. Other applications have targeted reducing waste through the food supply chain [123] and also at the household side by helping manage food consumption [121]. One has the challenge of supporting multiple stages of the chain while the other to support a large number of consumers.
- **Ensure food safety:** Food fraud, where suppliers deceive customers about food quality and contents, is a growing global issue [130]. Tackling this requires traceability and authenticity checks along the supply chain [125–127]. Combining RFID, IoT devices, and blockchain across the agri-food supply chain ensures food safety by gathering and securing data throughout production, processing, warehousing, distribution, and sales [128,129].

- **Ensure food security:** To improve food security (i.e., access to food) while reducing food waste, IoT and blockchain were adopted [135]. Other approaches target food security by monitoring food quality, safety, and provenance [136].
- **Improve food supply chain:** There is an increasing interest in using blockchain to improve the food supply chain while reducing waste and improving food provenance [140], food safety [142], and system scalability [141]. These features are provided by the transactions issued at each process of the supply chain. Such information provides traceability. To improve transparency, an RFID and proof-of-object-based authentication protocol was introduced, using unique RFID tags to monitor real-time product quality, with customizable sensors for added precision [138].

3.5.2. Blockchain Features

Transparency and traceability promote confidence across the processes by allowing customers to check the safe management of food [120,124]. Incentivization is a feature sought by supermarkets to help consumers keep food safe and reduce waste [130]. Traceability [125–129,141] and transparency [125,126,130] are widely adopted features sought to support food safety. These feature also allow stakeholders to step-up communication with customers, increase efficiency, and reduce risks and costs of collection in case of product recall [135,136].

3.5.3. Blockchain Frameworks

The frameworks proposed to reduce food waste are Hyperledger Fabric [120], SmartNoshWaste [121], Hyperledger Sawtooth [123], and consortium blockchain [124]. Public Blockchain [127–129] and IBM Hyperledger Framework [125,126,130] are used to create solutions to ensure food safety. Public blockchains have been proposed to support food security [133,136] and to support the food supply chain [138], as those can reach more consumers or to make data accessible to users [123].

3.5.4. Supporting Technologies

Supporting technologies such as using RFID tags [128,133,138] and other IoT devices [129,135,138] to track the food product along the supply chain have been widely adopted in the proposed blockchain systems that address food waste. For instance, QR codes [120,121,123], RFID [120], and cloud computing [121] are common supporting technologies on such works. QR code and cloud computing can improve data traceability and accessibility to every stakeholder, including the consumer. This approach can reduce the waste generated by a product of unknown origin [121] and allow consumers to track the history of a product by simply scanning a QR code [123]. IoT [129] and RFID [128] are used for traceability, finding food provenance, and enhancing food safety. These IoT devices digitize systems in farms, processing plants, plantation fields, and logistics companies. Customers can verify the information for the products they want to purchase by scanning the RFID tags [128]. Similarly, IoT [135] devices and RFID [133] strengthen food security by providing information regarding food location and product history along the supply chain. Furthermore, the result of machine learning (ML) classification methods presents food-related information to help the stakeholders better manage their supply chain [133].

3.5.5. Challenges

Food provenance is a major concern for consumers [130,143]. The food origin may indicate food properties or whether food is associated with a contamination recall. Transparency and traceability can help satisfy the demand for provenance information. Because the food supply chain is complex and extensive, and it involves many stakeholders, blockchain's scalability, transparent and data governance, and accessibility remain key challenges. Data governance is a particular challenge to support the private sector as it is a major stakeholder of the food supply chains. Although blockchain and smart contracts can help users navigate the intricacies of regulation and compliance for the food supply chain systems, how they can be standardized and implemented across the numerous stakeholders along the supply chain remains an open issue.

3.6. Water Management

Water scarcity is a pressing and recurring issue faced by countries worldwide [144]. Climate change and extreme weather events keep increasing concerns on water availability and quality. The critically needed water management, in general, suffers from issues such as information asymmetry [145], staff shortage [146], and data tampering [146]. Research groups have proposed using blockchain as necessary tool for effective water management. Works on water management using blockchain focused mainly on three objectives: improving water management, supporting water trading, and conserving water resources, as indicated in Figure 8 and summarized in Table 8. The table also summarizes the adopted approaches, supporting technology, and identified challenges.

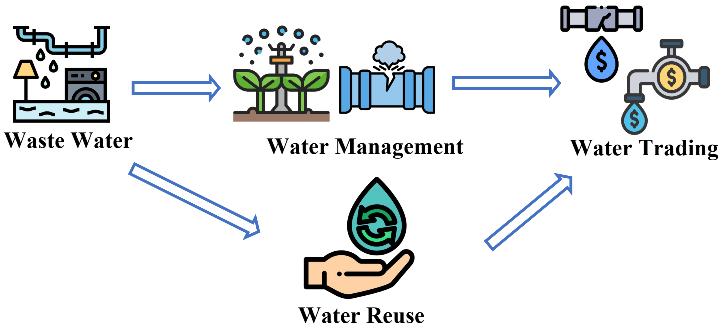

Figure 8. Objectives of blockchain applications on water management.

Table 8. Blockchain applications on water management.

Objective	Sector	Blockchain Features	Framework (Consensus)	Supporting Technologies	Challenges
Improve water management	Wastewater [146–153]	SC, DS, IN, TC, TK, TP, TR	Hyperledger Fabric (Kafka) [148], double blockchain [152], (DPoS) [150], (PoSL) [147], (PoML) [147]	ML [148,152], IoT [147,148,152], IIoT [146]	Scalability [148]
	Harvested water [145,154–159]	SC, DS, TC, TP	(PoAh) [154], Ethereum [157], Hyperledger fabric [158]	IoT [154,156,159], IoUT [154], IoAT [157], IPFS [158]	
	Irrigation [160–172]	SC, DS, TC, TK, TP, TR	Ethereum [160,161, 164], Hyperledger Fabric [168], (PoW) [160], Alliance chain (PBFT) [165], PoST [167]	IoT [163,164,169], IoUT [169], IoWT [172], sensors [160,169], RFID [161], LPWAN [163], Fuzzy logic [162]	
	Municipal [173–179]	SC, DS, IN, TC, TK, TP	Private Blockchain [177], Hyperledger Fabric [176]	Smart meter [175–178], ML [173], IoT [173,175–177], Bloom filter algorithm [177]	

Table 8. *Cont.*

Objective	Sector	Blockchain Features	Framework (Consensus)	Supporting Technologies	Challenges
Support water trading	Agriculture [160], Municipal [180, 181]	SC, PY, TK, TP	Ethereum (PoW) [160], Ethereum (PoA) [180]	WSN [180], sensors [160,180], IoT [181]	Computational and storage overhead, high latency [180]
Conserve water resources	Municipal [182, 183]	SC, PY, TP	Hyperledger Fabric [183]	IoT [182,183], cloud computing [182]	
	Harvested water [15,184–186]	DS, TC, TP	Ethereum [186], (PoW) [184], Alliance chain [185], Corda [15]	User interface [15]	Energy consumption, lack of regulation [184, 185]

3.6.1. Objectives

Improve water management: A significant amount of work has focused on improving water management for both waste water as well as other fresh water use. Wastewater is the water discharged from industry and households [148]. Direct wastewater disposal potentially pollutes the water and damages aquatic life [150]. Thus, wastewater treatment and its management is increasingly necessary. Blockchain-based systems were proposed to manage wastewater treatment systems [148], to secure and verify water permits and license information [151] and compliance [153]. The management of water distribution system is also of great importance [147]. Information asymmetry is also of concern in water management systems that has attracted commercial blockchain management solutions [145]. Because of water scarcity, many cities are resorting to ground water, but that also calls for accurate management systems for sustainability [155], efficiency [154], trading [159], and decision making [158]. The water crisis is a common problem faced by the irrigation community [163,164]. Water trading, as a solution, requires support by providing real-time transactional data [165]. Incentivization of sustainable water practices [166] and securing data in water monitoring [162] are also critical applications. Water conservation can be incentivized by the application of penalties and rewards, for which blockchain can support monitoring and reward management [167]. Monitoring household water consumption [173,176,177] and preservation of smart meter data [178] are key measures for improving water usage within municipalities.

Support water trading: The lack of transparency between stakeholders, administrative complexities, and complicated financial settlement processes are challenges for the current water trading market. As in other trading applications, blockchain is being adopted for water trading to increase transparency, manage payments, and seal agreements with smart contracts, where water rights are also of increasing importance [180].

Conserve water resource: Conserving [182,183] and protecting water against pollution [15,184–186] have motivated the adoption of blockchain in water management. Blockchain is used to manage the use of water resources [182], to ensure water resource protection [184], and to trade water rights [185]. Blockchain has been widely considered for monitoring water quality, with measurements of PH, turbidity for water, carbon dioxide, and carbon monoxide [186], which is particularly important for drinking water [183] and for protecting aquifers and reservoirs [15].

3.6.2. Blockchain Features

Blockchain-based water management systems mainly aim at enhancing transparency to reduce water information asymmetry between stakeholders, improving water-use cooperation. Most of these features are leveraged by the use of smart contracts and the general properties of blockchain. The access to consistent data and secure payment enabled by smart contracts also allows entities to trade water and to exercise water rights. The water management system also uses blockchain tracking to find locations with inadequate water quality [176,177], and traceability features to trace water quality [178].

3.6.3. Blockchain Frameworks

Blockchain-based water management systems are implemented on Hyperledger Fabric [148,153,158,168,176,183], Alliance chain [165,184,185], Ethereum [157,160,161,164,180], Ethereum Light Client (ELC) [186], and R3 Corda [15]. Hyperledger Fabric was used to check the feasibility of real-time data storage [176]. A system using a static blockchain for one-time intervals and two dynamic blockchains for time series was proposed considering different security levels based on the consensus (PoW, PoT, or PoV) used by the network [152]. A private blockchain uses k-means++ to group users into clusters, where each cluster has a private blockchain to record the data of members [177].

3.6.4. Supporting Technologies

IoT devices are commonly deployed to collect data for wastewater treatment management [146–153], harvested water [145,154–159], agricultural water management [160–172], and municipalities [173–179]. IIoT devices, developed for industrial applications, are deployed for wastewater treatment management where the risk factor is high [146]. Internet of Underwater Things (IoUT) [154] and Internet of Agricultural Things (IoAT) [157] devices are used as specific hardware to monitor water. Industrial Internet of Water Things (IIoWT) was considered for data standardization, interoperability, and data security among different water institutions [172]. IoT [147,148,152,154,156,163,164,169,173,175–177,182,183] and IIoT [146] devices may monitor water use and directly interact with blockchain through Low Power Wide Area Networks (LPWAN) [163]. ML techniques predict water use [173] and detect anomalies in data [148]. For agricultural water management, RFID readers are adopted to grant users water access according to the rules set by the community, also referred to as irrigation receipt [161].

3.6.5. Challenges

The identified challenges of blockchain for water management from a number of the reviewed literature are policy and regulation-based [151,184]. Considering that water rights and access to water often cross national borders, the implementation of blockchain for water management needs to consider international laws and national policies, as well as geopolitical cases, to allow collaboration and cooperation amongst stakeholders across borders.

Technical challenges that blockchain-based systems face are the energy consumption of the blockchain application [184,185] and the scalability of the system [148,180], especially under a massive number of IoT devices and sensors. Transparency of information could facilitate informed decision-making and encourage collaboration. The cost and complexity of monitoring the vast water systems require significant resources and collaboration. A feasibility study could be an important first step towards filling this gap.

3.7. Circular Economy and Blockchain

A circular economy (CE) is a mechanism that reuses, renews, and regenerates materials, products, or services to keep them or make them more sustainable or environmentally friendly [187,188]. Figure 9 shows an overview of the circular economy concept. CE is emerging as a sustainable alternative to the traditional linear economy system, where consumers buy a product, use it, and dispose of it [189]. However, the implementation of a CE faces many economic and management challenges, such as tokenization of the resources used along the supply chain, mechanisms for tracking, and setting the value proposition of recycled materials and resources, among others [188–190]. Therefore, there is an increasing interest in exploring blockchain as a solution to address some of these challenges.

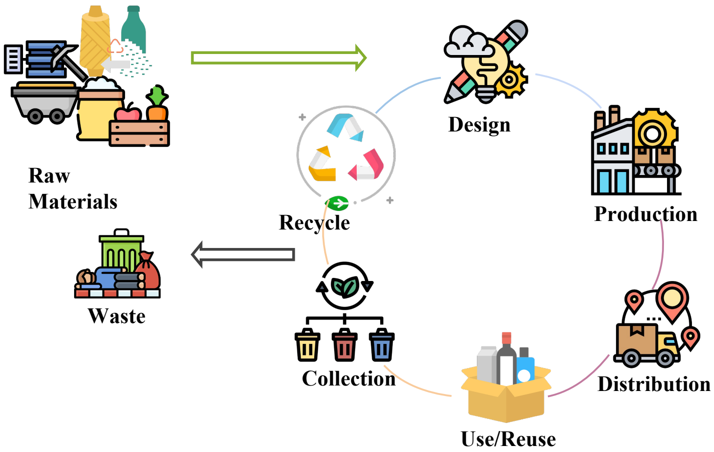

Figure 9. Representation of stages involved in a circular economy.

3.7.1. Objectives

Table 9 categorizes the existing blockchain solutions into circulate supply chain products, recycle e-waste, and reuse plastics.

Table 9. Blockchain applications for the management of a circular economy.

Objective	Blockchain Features	Blockchain Framework	Supporting Technologies	Challenges
Circulate supply chain product [191–197]	SC, DG, TC, TP	Hyperledger Fabric [196]	N/A	DApp for stakeholder interaction with blockchain [192], scalability [194]
Recycle e-waste [198,199]	SC, TC, TK, TP	Algorand blockchain (implemented) [198], Hyperledger Fabric [199]	IoT [199]	Scalability [198], security and privacy policy [199]
Reuse plastic [108,200,201]	SC, DG, TC, TK, TP	Hyperledger Fabric (implemented) [200]	ML [201], sensors [108]	Interoperability [200]

Circulate supply chain products: Most of the works on blockchain applications for the management of circular economy aim to address the question of how to circulate the products for reuse along the supply chain [191–196]. Blockchain has been explored in digitization of supply chain records to provide reliable data to track waste and inventory [191,192]. A conceptual analysis of using blockchain for product deletion in a circular economy is proposed [194]. Triple Retry is a blockchain-based CE framework that employs Hyperledger Fabric to improve throughput and speed [196]. In e-commerce, IoT and blockchain have crucial influences on the virtual supply chain to achieve a virtual closed-loop supply chain for informed policy making [197]. Blockchain solutions have also been explored in the renewal energy grid management [193] and building and construction sector [195] as case studies for achieving circular economy.

Recycle electronic waste: Recycling electronic waste or e-waste is another objective of blockchain implementation for circular economy [198,199]. Authentication, synthesis, circulation, and reuse of electronic components are objectives for effective tracking [198]. Federated learning has been also objective of interest to distribute the computationally heavy CE business tasks to conserve resources while keeping confidentiality [199].

Reuse plastics: Plastic reuse is another primary application of blockchain in CE [108,200,201]. In such scenarios, participants in CE are rewarded with tokens when they collect, recycle, and reuse plastic waste. The tokens can be traded for goods. However, at a larger scope, forecast of the generation of plastic is considered to allocate resources for responding to surges of products [108]. ML is the resorted tool to perform such forecasts [201].

3.7.2. Blockchain Features

Smart contracts, traceability, and transparency are features sought in circular economy for tracing products, recycling, and reusing second-life materials. Given the complexity of the circular supply chain involving numerous stakeholders, stages, and second-life product record keeping and tracing, data governance emerges as a crucial aspect [195,197,200] to control data access from different stakeholders of the supply chain [192,196]. Tokenization is often reported as a feature in implemented systems [198,200].

3.7.3. Blockchain Framework

Despite the limited existing works on circular economy, Hyperledger fabric is the most popular adopted blockchain [195,196,199,200]. Algorand, a proof-of-stake fast-consensus blockchain platform, has been reportedly adopted for the implementation to provide digital tokens for second-life e-waste for easier tracking [198].

3.7.4. Supporting Technologies

A circular economy comprises many processes and stages in the life cycle of a product or material. Therefore, it requires many and various sensors, data input devices, processing, and recording systems. IoT devices [199], sensors [108], and ML techniques [201] are used to keep track of second-life products and provide decision support based on the collected data are reportedly used.

3.7.5. Challenges in Blockchain Solutions for a Circular Economy

Scalability remains one commonly identified challenge for blockchain solutions for circular economy applications [194,198]. However, easy-to-use interfaces such as DApp are needed to allow stakeholders to interact with blockchains [192]. Additionally, establishing security and privacy policy [199] must be considered together with leveraging support for interoperability of different systems that rely on the required system features [200].

As in the previous topics, most of the blockchain proposals for circular economy are conceptual. Therefore, the cost and ease of implementation and whether business incentives can make the public embrace a circular economy are unknown. While the concept seems to pack great not only sustainable but also economic benefits, a suitable implementation framework is required. The high energy cost for the implementation of blockchain is also a concern for achieving sustainable development with an energy-intensive computational infrastructure. This topic requires further exploration.

4. Discussion and Future Challenges

As observed in the previous sections, blockchain has been adopted to digitize records, facilitate tracking and traceability of products and materials, and automate tokenization in the trading of products and services to enhance truthful monitoring of environmental variables. The immutability of records supports trust and transparency within the system. While the body of existing work on blockchain applications in waste and natural resource management is large, focused and practical work is still needed to identify the far-reaching potential of blockchain.

As consensus algorithms in blockchain implementations require intensive computation, energy efficiency is a major concern. The trade-offs between energy efficiency, performance, and security are yet to be understood.

Data security has been identified as a feature sought by some of the proposed approaches but existing work lacks identification of actual threats to data. The reason for this void is that data security is a desirable feature of databases rather than of blockchain. Approaches to data security have been recently proposed [154,202,203].

The proliferation of sensors, IoT devices, VANETs, and video feeds is large in blockchain applications. Therefore, the amount of sensing data for the environment grows at a staggering rate. That might challenge the scalability of blockchain systems and also methods to efficiently harvest, represent, and analyze these data. Furthermore, work on data analysis might offer additional views on the impact of the use of blockchain. Some approaches to improve scalability of a blockchain may be the increase of transaction throughput through partitioning of the consensus algorithm, such as sharding [204], by compressing the contents in transactions to increase the capacity of a block [46], or by designing a fast consensus algorithm without losing the design principles of data protection of blockchain [205].

We observed that the management of carbon and plastic has attracted much attention from companies and for-profit organizations, which have come up with their own blockchain-based solutions. However, their implemented systems are mostly proprietary and do not offer technical details on the blockchain they use or share data for public access. Due to the lack of information and outcome measurement, it is unclear how the environmental impact of these systems is evaluated and whether they are effective.

The use of data to trace and track materials or products owned by consumers using blockchain may also raise privacy concerns. The collection of data on the life cycle of the material may offer information on the activities of a consumer. Therefore, measures to protect the privacy of consumers while providing tracking, tracing, and transparency features, among others, to the blockchain-based management systems merit future research.

We highlight the reported blockchain applications that not only have been practical and implemented studies but also share part source code. These implementations encompass blockchain or smart contract codes, as detailed in Table 10. While our presentation of this code does not imply endorsement (nor the opposite), we provide the associated links to facilitate thorough examination. The descriptions of the code can be found in the corresponding references.

Table 10. Implementations of blockchain with available source code.

Topic	Authors	Implementation	Link (accessed on 13 July 2024)
Greenhouse gas	Nußbaum et al. [36]	SC	https://github.com/JCCLaude/IoT-Blockchain
Carbon emissions	Effah et al. [60]	Blockchain	https://github.com/De-miles1/Carbon/tree/master
	Eckert et al. [71]	Blockchain	https://github.com/LiTrans/BSMD-ML
	Yuan et al. [62]	Blockchain	https://github.com/xisiot/HyperETS
Solid waste	Ahmad et al. [93]	SC	https://github.com/AhmadKhalifaUniversity/Code/tree/main
	Le et al. [94]	Blockchain	https://github.com/Masquerade0127/medical-blockchain
Plastics	Alnuaimi et al. [114]	SC	https://github.com/eimalnuaimi/RecycleChain
Food waste	Dey et al. [121]	Blockchain	https://github.com/somdipdey/SmartNoshWaste
	Baralla et al. [123]	SC	https://github.com/0xjei/SawChain
Water	Iyer et al. [148]	Blockchain	https://github.com/sreeragiyer/Wastewater-Reuse
	Mahmoud et al. [152]	Blockchain	https://github.com/HaithamHmahmoud/WDSchain
	Mughal et al. [158]	SC	https://github.com/muhammadhussainmughal/
Circular economy	Eshghie et al. [198]	Blockchain	https://github.com/Kasche153/CircleChain

5. Conclusions

This paper provides a review of the recent existing blockchain applications for protecting data in the management of emissions, waste, food, and water to minimize negative impacts on environmental sustainability and categorizes the broad area of environmental monitoring into greenhouse gas emissions, carbon, solid waste, plastic waste, water, food, and the circular economy.

We identified the motivations for using blockchain in the reviewed research work and development, the frameworks used and consensus algorithms, and the supporting technologies, highlighted the features that existing work aimed to achieve through the use of blockchain, and unveiled the remaining challenges in each of the different application categories.

We discussed the remaining challenges that signal the direction for future research. For practical value, we identified those works that reportedly reached implementation states and shared source code used to model blockchain artifacts in the presented systems. Therefore, we provided answers to the proposed research questions according to recent reported work in the reviewed environmental factors and blockchain.

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