



sustainability



Perspective

Leveraging Blockchain and Smart Contract Technologies to Overcome Circular Economy Implementation Challenges

Nallapaneni Manoj Kumar and Shauhrat S. Chopra

Special Issue

Resources Conservation, Recycling and Waste Management

Edited by

Dr. Nallapaneni Manoj Kumar, Dr. Subrata Hait, Dr. Anshu Priya and Dr. Varsha Bohra



<https://doi.org/10.3390/su14159492>

Perspective

Leveraging Blockchain and Smart Contract Technologies to Overcome Circular Economy Implementation Challenges

Nallapaneni Manoj Kumar *  and Shauhrat S. Chopra * 

School of Energy and Environment, City University of Hong Kong, Kowloon, Hong Kong

* Correspondence: mnallapan2-c@my.cityu.edu.hk (N.M.K.); sschopra@cityu.edu.hk (S.S.C.)

Abstract: Adopting a circular economy (CE) has rapidly emerged among policymakers and business community stakeholders to promote material circularization and ensure sustainable development. While the inclination for a paradigm shift away from the linear economy is evident, many challenges have been quoted in the literature regarding its implementation. Lately, it has become common to propose Information and Communication Technologies (ICT)-based approaches to address these challenges. However, they do not question the practicality of the solutions in the context of CE. This paper aims to find an appropriate digital solution for CE implementation, which is not possible without a complete understanding of the existing challenges. A thorough literature review broadly classified the challenges under five barrier categories: Technological, Financial, Infrastructural, Institutional, and Societal, which was followed up with an investigation into the failure of ICT solutions to address CE challenges. Among the various technologies, blockchain and smart contract technologies show some promise as data-driven decision-making tools; however, they are not without their limitations when applied in the context of CE. This perspective explores the role of blockchain smart contract technology-scape in overcoming CE challenges and presents a circular economy blockchain (CEB) architecture development. The findings suggest that CEB may enable CE business models that improve trust and transparency in supply-chain networks, shared and performance economy platforms, stakeholder participation, and governance and management of organizations. Ultimately, this study highlights critical areas for research and development for the *blockchainification of CE*.

Keywords: circular economy; circular economy limitations; circular economy barriers; digital circular economy; ICT in circular economy; blockchain architecture for circular economy; circular economy blockchain; digital circular economy architecture



Citation: Kumar, N.M.; Chopra, S.S. Leveraging Blockchain and Smart Contract Technologies to Overcome Circular Economy Implementation Challenges. *Sustainability* **2022**, *14*, 9492. <https://doi.org/10.3390/su14159492>

Academic Editor: Antonella Petrillo

Received: 9 May 2022

Accepted: 26 July 2022

Published: 2 August 2022

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.



Copyright: © 2022 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

The circular economy (CE) paradigm is key to the life extension of products, components, and materials (PCMs). It has been viewed and understood differently by various stakeholders across the value chain [1]. For instance, while some understand it as a concept (i.e., theoretical), many others say that it is a framework (i.e., systematic and potentially a quantitative one) aimed at promoting the circularity of the PCM [2,3]. However, Ellen Macarthur defined the CE as “Looking beyond the current take-make-dispose extractive industrial model, the circular economy is restorative and regenerative by design . . . ” [4] and designed a framework for implementation. Though it has varied interpretations, the potential of this paradigm shift from a linear economy to CE is evident.

In early 2011, the European Commission developed a strategic roadmap for implementing a low-carbon economy in the European Union (EU) [5]. This strategic roadmap aims to minimize waste generation that characterizes the linear economy model (LEM) and maintain the continuous flux of materials [6–8]. Meanwhile, the policy initiatives by countries such as China, Japan, and Germany for CE implementation have increased attention to this concept [9–13]. Moreover, recently, the EU has explored convenient options with varying degrees of success in CE implementation, giving utmost importance to CE

in meeting the sustainable development goals (SDGs) [11,12,14]. According to the Ellen MacArthur Foundation and the EU, implementing CE in the EU can create EUR 1 trillion in net economic benefits with 2 million new jobs by the end of 2030 [14–16]. Furthermore, it anticipated a 48% carbon dioxide emissions reduction. Another study from the seven European countries, called the club of Rome, has explored the options of reducing greenhouse gas emissions by up to 70% in each country by implementing CE [17]. It also concluded that the CE implementation measures could increase their workforce by 4% [3,17].

Even though traction towards CE is gaining, and many businesses and policymakers proclaim their support, its implementation seems to be in the early stages, and the reasons are many. The primary challenge that CE faces for implementation is the involvement of various stakeholders across the supply chain with different dynamics in their operations and attitudes [1,18,19]. So far, the CE implementation approach depends on various ‘R’ frameworks (R0-Refuse, R1-Rethink, and R2-Reduce are the strategies for improving the circularity for “smarter product use and manufacture”; R3-Reuse, R4-Repair, R5-Refurbish, R6-Remanufacture, and R7-Repurpose are the strategies in improving the circularity for “extended lifespan of the PCMs and their parts”; and R8-Recycle and R9-Recover are the strategies in improving the circularity for “useful application of materials”). The practitioners have used these ‘R’ frameworks in different applications based on a systems perspective [1,20,21]. Many have noted that due to the barriers and challenges associated with the CE concept, the stakeholders in the value chain could not achieve the real benefits [20–23]. This is due to the complexities seen in the technology evolution, organizational capabilities, regulations, working strategies, and market influence [24–26]. Since then, researchers in the CE field have started discussing how to overcome these barriers and challenges. Lately, some have said that digitalizing the CE implementation framework can address these barriers and challenges [27,28]. As a result, CE digitization has emerged as an active area of investigation using information and communication technologies (ICT) [29]. Although this move has facilitated the digital transition of CE stakeholders, it has failed to question the practicality of the ICT-enabled digital solutions across the CE network and for involved stakeholders when maintaining the continuous flux of resources [30]. Therefore, based on the above-highlighted issue, we need a digital solution that is more promising than conventional ICT.

Hence, this perspective aims to find an appropriate digital solution for CE implementation. The integration of ICT is challenging without a complete understanding of the existing challenges. Thus, this perspective first explored the challenges CE is currently facing; second, the role played by ICT and the reasons for its failure to enable CE transition, followed by recent trends in ICT that support CE. Considering this research scope, a critical review was conducted to find an appropriate digital solution for CE implementation.

The key contributions of this perspective include a critical review and a broad classification of CE challenges under five barrier categories: Technological, Financial, Infrastructural, Institutional, and Societal, followed by evidence on how ICT failed to focus on *ensuring traceability, transparency, durability, privacy, security, and process integrity* across the CE network and involved stakeholders. Other contributions include exploring the new ICT trends, i.e., blockchain and smart contracts. Blockchain is the trending disruptive technology based on distributed ledgers; it seems to be a potential solution [31]. With its features, blockchain technology (BCT) may enable data-driven decisions for implementing CE. Furthermore, using smart contract technology (SCT) coupled with BCT may enable the stakeholders to work as per the pre-approved rules of engagement in a CE network in an automated way. Therefore, in the quest to implement CE using these two new digital solutions, BCT and SCT, this perspective came up with a new concept called circular economy blockchain (CEB), where we thoroughly discussed the architecture development followed by CEB’s potential benefits and challenges that need to be further researched.

2. Barriers and Challenges While Implementing Circular Economy

The literature on CE suggests that considerable information exists regarding the barriers and challenges to CE implementation. The first class of challenges is related to stakeholder collaboration. *Cooperation of external partners* and *partner restrictions* are critical challenges due to the lack of proper control over the circular business model (CBM). For instance, imagine the shift from a throw-away of electrical and electronic equipment, where a clear understanding of each stakeholder or partner is necessary. Accordingly, incentives can be granted to those who effectively attract electrical waste from consumers. In such cases, cooperation between the partners may not exist [32].

The second class of challenges can be described as being related to market dynamics. *Fashion change* and *fashion vulnerability* are challenges that depend on the aesthetic of the PCM, place of remanufacturing, circular PCM design, and modularity [32]. The challenge of *capital tied up* is raised as it would create risks when the financial transactions happen between the stakeholders. For example, when the infrastructure for implementing CE is considered on a rental basis, the financial inflows and outflows are shared between the investors. Another situation is that the financial transaction between the customer and producer would result in tied-up capital. However, the risk of *capital tied up* can be addressed by focusing on the customer types and their specific interests, as suggested in [32,33].

Another class of challenges can be seen as being related to demand-side issues. It is also suggested that *customer type restriction* is one of the challenges for CE where the customers may not show much interest in the remanufactured PCM [34]. While in another study, the challenge of *product category restrictions* is reported [35]. The remanufacturing requires *technological expertise* in redesigning the PCM to match the current demands as per the customer types and needs, which is another challenge for CE [36]. A challenge of *operational risk* due to the use of second or lower-grade technical solutions is highlighted in [37]. Many other studies in the literature highlighted the *return flow challenges* in CE, describing the problem of return flows to the investment and challenges of *predictability and reliability of return flow* while planning the CE solution [38–41]. The *return flow issue* challenge is assumed to have a solution when the stakeholder or customer relationships become closer [35,39]. The challenge of “*risk of cannibalization*” was reported, where the introduction of the CBM over the traditional LEM could decrease sales, as highlighted in [42,43]. Few other studies stress the challenges such as “*lack of awareness*” and *lack of support from related policy, laws, and regulations* as they could restrict the CE shift [37,44].

Various studies were built upon the above-discussed literature. In one study, six significant challenges that a CE is facing are highlighted; they include *complex international supply chains*, *high up-front costs*, *failures in company cooperation*, *lack of consumer enthusiasm and limited dissemination of innovation*, and *resource-intensive infrastructure lock-in* [45]. Later, a literature survey on CE challenges concerning policy options highlighted a few key factors limiting CE progress. These factors include the *economic signals that do not encourage efficient resource use*, *lack of awareness and information*, *limited sustainable public incentives*, *insufficient investment in technology*, *pollution mitigation or innovation*, and *minor consumer and business acceptance* [46]. On the other side, the managing director of Acceleratio conducted a literature survey specifically concerning the barriers and drivers towards CE implementation in a multidimensional approach and highlighted the 22 barriers [47]. Focusing on the case studies of small and medium enterprises (SMEs), the CE challenges are explored in [48]. These include *environmental culture*, *financial barriers*, *limited government support*, *lack of adequate legislation*, *information deficits*, *administrative burdens*, and *relatively low technical skills* [48]. The CE challenges in the view of Spanish SMEs are more or less similar to the above-discussed ones [26,49].

However, the most recent studies started exploring these challenges to better understand the CE implementation process. In line with this, a study explored the CE challenges in four categories: *cultural*, *regulatory*, *market*, and *technological* [16]. After four categories, they further listed them in 15 sub-barriers based on the extensive literature review by referring to the research articles and semi-structured interviews [16]. However, the one new

challenge of CE, which is less stressed by many of the researchers, highlighted in [25,50–52], is the *inadequate information management systems (IMS)*.

Despite increasing efforts by various countries, sectors, and organizations (both industry and academic institutions) toward CE implementation, certain limitations must be considered and explored further to find a solution. For that reason, we followed the new trend of categorical classification to classify the explored challenges under five barrier categories. A summary of the various challenges CE is facing is given in Table 1.

Table 1. Challenges in circular economy categorized into five barriers.

Barrier Category	Challenges	Reference
Technological	-Limited consideration in the present product design for the EOL phase	[47]
	-Limited recycled material availability	[47,52,53]
	-No proper evidence on the quality of recycled PCMs	[47,53]
	-Lack of experience, especially the proven and demonstrated CE projects and lack of technical framework on product redesign as the linear technologies are deeply rooted	[47]
	-Existing inefficiencies to develop new business strategies and sustainable footprint (e.g., eco-design, circular design, design for reuse-repair-refurbish remanufacture- recycling, design for services instead of ownership)	[47]
	-Lacking the manufacturing ability to deliver high-quality remanufactured PCMs	[16]
	-Operational risk due to the use of cheap or lower-grade technical solutions	[37]
	-Lack of tools and data models the define the efficiency of CE projects, thermodynamic limitations	[54–58]
Financial	-High or significant upfront investment costs	[16,45,47,54]
	-Low virgin material prices and recycled materials tend to be even more costly than fresh materials	[16,54]
	-Limited funding for CE business models	[16]
	-Challenges in the predictability and reliability of return flow	[40]
	-Environmental costs	[47]
	-A shareholder with short-term agendas dominates the company governance	[47]
	-Increased management and planning costs of CE projects	[47]
-Capital tied up between the stakeholders	[47]	
Infrastructural	-Limited applications of new business models	[47]
	-Lack of secure information exchange system (IES)	[47]
	-The capacity of reverse logistics limits-Exchange of materials	[47]
	-Inadequate information management system (IMS)	[47]
	-Lack of qualified professionals in environment management	[47]
	-Limited dissemination of innovation	[45]
	-Resource-intensive infrastructure lock-in	[45]
	-Very few large-scale demonstration projects	[16,53]
-Lack of technical resources or facilities	[36,47,48]	
Institutional	-Lack of global consensus	[16]
	-Obstructing laws and regulations	[16]
	-Lack of supportive policy frameworks	[16]
	-Lack of smart regulations	[16]
	-Limited circular procurement	[16]
	-Effective integration of circularity principles into policy innovation is still lacking	[47]
	-Financial governance incentive support for the linear business models still exists	[47]
	-Recycling policies to obtain high-quality material flows are inefficient	[47]
-Governance concerns related to duties, obligations, and ownership	[47]	
-Lack of support from the public institutions	[25,45,50]	
Societal	-Hesitant culture of the organization	[16]
	-Lack of awareness of benefits and readiness to work together throughout the value chain	[16]
	-A secure attachment to a linear system	[16]
	-Lack of visionary leadership for CE transition	[7]
	-The difference in attitudes and behavior of employees	[8]
	-Changing consumer preferences	[16]
	-Lack of awareness among consumers	[16]
	-Consumers prefer new products	[10]
	-The dynamic mindset of the consumers	[16]
	-Customer type restriction	[13]
	-Cooperation of external partners	[32]
-Challenges in collaborating with other companies due to partner restrictions	[32,54]	
-Lack of willingness to contribute to sustainability	[16]	
-Lack of confidence and trust is hampering the exchange of information	[47]	

3. Role of Information and Communication Technologies

Researchers have tried to identify possible solutions to many of the listed challenges in Table 1. They mentioned that it is difficult to address each challenge. The critical issues they would encounter are the lack of support infrastructure and the data availability [59,60]. Indeed, digital technologies such as ICT may enable CE progress [27,61]. In the first European Circular Economic Summit, held in Barcelona, Ellen MacArthur introduced a report on “Intelligence Assets”, highlighting the Internet of Things (IoT) role in CE. In her talk, Ellen MacArthur said, “IoT will allow the CE to develop at a much faster pace than it ever could without ICT and the IoT in telemetry” [28]. These IoT and ICT systems enable the fusion of digital innovation with CE by allowing features such as sense, store, communication, and decisions. Box 1 is provided with a brief case study showing the ICT and IoT role in electric vehicle (EV) battery charging. As said by Ellen MacArthur, the data-informed decision determines the cyclical process (e.g., repair, refurbish, and so on). By nature, CE has many interconnected cycles, which can be seen only when we visualize CE from a system perspective; these interconnected cycles are responsible for generating massive data [29]. Another study reported that using ICT to digitalize CE would help us collect data from every interconnected cycle [62]. The collected data would help the stakeholder make decisions related to the PCM life cycle. The decisions related to logistics and end-of-life (EoL) management of PCM can also be taken if the data is available [29]. The white paper by IBM highlighted that the growth of the CE is in the hands of disruptive digital innovations. According to IBM, the five key technologies, namely mobile technology (ubiquitous mobile access rules), M2M connectivity (the rise of the machines), cloud technology (dematerializing in the cloud), social media (sharing the social revolution), and big data analytics (by the numbers applying data analytics) would help in transforming the CE [63]. It is also suggested that the digitalization of CE may add intelligence to the PCM, thereby allowing the records of PCM’s attributes such as location, conditions, quality, and others over the complete life cycle in line with CE [63].

Box 1. Role of ICT and IoT in EV battery charging.

Consider the concept of battery charging in EVs. Here, the EV’s owners are provided with an option of renting or leasing the batteries where the manufacturer or the service provider’s responsibility is to provide the fully charged battery. In this example, ICT and IoT systems help us monitor the performance of batteries very clearly; when their performance falls below a threshold, the EV owners are given an option to replace the battery on the specific condition of recovering the old battery. Once the old batteries are received, they can be put under EoL management options to recover the valuable materials. In some cases, the EV charging concept can be implemented in a community where everyone owns the EVs with a pick and drop facility for the battery. In such a business case, it is quite challenging to assess the performance, e.g., who owns the responsibility for battery failures. To address this, ICT, combined with data analytics, can be used to identify how the decrease in battery performance varied between the first and last users. Monitoring and analytics will help the service providers make appropriate decisions regarding the user and service provider compliances. On the other side, combining numerous ICT techniques, such as big data, predictive analytics, data analytics, IoT, cyber-physical systems, data mining, artificial intelligence, and others, would lead to intelligent business models. These ICT techniques bring new ways to monitor and control the CE cycles and allow optimizations, which would help improve the performance of CE practice.

The European Policy Centre (EPC), after 18 months of critical investigation on “how digitalization can boost the circular economy?” stated that, with digitalization, the CE could get benefit in terms of *better use of resources, increase the efficiency of processes, stakeholder partnership facilitation, behavior of stakeholder, and knowledge on materials* [64]. Although ICT and IoT facilitate the CE, few concerns regarding digitalization exist, namely *lack of resources, legal certainties, data security, and others* [63,64]. On the other side, the scope of ICT for sustainability beyond efficiency is suggested by focusing on the three primary digital optimizations for sustainability in CE [64]. Recently, the information technology giant ‘Deloitte Finland’ came up with a study connecting the CE and the current digital innovations [65]. Their study shows that the digitalization of CE will help only in certain aspects. For instance, connecting the data centers, stakeholders, or partners with devices and customers in individual/separate parts of the value chain [65]. As stated in [64,65], the CE will boost or create value for companies by selling the services rather than PCM. Even

though the hype of ICT techniques adds value to the CE, there exist numerous challenges; for example, Pardo from the EU's EPC raised concerns regarding how to enable the *free flow of data across borders, fostering trust in the data economy, and maximizing synergies between the digital and circular economy agendas* [66]. However, in the digitalization process, many still follow the centralized databases where data-related challenges are given more importance. However, with the current digital technologies, *ensuring access to data, data ownership, data sharing, ensuring trust and transparency between the competitors, ensuring privacy, and property rights* are more crucial. This would become much more challenging when the marketplace is created where multiple actors will be involved in managing both the flow of information and the physical flows of PCM. However, the challenges can be addressed by shifting to decentralized systems, for example, blockchain technology. Here, blockchain adoption in the CE could improve data-driven decisions by overcoming the challenges related to *trust, traceability, privacy, and transparency*.

4. Blockchain in General and Scope for Circular Economy Blockchain Implementation

Blockchain, the underlying technology of bitcoin initially designed for the financial sector, has revolutionized distributed ledger technology (DLT). Regardless of its origin, blockchain has become a buzzword and started gaining attention from other sectors [67]. The popularisation and continuous attempts to explore the BCT implications in various sectors are due to "decentralized architecture, fault tolerance, and cryptographic security benefits such as pseudonymous identities, data integrity, and authentication," which are essential in CE's digital transition [31,68]. As a result, BCT has identified its technical space in various sectors beyond its original application of cryptocurrency transactions. Across the globe, many have declared that they have been engaged in BCT for various applications [69].

4.1. Blockchain Features and Implementation Steps

Blockchain is a new form of data storage formed out of distributed software architectures and computational infrastructures. It enables decentralization and a distributed nature for the data [70]. With its distributed nature, blockchain keeps track of transactions between the parties in the CE network and protects them from tampering. It also allows peer-to-peer (P2P) interactions from any device (for instance, smartphone operation in an energy-efficient manner compared to conventional desktop systems) and helps improve their trust by providing a verification facility [71,72]. In BCT-based applications, transactions signed between two or more peers or stakeholders will typically happen, and these transactions denote the type of agreements defined between the peers. Mostly, the agreements are signed using SCT [73]. Depending on the agreements, the transactions might involve a physical flow of PCMs or digital assets and sometimes the task execution alone.

In any situation, at least one of the participants or the peer in the CE network must sign this transaction to circulate within the defined network of participants in CE. In a blockchain network or functionality structure, we have a variety of terminologies, out of which a node (small or complex) is essential. Any entity or participant connected to the blockchain in a defined CE network is considered a node. Generally, it is referred to as a small node. A few nodes are needed to verify the rules whenever a transaction happens between such entities, as per the SCT-based agreements. Such nodes are referred to as complex nodes. The function of these complex nodes is to group the transactions into blocks [74]. These complex nodes manage the endorsement and decisions regarding the transaction validity and its inclusion in the blockchain. Overall, the blockchain keeps the list of completed transactions in the form of a ledger typically synchronized across the network of nodes while ensuring security. On the other side, blockchain also ensures the ledger update, which is generally based on the participant or peer approval. These approvals by the complex nodes are only implemented through the reliable consensus algorithm or protocols depending on the blockchain platform types (see list mentioned under Step 2 of Figure 1) [75].

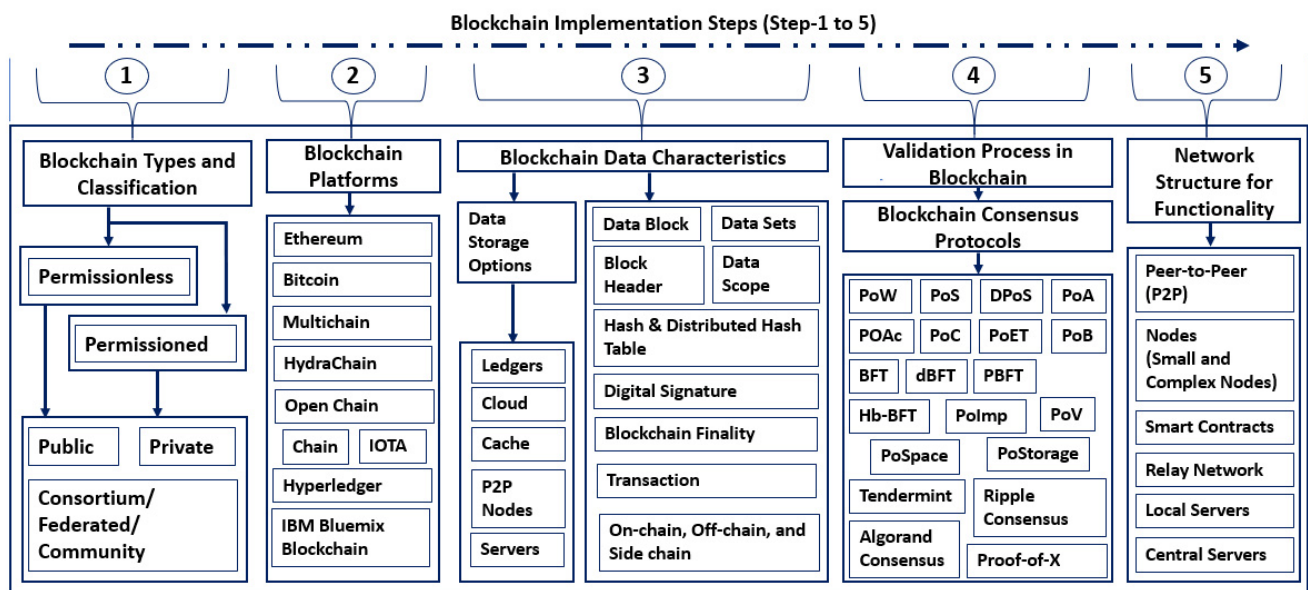


Figure 1. Implementation of blockchain in five steps considering its system based on user interest.

To understand BCT and its implementation, one can consider the blockchain system governance shown in Figure 1. We have shown the implementation process grouped into five steps. It is a set of interconnected mechanisms formed by integrating the software and hardware infrastructures with numerous cryptographic features. Details of each step are given below.

Step 1 is based on the BCT functionality and SCT-based agreements; the user can opt for one of the blockchain categories (as shown in the first step of Figure 1). As per the current literature [72,76,77], blockchain is categorized as public, private, or federated. This classification is based on the network's management and the permissions defined by the users in most cases. In general, the public blockchains are permissionless, where anyone can join as a node and can involve in performing the blockchain operations. Some of the well-known public blockchain implementations are Bitcoin, Ethereum (in Ethereum, both public and private are possible), Litecoin, and other digital currencies [78,79]. In a public blockchain, the overhead management cost and activities will be reduced for the user, mainly due to the self-maintained public node infrastructure. Other sets of blockchains are private and federated, which belong to the permission category. In the permission category of blockchains, only the specific nodes defined, or the nodes part of the consortium, can be involved in blockchain operations. Some well-known permissioned blockchain implementations are Hyperledger, Multichain, Cardano, and others. The applications of private and federated blockchain include “database management, auditing, banking, industrial sectors, and other service-oriented sectors” [70,75].

Step 2 allows the blockchain platform selection depending on the network category type, as mentioned in Step 1. Under those categories, many blockchain platforms exist. Some well know platforms are Bitcoin, Ethereum, Multichain, HydraChain, Open Chain, Chain, IOTA, Hyperledger, IBM Bluemix, and others. However, their selection should be appropriate and based on the functionality and other requirements that are bought by each involving node in the network [77].

Step 3 is the blockchain data characteristics. In blockchains, each transaction between the participants is stored with cryptographic features. For storage, numerous options exist, including the ledgers, cloud, cache, peer-to-peer (P2P) nodes, servers, and others. All such data storage options can broadly be classified under local and network storage. Depending upon the availability, users can opt for one from the wider availability. However, the most suggested one for blockchain applications is network storage. Cloud storage is an ideal network storage option mainly used for commercial applications where flexibility and easy

access to data retrieval is needed. When a transaction is initiated between the nodes, as per the agreements, such a process represents the state change in the blockchain. A group of such initiated transactions which are not yet approved represents the block. The data handling capacity of a block entirely depends upon the type of blockchain platform; for example, the Bitcoin blockchain has a block size of 1 MB, which can accommodate a large number of transactions [77]. A typical block has the block header indicating the transaction time, a previous block's hash, blockchain version number, and the random nonce. These blocks are distributed over the network based on the defined agreements, which happens when the minor nodes validate the transaction. The process of transaction/block validation and its addition to the blockchain network is called mining. The mining process varies depending upon the blockchain platforms. For instance, in the case of the Bitcoin blockchain, this process is conducted by solving the complex cryptographic hash puzzle, which is generally referred to as the digital signature for the block. Here, the nodes in the network compete and solve the hash puzzle, and then the block will be added to the blockchain network. When a new block is added to the blockchain, the transaction is considered approved or completed. This approval process again varies depending on the blockchain platforms, as they are governed by different consensus protocols [80].

Step 4 is the block validation using consensus protocols. This step decides whether the blockchain is functioning according to the agreements or not, as it is responsible for maintaining the process of transactions and their approval. As shown in Figure 1, there are different consensus protocols, which mainly depend on the blockchain types and platforms. However, the most famous consensus protocol is Proof-of-Work (PoW), used in the Bitcoin blockchain. In PoW-based consensus protocol, the nodes in the network compete to solve the cryptographic hash puzzle and submit the proof to the rest of the nodes in the network and the block for validation. Attaining a solution to the cryptographic hash is difficult as it is a complex digital signature most sensitive to minor changes. Hence, it requires substantial computational power where the wealthiest person can be dominant in terms of computational power. The PoW is responsible for splitting the blocks about the available computational power needed for solving the hash (power for hash rate) [81]. Another famous consensus protocol is the Proof-of-Stake (PoS); in this, the minor nodes that help approve the transaction are selected based on splitting the available stake of blocks. The PoS consensus ensures fairness in the network of nodes rather than just being dominant based on computational power [82]. Apart from these two, there are other consensus protocols among them; a few are Byzantine Fault Tolerance (BFT)-based. In BFT-based consensus protocols, block validation is completed when an elected validator gets a two-thirds majority of votes. Then, the block is added to the blockchain. Here, the validator is elected using the round-robin approach [77,83]. In other consensus such as Tendermint and ripple, the electing node-validator is conducted based on the elections and where two-thirds majority votes are needed. In practice, the blockchain stores the state change of something based on the consensus protocol of respective blockchain platforms, representing the final confirmation of transactions. In many blockchains, the time taken for transaction confirmation varies depending upon the type and category. In a Bitcoin-based blockchain and other public types, the transaction approval would take up to 60 min. In contrast, in the case of some private and consortium blockchains, such as Hyperledger, Tendermint, Algorand, and others of similar types, the transaction gets approved instantly [77,80].

Step 5 is the network structure functionality where the blockchain system of interest extends to cover the interactions with the physical world as per the defined agreements. For example, the smart contracts, where the system uses the nodes (either small or complex nodes) to execute a specific task based on their set agreements. Even in the P2P network, a similar strategy of smart contracts is adopted. When the blockchain is extended to human interactions, the state change of transactions would become much more complex, which essentially has to be stored and updated dynamically. These transactions in the network can only be updated using distributed computing.

Therefore, the blockchain system of interest shown in the five steps deals with selecting blockchain types, platforms, consensus, and how these come together to make up a blockchain system for specific applications.

4.2. Circular Economy Blockchain: Scope, Architecture, and Implementation Steps

Based on the brief study in Section 4.1, it can be understood that the scope for blockchain is very high in applications that need data-related security and privacy support. Currently, CE suffers numerous challenges, and many are related to data. *Blockchainification of CE* may ease certain implementation-related challenges as it ensures ‘access to data’, ‘data ownership’, ‘data sharing’, ‘traceability, trust, and transparency between the competitors’, ‘privacy’, and ‘property rights’. Considering this, we proposed a seven-step system architecture for implementing CE, calling it a circular economy blockchain (CEB), as shown in Figure 2.

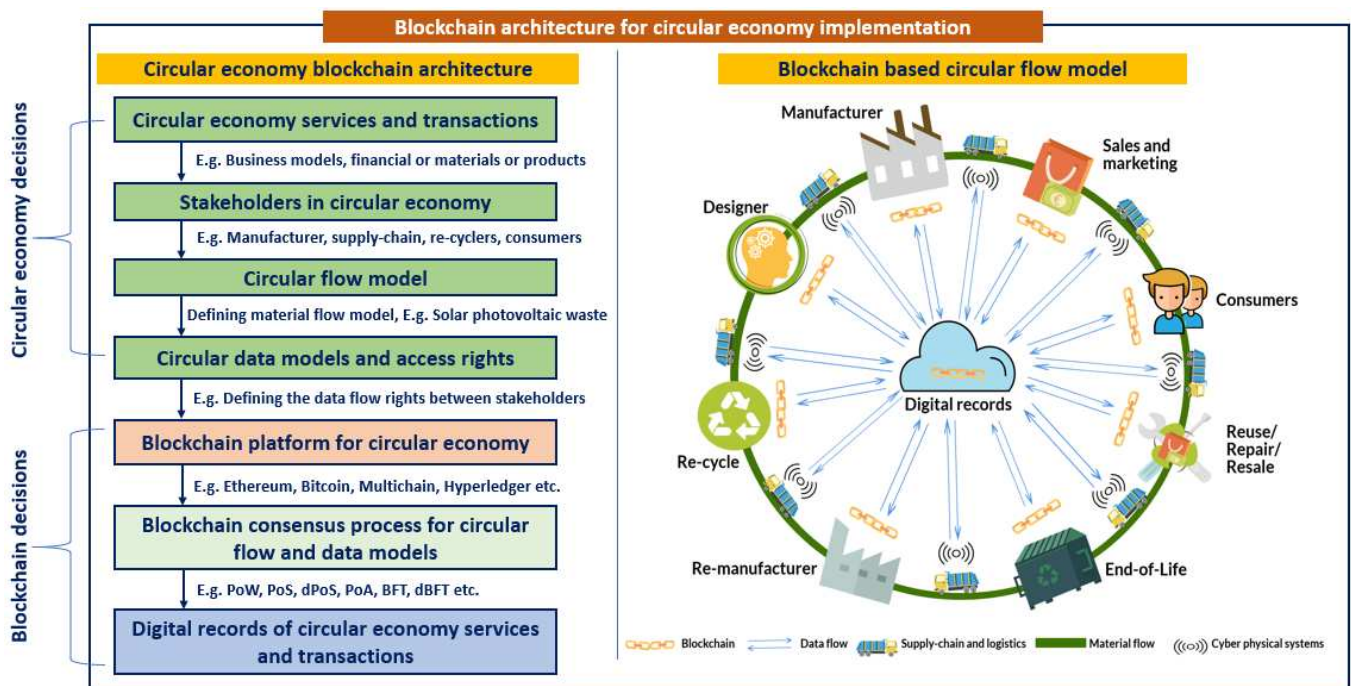


Figure 2. Circular economy blockchain architecture for implementing circular economy.

This architecture identifies the key functionalities involved in practicing CE. It then helps in categorizing the decisions based on the CE stakeholder roles. While implementing CEB, the proposed architecture is expected to be influenced by two types of decisions: CE decisions and blockchain system of interest decisions. Among the seven steps, the first four are framed based on the CE decisions, where the critical functions of CE practice and roles played by the involved stakeholder are given more importance. The next three steps are based on the blockchain system design decision for CE implementation. These three steps are essential in defining software architecture with cryptographic features.

The CEB architecture implementation steps are thoroughly explained below:

Step 1 is identifying the CE services and the type of transactions between stakeholders in the CE network. The transactions include the records of every activity of PCMs respective of the life cycle stage in a circular network. Such transactions are executed as needed by stakeholders’ operation, and they form the agreements resulting in decisions for SCT implementation in CE. In most cases, the stakeholders’ operations are defined as per the CBMs, for example, product as service, product life extension, and others.

Step 2 is the identification of the stakeholders concerning the CE implementation process. For any CE practice, the general stakeholders include raw material suppliers,

manufacturers, sales and marketing, consumers, EoL management team, supply chain, and logistics. However, depending on the CBMs, the stakeholders mentioned above might change. Therefore, this step allows us to identify the stakeholders specific to CE practice.

Step 3 is defining the circular flow model (CFM) depending upon the CE application. For example, the CFM for solar photovoltaics application in the context of CE follows the below-mentioned life cycle stages [84].

Mining → Industrial silicon smelting → Silicon production → Ingot casting and wafer slicing → Photovoltaic cell processing → Module assembling → Marketing and use phase → EoL for material recovery → Market for recovered materials → Reuse in the manufacturing of the same product or other.

Step 4 is defining the circular data models and access rights. This step in the CEB architecture allows the data flow between the stakeholders, and the access rights were defined according to the transactions between them so that it allows privacy.

Step 5 is about the decision related to blockchain platform selection, which usually happens after considering CE decisions (as shown in Steps 1 to 4). Here, we will have various blockchain platforms, for example, public, private, consortium, or federated. Alternatively, options based on the blockchain evolution category are also possible. However, for a CE network with a defined stakeholder, private and consortium or federated would be better.

Step 6 is essential in the blockchain decisions, where it involves the selection of appropriate consensus mechanisms from the available list, PoW, PoS, BFT, and others, to name a few. However, this consensus mechanism depends again on the blockchain platform chosen in Step 5.

Step 7 generally deals with maintaining the digital records of CE transactions and services. By nature, blockchain allows cryptographic features to store the transaction and service data in the cloud. However, users will also have privileges of selecting the storage option at the node itself as per their requirements but only after a thorough discussion with the stakeholders. Sometimes, the option of on-chain and off-chain storage is also possible.

5. Benefits and Challenges of Circular Economy Blockchain

5.1. Benefits and Promises of Circular Economy Blockchain

Blockchains are, theoretically, disruptive and strongly believed to aid the CE implementation. CEB's ability of information sharing facilitates the relationship between the stakeholders involved in CE. Furthermore, the CEB enables information sharing more reliably, allowing *traceability*, *transparency*, *authenticity*, and *trusted agreements*. These CEB features help the CE prevent the fraud and falsification of compliance-related information and reduce both direct/indirect risks [85]. Finally, this addresses the CE challenge by improving the *cooperation of external partners* and *reducing the partner restrictions*. Blockchain can even support disruptions in the CE supply chain [86].

CEB records the information of PCM, mainly their origin, supply chain-related, involved stakeholders at every stage of CE and the PCM life cycle. The recorded information is made visible to all the CEB stakeholders with individual access rights. Conversely, the information in CEB will be highly secure as it is time-stamped with cryptographic features. This enables P2P with more *visibility*, *verifiability*, and *authenticity*, where each stakeholder in CE can track the status of imports and exports of PCM [78,87,88]. Many contracts or agreements exist among the CE stakeholders, which can be compensated with blockchain-based smart contracts. In general, the smart contract refers to the digitally signed contracts related to PCM or any other between the stakeholders (agreements might include financial transactions, monitoring, information exchange, payment transfers, payment tracing, and others) [89].

With its analytics features and predictive capabilities, blockchain can show the PCM circulation related to fashion changes and fashion vulnerability information. It keeps recording the information related to PCMs aesthetic, manufacturing place, design quality, modularity, etc. Furthermore, the challenge of *capital tied up* and other supply chain issues always affect firms and limit market services. In this situation, most firms are interlocked.

This is further extended into the CE network (for example, the suppliers, the government, employees, consumers, EoL management team, and others). Privacy is the concern here; many try to tamper with the data, but with CEB, this privacy issue may be resolved, and the same can be seen from a study focused on privacy-preserving of healthcare predictive modeling as shown in [90].

With its traceability feature, CEB can allow the firms to share and track the PCM flow in the CE network and hence can address the challenge of *capital tied up*. On the other side, the *tied-up capital* would create risks when the financial transactions happen between the stakeholders, for which a smart contract would be the solution. On the other hand, blockchain also enables us to build a strong relationship between CE participants and bring them closure on digital agreements. Mostly in CEB, the closed-looped PCM activities between stakeholders are essential [86].

Blockchain as a technology has the potential to contribute and show few benefits in creating more wealth by allowing the CE stakeholder to be a part shared economy platform. The only possibility of making that is to allow the stakeholders to monetize their transactions on a safe and secure platform [91]. On the other side, the blockchain-based value system that supports social sharing and enables the transition of the industrial economy to the information economy is also discussed in [92].

Blockchain also has the potential to contribute to the digital manufacturing of PCM. As per industry 4.0, many manufacturing industries are currently looking to automate their maintenance and control operations even with the facility of query verifications blockchain [93]. Blockchain technology, along with edge computing features, seems to have great potential. This blockchain-based distributed ledger architecture ensures the product design that is suitable for CE [94].

Blockchain can also contribute to the PCM sustainability assessment in the manufacturing stage. This is possible with the creation of a decentralized manufacturing network. In a study, 'FabRec' is proposed, where the decentralized network of machines and computing nodes are created with the capabilities of allowing transparency, verification facility, and others. These applications in PCM manufacturing will allow us to assess the PCM life cycle assessments to quantify sustainability [95].

In CE practice, due to compliance issues, many firms try to tamper with the data related to PCMs that are not sustainable (for example, the PCM deletion) [96]. Such issues can be easily traced if the manufacturing sectors are adapted to the blockchain service [86].

Even though the blockchain seems to be a very advanced technology, it could offer its promises and solutions to only a few CE challenges. Overall, it is understood that blockchain provides a unique and adequate information management system that can provide many solutions to CE digital transition and ensures *access to data, data ownership, and data sharing, ensuring trust and transparency between the competitors, ensuring privacy and property rights*.

5.2. Challenges with Circular Economy Blockchain

This perspective brings essential insight for CE practitioners in transiting from classic ICT-based to blockchain-based CE. Even though blockchain offers many benefits, some limits and challenges that need serious attention exist. This section explores the possible limitations of the circular economy blockchain, questioning its practicality and scalability. While identifying the limitations, the focus was made mainly on policy aspects, industry, and environmental regulators. On the other side, the technical aspects of blockchain integration with CE are also investigated to explore the challenges. Overall, its implementation will not be easy due to the issues shown in Figure 3.

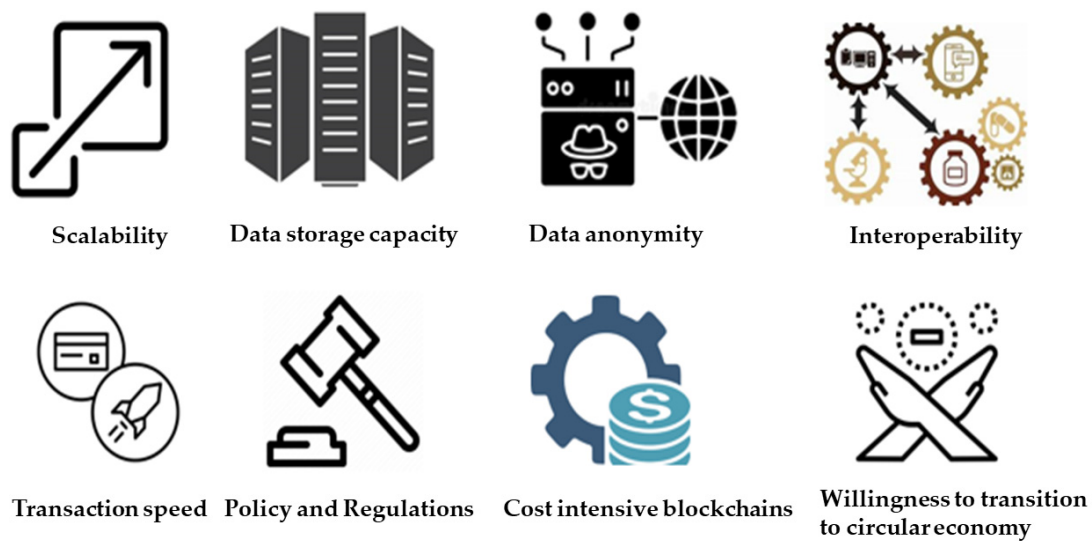


Figure 3. Blockchainification of CE: Challenges with circular economy blockchain.

5.2.1. Scalability, Data Storage Capacity, and Management Challenges

In the circular economy blockchain, the involved stakeholders in the network would be large in number. The transaction handling capacity of the blockchain is mostly varied depending on the chosen blockchain platform and the involved number of CE stakeholders. As the number increases, there are chances of slowing down the rate of transactions happening [97]. Considering the two popular public blockchain platforms: Bitcoin and Ethereum, where the transaction time is very slow, and in public blockchains, the transaction approval charges may go high as the involved stakeholders are high. Whereas in the private or federated blockchains, it is not the case; however, the question of scalability is still debatable [97]. Another critical concern is the data storage capacity and management; generally, the blockchain has very minimal capacity for storing transactions [87]. However, most circular economy applications are integrated with sensor systems (for example, RFID and IoT devices in the supply chain and other industrial processes) where the continuous track of information is possible. It is stated that these sensor devices can generate more than gigabytes of data on average for a real-world application [87,98]. Blockchain in current situations may not be able to handle this storage capacity and continuous transaction approval unless a minimum number of stakeholders exist on the CE network with a private blockchain platform. Some have suggested using on-chain and off-chain data storage options, but still, the question of storage capacity is debatable and needs further research [99].

5.2.2. Data Privacy, Anonymity, and Security

Data privacy and protection are concerning for most stakeholders while using blockchain [100]. However, the blockchain's main feature is data privacy and identity management. Many stakeholders in the network worry due to the anonymity that is not guaranteed in the public blockchain platforms [98]. The concerns related to data privacy, anonymity, and security could be addressed, to some extent, in a private blockchain, and it is also suggested to handle data loads [101]. However, when it comes to the CE network, where the involvement of other devices may not ensure privacy and security, we never know whether the data before feeding onto the blockchain ledgers have been tampered with or not [102–104]. Data integrity techniques, public verification, and restricted access control are suggested to ensure privacy and security [105]. It is also quite easy to hack the IoT devices that are connected to the CEB network, especially the supply chain-related ones [102].

5.2.3. Consensus, Smart Contracts, and Platforms

In the context of circular economy applications where it involves numerous sensing devices, it is quite unsuitable for some of the consensus mechanisms and some practical

issues with the execution of smart contracts [98]. At present, there are many consensus mechanisms or protocols for blockchain. Among them, most of them seem to be immature, and some have not been tested in all aspects related to performance (say, for example, energy consumption, transaction approval rate, and security level). The majority of the existing consensus is on proof-of-work (PoW), which is the most energy-intensive. However, it is always advised for CE applications to opt for a private blockchain where the computational power would be less [87,98,100]. In the context of CEB, smart contracts have few challenges while modeling the logic of IoT or other sensing devices [98]. For example, the product performance assessment over its lifetime involves real-time data from multiple sources and accessing this data would overload the execution of smart contracts. On the other hand, implementing smart contracts mostly using the Oracle platform and leveraging smart contract capabilities with big data and cloud computing platforms would be difficult [98].

There are currently many blockchain platforms, and it is quite challenging to investigate their performance specific to the CE applications. Only a few platforms have smart contracts and token development features. In the context of CEB, data analytics, payment options, and integration with IoT devices are essential, and these features are not possible in all blockchain platforms. Furthermore, in CEB, stakeholders need additional functionalities related to command line control for interaction, which may not be possible in all the platforms. In the current market, many claim to have blockchain applicability, but there might be a difference in actual execution, which is the major challenge in choosing the right technology [98].

5.2.4. Cultural and Organizational Challenges

In the context of CEB, the cultural and organizational challenges hinder blockchain adoption. For example, suppose an organization wishes to transform into a blockchain-based CE. In that case, they need to embed this practice into its vision and mission [106]. Moreover, they should be ready to accept the alternation possible with blockchain adoption. However, organizations may not be ready to do so. When they are converting to a new system, organizational changes in terms of culture and individual hesitations may be seen as most common. Limited technical expertise in the new system and well-established knowledge and the market for the current system may not allow them to change to a new system [107]. Fear of market down and financial instability due to transition seems to be a challenge in adopting CEB. Regarding the cultural aspect, the CEB represents an entire digital shift and demands a considerable change in the way of handling work. This shift mostly changes the work culture and values and demands behavioral changes from both employees and customers.

In the context of CEB, some business model's execution involves the collaboration of two or more stakeholders, where the issues such as work culture, relationships, and information sharing issues as per the organization's policies and rules might limit CEB progress [108]. Lack of understanding of these cultural and organizational rules is a definite challenge, eventually affecting the entire CEB network. There is a lack of awareness related to this technology and how it works. This mainly hampers the investors and top management who plan to invest in developing CEBs.

5.2.5. Policy and Regulatory Challenges

Both of the discussed concepts, CE and Blockchain, are individually facing challenges related to policy and regulations. In the context of CEB, similar challenges that limit the practical implementation exist. Government laws and regulation are still unclear on the use of blockchain for various applications where concerns related to market and organization arises. Considering Bitcoin blockchain alone, it has faced many transaction-related issues due to adverse policies implemented by several regulatory and government groups [100,109]. Due to the lack of policies, the willingness to direct and support the CEB implementation will be limited [110]. Thus, governments need to ensure that the policies and regulations they frame promote technological growth more sustainably.

5.2.6. Financial Challenges

Blockchain technology combines software and hardware infrastructure where implementation is not relatively straightforward and involves financial decisions [100]. Considering the CEB situation, this would be further difficult due to the network size and information storage capabilities. At present, there is considerable uncertainty in the market about blockchain technology service offerings. The reasons might be the hype in technology, business competition, or the exploitation of the situation. On the other side, there is a fee collected for transaction processing in the blockchain network, and it depends upon the speed and effectiveness of the blockchain platform. Generally, the most effective and high-speed transactions would cost more transaction processing fees.

5.2.7. Lack of Skilled Workforce

As the blockchain is still in its early stages, concerns related to the skilled workforce and the financing of such training facilities may exist. In the context of CEB, both the concepts (CE and Blockchain) are in the initial stages of development. The knowledge of implementing CE networks more efficiently is itself questionable. Conversely, using blockchain technology in CE needs additional knowledge and technical expertise [87]. Although there is a growing interest in CE adoption and blockchain technology, only a limited number of skilled forces exist [100].

6. Conclusions

This perspective aimed to shed light on the current state and the future research needs for the successful adoption of blockchain and smart contract technologies to enable a digital circular economy. The literature initially called for the integration of ICT to solve the challenges of CE implementation. However, the failure of conventional ICT-based solutions has seen an emergence of literature that is now calling for the exploration of blockchain for CE. In this perspective, we thoroughly investigated the blockchain and smart contract technology and how they offer solutions to CE challenges both with and without ICT. Blockchains have credibility, ensuring the information exchange in a transparent, secure manner, and the traceability feature can significantly benefit the CE implementation and its digital transition. Based on this, we developed the CEB architecture that allows for stakeholders' interactions and data-driven decision-making across the CE network. Blockchain-enabled data-driven tools may enable CE business models that improve trust and transparency in supply-chain networks, shared and performance economy platforms, stakeholder participation, and governance and management of organizations. However, considerable challenges exist when it comes to the implementation of blockchain for CBMS, as noted in the complexities of *blockchainification* of non-digital assets. Although researchers and blockchain venture developers will continue to proclaim that digital technologies will address CE-associated challenges, this perspective may serve as a cautionary note. It presents numerous research challenges for those who think the current hype of blockchain implication in CE may automatically translate into CE implementation accomplishments. To set a path for further research and potential exploratory studies on this topic, we provided some challenges and future research propositions. We feel that this review would help build the literature around the digital circular economy and the proposed circular economy blockchain.

Author Contributions: Conceptualization, N.M.K.; methodology, N.M.K.; validation, N.M.K. and S.S.C.; formal analysis, N.M.K.; investigation, N.M.K.; resources, S.S.C.; writing—original draft preparation, N.M.K.; writing—review and editing, N.M.K. and S.S.C.; visualization, N.M.K.; supervision, S.S.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

References

- Kirchherr, J.; Reike, D.; Hekkert, M. Conceptualizing the circular economy: An analysis of 114 definitions. *Resour. Conserv. Recycl.* **2017**, *127*, 221–232. [[CrossRef](#)]
- Bocken, N.M.P.; Olivetti, E.A.; Cullen, J.M.; Potting, J.; Lifset, R. Taking the Circularity to the Next Level: A Special Issue on the Circular Economy. *J. Ind. Ecol.* **2017**, *21*, 476–482. [[CrossRef](#)]
- Jacobi, N.; Haas, W.; Wiedenhofer, D.; Mayer, A. Providing an economy-wide monitoring framework for the circular economy in Austria: Status quo and challenges. *Resour. Conserv. Recycl.* **2018**, *137*, 156–166. [[CrossRef](#)]
- MacArthur, E. Circular Economy Overview. 2013. Available online: <https://www.ellenmacarthurfoundation.org/circular-economy/concept> (accessed on 24 December 2018).
- European Commission. (Ed.) *Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions A Roadmap for Moving to a Competitive Low Carbon Economy in 2050*; European Commission: Brussels, Belgium, 2011.
- European Commission. (Ed.) *Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. Accelerating Europe's Transition to a Low-Carbon Economy*; European Commission: Brussels, Belgium, 2016.
- European Commission. (Ed.) *Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. Closing the Loop—An EU Action Plan for the Circular Economy*; European Commission: Brussels, Belgium, 2015.
- de Oliveira, F.R.; França, S.L.B.; Rangel, L.A.D. Challenges and opportunities in a circular economy for a local productive arrangement of furniture in Brazil. *Resour. Conserv. Recycl.* **2018**, *135*, 202–209. [[CrossRef](#)]
- Mathews, J.A.; Tan, H. Circular economy: Lessons from China. *Nature* **2016**, *531*, 440–442. [[CrossRef](#)] [[PubMed](#)]
- Ohnishi, S.; Fujii, M.; Fujita, T.; Matsumoto, T.; Dong, L.; Akiyama, H.; Dong, H. Comparative analysis of recycling industry development in Japan following the Eco-Town program for eco-industrial development. *J. Clean. Prod.* **2016**, *114*, 95–102. [[CrossRef](#)]
- McDowall, W.; Geng, Y.-J.; Huang, B.; Barteková, E.; Bleischwitz, R.; Türkeli, S.; Kemp, R.; Doménech, T. Circular Economy Policies in China and Europe. *J. Ind. Ecol.* **2017**, *21*, 651–661. [[CrossRef](#)]
- Gregson, N.; Crang, M.; Fuller, S.; Holmes, H. Interrogating the circular economy: The moral economy of resource recovery in the EU. *Econ. Soc.* **2015**, *44*, 218–243. [[CrossRef](#)]
- Mathews, J.A.; Tan, H. Progress toward a circular economy in China: The drivers (and inhibitors) of eco-industrial initiative. *J. Ind. Ecol.* **2011**, *15*, 435–457. [[CrossRef](#)]
- Schulze, G. Growth Within: A Circular Economy Vision for a Competitive Europe. Ellen MacArthur Foundation and the McKinsey Center for Business and Environment. 2016, pp. 1–22. Available online: <https://www.mckinsey.com/business-functions/sustainability/our-insights/growth-within-a-circular-economy-vision-for-a-competitive-europe> (accessed on 24 December 2018).
- European Commission. *Study on Modelling of the Economic and Environmental Impacts of Raw Material Consumption*; European Commission: Brussels, Belgium, 2014.
- Kirchherr, J.; Piscicelli, L.; Bour, R.; Kostense-Smit, E.; Muller, J.; Huibrechtse-Truijens, A.; Hekkert, M. Barriers to the Circular Economy: Evidence From the European Union (EU). *Ecol. Econ.* **2018**, *150*, 264–272. [[CrossRef](#)]
- Wijkman, A.; Skanberg, K. *The Circular Economy and Benefits for Society—Swedish Case Study Shows Jobs and Climate as Clear Winners*; An interim report by the Club of Rome with support from the MAVA Foundation and the Swedish Association of Recycling Industries; Club of Rome: Canton Zurich, Switzerland, 2015.
- De Vries, B.J.; Petersen, A.C. Conceptualizing sustainable development: An assessment methodology connecting values, knowledge, worldviews and scenarios. *Ecol. Econ.* **2009**, *68*, 1006–1019. [[CrossRef](#)]
- Gladek, E. The Seven Pillars of the Circular Economy. 2017. Available online: <http://www.metabolic.nl/the-seven-pillars-of-the-circular-economy/> (accessed on 24 December 2018).
- Potting, J.; Hekkert, M.P.; Worrell, E.; Hanemaaijer, A. *Circular Economy: Measuring Innovation in the Product Chain*; PBL: The Hague, The Netherlands, 2017.
- Blomsma, F.; Brennan, G. The Emergence of Circular Economy: A New Framing Around Prolonging Resource Productivity. *J. Ind. Ecol.* **2017**, *21*, 603–614. [[CrossRef](#)]
- Lacy, P.; Rutqvistand, J. *Waste to Wealth: The Circular Economy Advantage*; Springer: Berlin/Heidelberg, Germany, 2016.
- de Jesus, A.; Mendonça, S. Lost in Transition? Drivers and Barriers in the Eco-innovation Road to the Circular Economy. *Ecol. Econ.* **2018**, *145*, 75–89. [[CrossRef](#)]
- Geng, Y.; Haight, M.; Zhu, Q. Empirical analysis of eco-industrial development in China. *Sustain. Dev.* **2007**, *15*, 121–133. [[CrossRef](#)]
- Geng, Y.; Doberstein, B. Developing the circular economy in China: Challenges and opportunities for achieving 'leapfrog development'. *Int. J. Sustain. Dev. World Ecol.* **2008**, *15*, 231–239. [[CrossRef](#)]
- Ormazabal, M.; Prieto-Sandoval, V.; Puga-Leal, R.; Jaca, C. Circular Economy in Spanish SMEs: Challenges and opportunities. *J. Clean. Prod.* **2018**, *185*, 157–167. [[CrossRef](#)]

27. Lacy, P. Using Digital Tech to Spin the Circular Economy. 2015, p. 105. Available online: <https://www.smart-circle.org/circulareconomy/circulaire-economie/using-digital-tech-spin-circular-economy/> (accessed on 24 December 2018).
28. Ellen MacArthur Foundation. *Intelligent Assets: Unlocking the Circular Economy Potential*; Ellen MacArthur Foundation: Cowes, UK, 2016; pp. 1–39.
29. Maria Antikainen, T.U. Digitalization Accelerates the Circular Economy. 2018. Available online: <https://vttblog.com/2018/06/27/digitalisation-accelerates-the-circular-economy/> (accessed on 3 January 2019).
30. Nallapaneni, M.K.; Chopra, S.S. Sustainability and Resilience of Circular Economy Business Models Based on Digital Ledger Technologies. In Proceedings of the Nature Conference on Waste Management and Valorisation for a Sustainable Future, Seoul, Korea, 26–28 October 2021.
31. Ruan, P.; Dinh, T.T.A.; Lohin, D.; Zhang, M.; Chen, G.; Lin, Q.; Ooi, B.C. Blockchains vs. Distributed Databases: Dichotomy and Fusion. In Proceedings of the 2021 International Conference on Management of Data, Virtual, China, 20–25 June 2021; pp. 1504–1517.
32. Mont, O.; Dalhammar, C.; Jacobsson, N. A new business model for baby prams based on leasing and product remanufacturing. *J. Clean. Prod.* **2006**, *14*, 1509–1518. [[CrossRef](#)]
33. Besch, K. Product-service systems for office furniture: Barriers and opportunities on the European market. *J. Clean. Prod.* **2005**, *13*, 1083–1094. [[CrossRef](#)]
34. Pearce, J.A. The profit-making allure of product reconstruction. *MIT Sloan Manag. Rev.* **2009**, *50*, 59.
35. Sundin, E.; Lindahl, M.; Ijomah, W. Product design for product/service systems: Design experiences from Swedish industry. *J. Manuf. Technol. Manag.* **2009**, *20*, 723–753. [[CrossRef](#)]
36. Berchicci, L.; Bodewes, W. Bridging environmental issues with new product development. *Bus. Strat. Environ.* **2005**, *14*, 272–285. [[CrossRef](#)]
37. Kuo, T.C.; Ma, H.-Y.; Huang, S.H.; Hu, A.H.; Huang, C.S. Barrier analysis for product service system using interpretive structural model. *Int. J. Adv. Manuf. Technol.* **2009**, *49*, 407–417. [[CrossRef](#)]
38. Seitz, M.A. A critical assessment of motives for product recovery: The case of engine remanufacturing. *J. Clean. Prod.* **2007**, *15*, 1147–1157. [[CrossRef](#)]
39. Östlin, J.; Sundin, E.; Björkman, M. Importance of closed-loop supply chain relationships for product remanufacturing. *Int. J. Prod. Econ.* **2008**, *115*, 336–348. [[CrossRef](#)]
40. Östlin, J.; Sundin, E.; Björkman, M. Product life-cycle implications for remanufacturing strategies. *J. Clean. Prod.* **2009**, *17*, 999–1009. [[CrossRef](#)]
41. King, A.M.; Burgess, S.C.; Ijomah, W.L.; McMahon, C.A. Reducing waste: Repair, recondition, remanufacture or recycle? *Sustain. Dev.* **2006**, *14*, 257–267. [[CrossRef](#)]
42. Guiltinan, J. Creative Destruction and Destructive Creations: Environmental Ethics and Planned Obsolescence. *J. Bus. Ethic.* **2009**, *89*, 19–28. [[CrossRef](#)]
43. Michaud, C.; Llerena, D. Green consumer behaviour: An experimental analysis of willingness to pay for remanufactured products. *Bus. Strat. Environ.* **2010**, *20*, 408–420. [[CrossRef](#)]
44. Linder, M.; Williander, M. Circular Business Model Innovation: Inherent Uncertainties. *Bus. Strat. Environ.* **2017**, *26*, 182–196. [[CrossRef](#)]
45. Preston, F. *A Global Redesign? Shaping the Circular Economy*; Chatham House London: London, UK, 2012.
46. Bicket, M.; Guilcher, S.; Hestin, M.; Hudson, C.; Razzini, P.; Tan, A.; ten Brink, P.; van Dijl, E.; Vanner, R.; Watkins, E. *Scoping Study to Identify Potential Circular Economy Actions, Priority Sectors, Material Flows and Value Chains*; Luxembourg Publications Office of the European Union: Luxembourg, 2014.
47. Van Eijk, F. Barriers & Drivers Towards a Circular Economy. Acceleratio BV. 2015. Available online: www.circulairondernemen.nl/uploads/e00e8643951aef8adde612123e824493.pdf (accessed on 24 December 2018).
48. Rizos, V.; Behrens, A.; Kafyeke, T.; Hirschnitz-Garbers, M.; Ioannou, A. The Circular Economy: Barriers and Opportunities for SMEs. CEPS Working Documents. 2015. Available online: <https://ssrn.com/abstract=2664489> (accessed on 24 December 2018).
49. Ormazabal, M.; Prieto-Sandoval, V.; Jaca, C.; Santos, J. An overview of the circular economy among SMEs in the Basque country: A multiple case study. *J. Ind. Eng. Manag.* **2016**, *9*, 1047–1058. [[CrossRef](#)]
50. Ritzén, S.; Sandström, G. Barriers to the Circular Economy—Integration of Perspectives and Domains. *Procedia CIRP* **2017**, *64*, 7–12. [[CrossRef](#)]
51. Rizos, V.; Behrens, A.; Van Der Gaast, W.; Hofman, E.; Ioannou, A.; Kafyeke, T.; Flamos, A.; Rinaldi, R.; Papadelis, S.; Hirschnitz-Garbers, M.; et al. Implementation of Circular Economy Business Models by Small and Medium-Sized Enterprises (SMEs): Barriers and Enablers. *Sustainability* **2016**, *8*, 1212. [[CrossRef](#)]
52. Van Renswoude, K.; ten Wolde, A.; Joustra, D.J. *Circular Business Models—Part 1: An introduction to IMSA’s Circular Business Model Scan*; IMSA: Amsterdam, The Netherlands, 2015.
53. Amsterdam, I. *Unleashing the Power of the Circular Economy*; IMSA: Amsterdam, The Netherlands, 2013.
54. Mont, O.; Plepys, A.; Whalen, K.; Nußholz, J.L.K. *Business Model Innovation for a Circular Economy: Drivers and Barriers for the Swedish Industry—The Voice of REES Companies*; Mistra REES: Lund, Sweden, 2017. Available online: https://lucris.lub.lu.se/ws/portalfiles/portal/33914256/MISTRA_REES_Drivers_and_Barriers_Lund.pdf (accessed on 24 December 2018).

55. Korhonen, J.; Honkasalo, A.; Seppälä, J. Circular Economy: The Concept and its Limitations. *Ecol. Econ.* **2018**, *143*, 37–46. [[CrossRef](#)]
56. Reuter, M.A.; Matuszewicz, R.; van Schaik, A. Lead, Zinc and their minor elements: Enablers of a circular economy. *World Met.-Erzmetall* **2015**, *68*, 132–146.
57. Shuva, M.A.H.; Rhamdhani, M.A.; Brooks, G.A.; Masood, S.H.; Reuter, M.A. Thermodynamics data of valuable elements relevant to e-waste processing through primary and secondary copper production: A review. *J. Clean. Prod.* **2016**, *131*, 795–809. [[CrossRef](#)]
58. van Schalkwyk, R.; Reuter, M.; Gutzmer, J.; Stelter, M. Challenges of digitalizing the circular economy: Assessment of the state-of-the-art of metallurgical carrier metal platform for lead and its associated technology elements. *J. Clean. Prod.* **2018**, *186*, 585–601. [[CrossRef](#)]
59. Shi, J.; Zhou, J.; Zhu, Q. Barriers of a closed-loop cartridge remanufacturing supply chain for urban waste recovery governance in China. *J. Clean. Prod.* **2018**, *212*, 1544–1553. [[CrossRef](#)]
60. Pheifer, A.G. Barriers & Enablers to Circular Business Models. White Paper. *ValueC, Brielle*. 2017. Available online: <https://www.scribd.com/document/502885354/Barriers-and-Enablers-to-Circular-Business-Models#> (accessed on 9 January 2019).
61. Pagoropoulos, A.; Pigosso, D.C.; McAloone, T.C. The Emergent Role of Digital Technologies in the Circular Economy: A Review. *Procedia CIRP* **2017**, *64*, 19–24. [[CrossRef](#)]
62. Antikainen, M.; Uusitalo, T.; Kivikytö-Reponen, P. Digitalisation as an Enabler of Circular Economy. *Procedia CIRP* **2018**, *73*, 45–49. [[CrossRef](#)]
63. Townsend, J. ICT for Sustainability Beyond Efficiency: Pushing Cleantech and the Circular Economy. In ICT4S. 2018. Available online: <https://www.easychair.org/publications/download/L74j> (accessed on 9 January 2019).
64. European Policy Centre (EPC). Digital Roadmap for a Circular Economy. Sustainable Prosperity for Europe. Available online: https://www.epc.eu/prog_forum.php?forum_id=77&prog_id=2 (accessed on 9 January 2019).
65. Deloitte. Circular Goes Digital. 2018, pp. 1–2. Available online: <https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&ved=2ahUKEwjWh9695pr5AhWGEKYKHZmDCm4QFnoECBgQAQ&url=https%3A%2F%2Fwww2.deloitte.com%2Fcontent%2Fdam%2FDeloitte%2Ffi%2FDocuments%2Ffrisk%2FCircular%2520goes%2520digital.pdf&usq=AOvVaw3mLQ10u27FTtcP5HMkhEwF> (accessed on 9 January 2019).
66. Pardo, R. How the Circular Economy can benefit from the Digital Revolution. *EPC Commentary*, 11 April 2018.
67. Jaoude, J.A.; Saade, R.G. Blockchain Applications—Usage in Different Domains. *IEEE Access* **2019**, *7*, 45360–45381. [[CrossRef](#)]
68. Makhdoom, I.; Abolhasan, M.; Abbas, H.; Ni, W. Blockchain’s adoption in IoT: The challenges, and a way forward. *J. Netw. Comput. Appl.* **2018**, *125*, 251–279. [[CrossRef](#)]
69. Christidis, K.; Devetsikiotis, M. Blockchains and Smart Contracts for the Internet of Things. *IEEE Access* **2016**, *4*, 2292–2303. [[CrossRef](#)]
70. Ruan, P.; Chen, G.; Dinh, T.T.A.; Lin, Q.; Ooi, B.C.; Zhang, M. Fine-grained, secure and efficient data provenance on blockchain systems. *Proc. VLDB Endow.* **2019**, *12*, 975–988. [[CrossRef](#)]
71. Li, J.; Peng, Z.; Gao, S.; Xiao, B.; Chan, H. Smartphone-assisted energy efficient data communication for wearable devices. *Comput. Commun.* **2017**, *105*, 33–43. [[CrossRef](#)]
72. Gao, S.; Peng, Z.; Xiao, B.; Xiao, Q.; Song, Y. SCoP: Smartphone energy saving by merging push services in Fog computing. In Proceedings of the 2017 IEEE/ACM 25th International Symposium on Quality of Service (IWQoS), Vilanova i la Geltrú, Spain, 14–16 June 2017; pp. 1–10.
73. Luu, L.; Chu, D.-H.; Olickel, H.; Saxena, P.; Hobor, A. Making smart contracts smarter. In Proceedings of the 2016 ACM SIGSAC Conference on Computer and Communications Security, Vienna, Austria, 24–28 October 2016.
74. Narayanan, A.; Bonneau, J. *Bitcoin and Cryptocurrency Technologies: A Comprehensive Introduction*; Princeton University Press: Princeton, NJ, USA, 2016.
75. Ølnes, S.; Ubacht, J.; Janssen, M. Blockchain in government: Benefits and implications of distributed ledger technology for information sharing. *Gov. Inf. Q.* **2017**, *34*, 355–364. [[CrossRef](#)]
76. Buterin, V. On Public and Private Blockchains. Ethereum Blog. Posted on 7 August 2015. Available online: <https://blog.ethereum.org/2015/08/07/on-public-and-private-blockchains/> (accessed on 10 January 2019).
77. Zheng, Z.; Xie, S.; Dai, S.-N.; Chen, X. Blockchain challenges and opportunities: A survey. *Int. J. Web Grid Serv.* **2018**, *14*, 352–375. [[CrossRef](#)]
78. Nakamoto, S. Bitcoin: A Peer-to-Peer Electronic Cash System. 2008. Available online: https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3440802 (accessed on 10 January 2019).
79. Haferkorn, M.; Diaz, J.M.Q. Seasonality and interconnectivity within cryptocurrencies—an analysis on the basis of Bitcoin, Litecoin and Namecoin. In *International Workshop on Enterprise Applications and Services in the Finance Industry*; Springer: Berlin/Heidelberg, Germany, 2014.
80. Casino, F.; Dasaklis, T.K.; Patsakis, C. A systematic literature review of blockchain-based applications: Current status, classification and open issues. *Telematics Informatics* **2018**, *36*, 55–81. [[CrossRef](#)]
81. Vukolić, M. The quest for scalable blockchain fabric: Proof-of-work vs. BFT replication. In *International Workshop on Open Problems in Network Security*; Springer: Berlin/Heidelberg, Germany, 2015.
82. Kiayias, A.; Russell, A.; David, B.; Oliynykov, R. Ouroboros: A Provably Secure Proof-of-Stake Blockchain Protocol. *IACR Cryptology ePrint Archive*. 2016, pp. 1–67. Available online: <https://eprint.iacr.org/2016/889.pdf> (accessed on 28 September 2019).

83. Castro, M.; Liskov, B. Practical byzantine fault tolerance and proactive recovery. *ACM Trans. Comput. Syst.* **2002**, *20*, 398–461. [[CrossRef](#)]
84. Huang, B.; Zhao, J.; Chai, J.; Xue, B.; Zhao, F.; Wang, X. Environmental influence assessment of China's multi-crystalline silicon (multi-Si) photovoltaic modules considering recycling process. *Sol. Energy* **2017**, *143*, 132–141. [[CrossRef](#)]
85. Kouhizadeh, M.; Sarkis, J.; Zhu, Q. At the Nexus of Blockchain Technology, the Circular Economy, and Product Deletion. *Appl. Sci.* **2019**, *9*, 1712. [[CrossRef](#)]
86. Manupati, V.; Schoenherr, T.; Ramkumar, M.; Panigrahi, S.; Sharma, Y.; Mishra, P. Recovery strategies for a disrupted supply chain network: Leveraging blockchain technology in pre- and post-disruption scenarios. *Int. J. Prod. Econ.* **2021**, *245*, 108389. [[CrossRef](#)]
87. Swan, M. *Blockchain: Blueprint for a New Economy*; O'Reilly Media, Inc.: Sebastopol, CA, USA, 2015.
88. Cartier, L.E.; Ali, S.H.; Krzemnicki, M.S. Blockchain, Chain of Custody and Trace Elements: An Overview of Tracking and Traceability Opportunities in the Gem Industry. *J. Gemmol.* **2018**, *36*, 212–227. [[CrossRef](#)]
89. Raj, P.V.R.P.; Jauhar, S.K.; Ramkumar, M.; Pratap, S. Procurement, traceability and advance cash credit payment transactions in supply chain using blockchain smart contracts. *Comput. Ind. Eng.* **2022**, *167*, 108038. [[CrossRef](#)]
90. Kuo, T.-T.; Ohno-Machado, L. Modelchain: Decentralized privacy-preserving healthcare predictive modeling framework on private blockchain networks. *arXiv* **2018**, arXiv:1802.01746.
91. Huckle, S.; Bhattacharya, R.; White, M.; Beloff, N. Internet of Things, Blockchain and Shared Economy Applications. *Procedia Comput. Sci.* **2016**, *98*, 461–466. [[CrossRef](#)]
92. Pazaitis, A.; De Filippi, P.; Kostakis, V. Blockchain and value systems in the sharing economy: The illustrative case of Backfeed. *Technol. Forecast. Soc. Chang.* **2017**, *125*, 105–115. [[CrossRef](#)]
93. Wu, H.; Peng, Z.; Guo, S.; Yang, Y.; Xiao, B. VQL: Efficient and Verifiable Cloud Query Services for Blockchain Systems. *IEEE Trans. Parallel Distrib. Syst.* **2021**, *33*, 1393–1406. [[CrossRef](#)]
94. Isaja, M.; Soldatos, J.K. Distributed Ledger Architecture for Automation, Analytics and Simulation in Industrial Environments. *IFAC-PapersOnLine* **2018**, *51*, 370–375. [[CrossRef](#)]
95. Angrish, A.; Craver, B.; Hasan, M.; Starly, B. A Case Study for Blockchain in Manufacturing: “FabRec”: A Prototype for Peer-to-Peer Network of Manufacturing Nodes. *Procedia Manuf.* **2018**, *26*, 1180–1192. [[CrossRef](#)]
96. Zhu, Q.; Kouhizadeh, M. Blockchain Technology, Supply Chain Information, and Strategic Product Deletion Management. *IEEE Eng. Manag. Rev.* **2019**, *47*, 36–44. [[CrossRef](#)]
97. Yli-Huumo, J.; Ko, D.; Choi, S.; Park, S.; Smolander, K. Where Is Current Research on Blockchain Technology?—A Systematic Review. *PLoS ONE* **2016**, *11*, e0163477. [[CrossRef](#)] [[PubMed](#)]
98. Reyna, A.; Martín, C.; Chen, J.; Soler, E.; Díaz, M. On blockchain and its integration with IoT. Challenges and opportunities. *Futur. Gener. Comput. Syst.* **2018**, *88*, 173–190. [[CrossRef](#)]
99. Eberhardt, J.; Tai, S. On or off the blockchain? Insights on off-chaining computation and data. In Proceedings of the European Conference on Service-Oriented and Cloud Computing, Oslo, Norway, 27–29 September 2017; Springer: Berlin/Heidelberg, Germany, 2017.
100. Mougayar, W. *The Business Blockchain: Promise, Practice, and Application of the Next Internet Technology*; John Wiley & Sons: Hoboken, NJ, USA, 2016.
101. Pongnumkul, S.; Siripanpornchana, C.; Thajchayapong, S. Performance analysis of private blockchain platforms in varying workloads. In Proceedings of the 2017 26th International Conference on Computer Communication and Networks (ICCCN), Vancouver, BC, Canada, 31 July–3 August 2017.
102. Lopez, J.; Rios, R.; Bao, F.; Wang, G. Evolving privacy: From sensors to the Internet of Things. *Futur. Gener. Comput. Syst.* **2017**, *75*, 46–57. [[CrossRef](#)]
103. Roman, R.; Zhou, J.; Lopez, J. On the features and challenges of security and privacy in distributed internet of things. *Comput. Networks* **2013**, *57*, 2266–2279. [[CrossRef](#)]
104. Li, Z.; Gao, S.; Peng, Z.; Guo, S.; Yang, Y.; Xiao, B. B-DNS: A Secure and Efficient DNS Based on the Blockchain Technology. *IEEE Trans. Netw. Sci. Eng.* **2021**, *8*, 1674–1686. [[CrossRef](#)]
105. Liu, C.; Yang, C.; Zhang, X.; Chen, J. External integrity verification for outsourced big data in cloud and IoT: A big picture. *Futur. Gener. Comput. Syst.* **2015**, *49*, 58–67. [[CrossRef](#)]
106. Mathiyazhagan, K.; Govindan, K.; NoorulHaq, A.; Geng, Y. An ISM approach for the barrier analysis in implementing green supply chain management. *J. Clean. Prod.* **2013**, *47*, 283–297. [[CrossRef](#)]
107. Jharkharia, S.; Shankar, R. IT-enablement of supply chains: Understanding the barriers. *J. Enterp. Inf. Manag.* **2005**, *18*, 11–27. [[CrossRef](#)]
108. Gorane, S.; Kant, R. Modelling the SCM implementation barriers: An integrated ISM-fuzzy MICMAC approach. *J. Model. Manag.* **2015**, *10*, 158–178. [[CrossRef](#)]
109. Kiviat, T.I. Beyond bitcoin: Issues in regulating blockchain transactions. *Duke Law J.* **2015**, *65*, 569–608.
110. Mangla, S.K.; Luthra, S.; Mishra, N.; Singh, A.; Rana, N.P.; Dora, M.; Dwivedi, Y. Barriers to effective circular supply chain management in a developing country context. *Prod. Plan. Control* **2018**, *29*, 551–569. [[CrossRef](#)]