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Barriers to Blockchain Adoption in the Circular Economy: A Fuzzy Delphi and Best-Worst Approach

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Abstract: Blockchain can help to fundamentally alter aspects of circular economy (CE) activities and overcome pressing sustainability issues. Nevertheless, limited studies have investigated the barriers to blockchain adoption in the CE. This study aims to close the knowledge gap by providing a comprehensive review of the barriers hampering the adoption and integration of blockchain technology in the CE. An integrated approach based on fuzzy Delphi and best-worst methods has been applied to analyze and rank the barriers. Sixteen barriers to blockchain adoption in the CE were identified from the academic literature and validated by a panel of experts. The findings from the fuzzy Delphi technique identified ten significant barriers for further analysis. Then, using the best-worst method, the optimal weights were determined based on the experts' judgment to recognize the importance of each barrier. The findings from this method showed that a lack of knowledge and management support, reluctance to change and technological immaturity are the most significant barriers. In contrast, the least significant barriers are investment costs, security risks, and scalability issues. Theoretically, this study is the first to apply an integrated approach combining fuzzy Delphi and best-worst techniques to prioritze the barriers to blockchain adoption in the CE. It also provides valuable insights for managers and decision-makers that can be used to optimize blockchain implementations in the CE.

Keywords: blockchain; circular economy; barriers; technology; sustainability; best-worst method; fuzzy Delphi

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1. Introduction

The exponential growth of the world population and the increasing pace of economic activities have led to unsustainable resource use, socioeconomic disparities, and environmental degradation [1,2]. The finiteness of resources has raised calls for enhancing the productivity of resource consumption to achieve sustainability [3]. For firms, it is critical to realize that the endless consumption of resources to create value is no longer conceivable, and linear business models necessitate rethinking [4,5].

Amid the calls for mitigation of climate change risks from various stakeholders, the circular economy (CE) has been introduced as an alternative to the linear economy in order to "keep resources in a loop as much time as possible, try to maintain their value while in use, and repurpose for generation of new products at the end of utilization" [6]. Firms are currently considering the CE as an approach to integrate sustainability into economic activities [7]. The CE aims to achieve sustainable production and consumption by decoupling economic growth from resource consumption and waste accumulation [8]. As an umbrella notion [9], the CE originates from different schools of thought, including industrial symbiosis, industrial ecology, blue economy, cradle-to-cradle, product-service systems, and biomimicry [10]. From a manufacturing and supply chain perspective, the CE could be used to substitute the end of life (EoL) approach with strategies such as reuse, remanufacturing, and recycling by reconfiguring business models, supply chains, and offerings [11].

Given that the transition towards the CE requires reconsidering and redesigning current business models and practices, firms can rely on new technologies to leverage this move through collecting, analyzing, and integrating CE-related data [12]. Digitalization can facilitate CE implementation through the adoption of Industry 4.0 technologies, such as cyber-physical systems, the internet of things (IoT), cloud computing, big data analytics, and virtual and augmented reality [13,14]. As a key enabler for the CE, blockchain technology has the potential to support the CE transition in many ways. For instance, blockchain supports CE activities by promoting information reliability, transparency, and automation. Examples of information available on blockchain include the sources of raw materials, parts, products, CE stakeholders, processes, and resource use. A blockchain system combined with tracking technologies such as global positioning systems (GPS) can enable the traceability of materials and products throughout their lifespan. These prospective blockchain capabilities can pave the way to reusability, recycling, upcycling initiatives, and CE performance management.

Conceptually, blockchain represents a distributed digital ledger in which transactions between diverse participants can be recorded, stored, and updated concurrently and in real time [15,16]. A blockchain is structured to ensure that these transactions can be validated in a trustworthy manner, and the records are immutable [17]. As a peer-to-peer system, blockchain helps to avoid the power asymmetry that centralized authorities hold over business transactions due to their role in maintaining and accessing transaction records. As a result, the technology supports the coordination of transactions, stakeholder involvement, and machine operations, which is a vital characteristic and aim of Industry 4.0. Furthermore, adopting Industry 4.0 technologies implies interconnectivity and communication between digital and physical objects such as smart devices (e.g., smartphones), electronics, and transportation systems [18]. In this regard, blockchain can support and deliver security to Industry 4.0 applications. The technology can also increase the automation of transactions and processes in a verifiable and permanent way [15], saving resources and time and minimizing waste and operational inefficiencies.

Despite blockchain's transformative potential for the CE, several barriers to adoption remain. For instance, [19] argued that blockchain technology is still in its infancy and suffers from a number of limitations, including scalability, security, privacy, and energy consumption. As a result, these barriers must be removed entirely to ensure the technology's effective integration into the CE. It is critical to understand the potential barriers to blockchain adoption in the CE and how they would interact. The majority of scholarly research in the blockchain field lacks a systematic discussion of the technology's applications in business and management-related topics, including the CE [20]. To facilitate blockchain adoption within the CE, it is essential to first identify and then to prioritize the barriers. To the best of the authors' knowledge, there is a dearth of research examining the barriers to blockchain adoption in the CE and assisting decision-makers in modeling the causal relationships between these barriers and their weighted contributions to blockchain adoption. This new technology is critical for the CE because it has the potential to significantly accelerate the CE transition. Academic research on the subject is even more necessary in light of the fragmented knowledge on blockchain in the CE context. Given the concept's novelty in academic research, we hope to contribute to the CE literature by identifying the most significant impediments to developing blockchain-enabled CE business models. In a nutshell, we sought to address the following research questions:

- What are the barriers to blockchain adoption in the CE?
- Among barriers, what are the most important ones that require immediate attention from CE managers and experts?

This study was motivated by several considerations: first, the urgent need to optimize resource use and understand the potential of technological enablers in the CE; second, the emergence of blockchain technology as a promising paradigm to accelerate the CE transition; and, third, to extend understanding of the main forces that affect blockchain adoption in the CE.

The remainder of this article is structured as follows. Section 2 provides the theoretical background of blockchain technology and its potential for the CE. Section 3 reviews the barriers to blockchain in the CE based on existing academic works. Section 4 describes the research methodology used and operates our proposed research framework. Section 5 discloses the outcomes from the used framework. Section 6 discusses the findings briefly and concludes the paper by highlighting the research implications and limitations in Section 7.

2. The Theoretical Background

2.1. Blockchain Technology

Blockchain technology has risen to prominence as one of the most significant innovations of the modern era. In its simplest form, blockchain is a distributed ledger that facilitates data exchange on a peer-to-peer network [19]. Blockchain technology involves multiple participants, and the data exchange process is authenticated using cryptographic algorithms [21]. Blockchain technology is an extremely secure method of storing and maintaining records. Once a transaction has been created and validated by all parties involved, it becomes immutable and cannot be modified or resequenced [22]. Thus, blockchain is expected to disrupt traditional transactional methods, enabling a slew of new applications in a wide variety of potential fields [17,23]. Blockchain technology is based on a distributed [24] and decentralized database [25] that is open and publicly accessible, ensuring a high degree of integrity for business transactions that take place within the blockchain system [26]. As a digital database, blockchain can store any type of information, including records, transactions, and events, with specific procedures for information updates [27]. The blockchain is made up of blocks that are created continuously as new transactions are added to the network. The accumulation of blocks results in the formation of a chain linked to the first block ever generated using hashes [28]. The blockchain technology is a general-purpose technology that enables the control of currency exchanges via predefined rules or smart contracts that can be executed on a blockchain [26]. The use of blockchain technology eliminates the need for third-party facilitators or intermediaries to facilitate transactions and secure the ledger. Blockchain technology's transparent consensus algorithm ensures that only legitimate transactions are permitted within the system [29]. All transactions are visible to all system users [30]. As a result, blockchain technology prevents network participants from engaging in malicious or suspicious behaviors [31].

2.2. Potential of Blockchain for the CE Transition

Blockchain technology can accelerate the CE transition in a variety of ways. Internally, the adoption of blockchain in the CE can support business processes. For instance, large firms with fragmented and complex facilities can take advantage of a blockchain [32]. Utilizing blockchain, organizational processes and shop-floor operation monitoring can include materials, products, waste, and energy monitoring. Thus, the digitization of firm processes offers a foundation for green performance evaluation and management [20]. In the CE, processes consuming excessive resources and generating abundant wastes could be optimized or eliminated by blockchain implementation [33–35].

CE implementation requires strong collaborative relationships between supply chain partners, particularly in closed-loop operations such as reuse, recycling, remanufacturing, and recovering. In this regard, blockchain technology facilitates product recovery, increases transparency, and ensures product traceability throughout the supply chain. Blockchain technology is particularly advantageous for end-of-life operations, such as tracking and tracing raw materials and end products across circular supply chains [36]. Additionally, blockchain enables product reuse and sharing, as well as decentralized production and peer-to-peer circularity. The technology enables the mitigation of circular economy rebounds [37], which occur when overall production, resource use, and consequently environmental impacts increase [38].

A recent approach garnering substantial attention for driving the CE transition is the support of repair activities. Firms are compelled to share the blueprint of their products so consumers and other firms would be able to repair products and increase their durability. Information related to product repairability can be shared via blockchain technology. Similarly, the technology creates exciting opportunities for open innovation thanks to its ability to streamline knowledge sharing for CE activities. As an open innovation platform [39], blockchain integrates CE processes across firm boundaries and enables organizations to spur innovations into their activities. Furthermore, blockchain could leverage product deletion management by offering trustworthy and accurate information concerning shared resources, products, and services [40,41]. The greatest strength of blockchain is maintaining reliable and precise data regarding the quality, circularity potential and performance, and locations of products throughout their lifecycle. Therefore, this maximizes the opportunity to track and assess products' durability, performance, and reusability.

Beyond product recovery activities, the adoption of blockchain technology may result in an increase in product prices; this difference in price from the normal price is referred to as the circular premium [42]. Thus, incentives via blockchain can help promote circular business models, thereby increasing consumer acceptance of circular premiums [43].

Waste minimization boosts environmental performance. While wastes generated throughout the supply chain can be overcome [44], downstream supply chain waste is challenging to measure with traditional systems. Nevertheless, the introduction of blockchain can solve this concern by affording a platform to link all CE stakeholders, including customers [13]. The transparency and traceability of the technology can facilitate the tracking of product waste generated in the supply chain. Consumers can collaborate with manufacturers to identify the amounts of waste to be reduced and thus be awarded through tokenization for their sustainable behaviors [19]. This information improves and sustains waste management and reduction strategies. The use of smart contracts makes blockchain capable of storing conditions and terms of waste strategies and digitally initiating the necessary recovery plans. This capability can improve waste management among firms [45].

In the CE context, the lack of information throughout products' lifecycle constitutes a significant barrier to the effective implementation of CE principles [46]. As a result, the capabilities of blockchain to ensure reliable and accurate information sharing are beneficial for CE stakeholders to trace closed-loop supply chain operations. Blockchain participants can trace current transactions, identify the status of products, and exchange information efficiently. Blockchain also offers a common and secure platform for exchanging information and resources and managing trade procedures [17]. The technology further provides several opportunities for overcoming CE and sustainability issues. Blockchain enables CE stakeholders to share resources more efficiently. Suppliers can use the technology to share their unused resources via a peer-to-peer system without the necessity for trust among involved parties. Blockchain is designed to increase trust and eliminate intermediaries from the transactional process, thereby making transactions among CE stakeholders more efficient and flexible.

To make the sharing economy models attractive [43], blockchain can establish a market of firms that share their excess resources, leading to lower waste and better management of idle resources [19,47]. For example, firms can rely on blockchain to share their excess capacities in transportation and storage, which helps reduce environmental degradation and carbon emissions [48]. This approach stimulates the sharing economy and collaborative consumption [19], which are particularly pertinent to the development of circular supply chains and reduction of resource use [20]. Fueled by the trend towards using renewable energy resources, blockchain also facilitates decentralized energy management by supporting energy distribution, trade, and payment. Moreover, blockchain provides a clear idea of market dynamics and the impact of consumer energy resource preferences, sales volumes, and market shares on energy prices [49]. Efficient distribution and control of energy-related processes can be carried out through blockchain ledgers [50].

3. Literature Review of Barriers to Blockchain Adoption in the CE

Despite blockchain's enormous potential for the CE transition, several barriers continue to exist. We conducted a thorough literature review to ascertain the state of the literature on the barriers to blockchain adoption in the CE. The screening process for relevant literature was guided by the objective of identifying studies that examined blockchain applications in the context of CE. We searched multiple databases, including Scopus and Web of Science, for terms blockchain and the circular economy, as well as their variants, which include circularity, closed-loop, zero waste, industrial symbiosis, cradle-to-cradle, recycling, reuse, and remanufacturing. The search returned 55 articles discussing blockchain and the CE. Following a thorough examination of these articles, sixteen barriers to blockchain adoption in the CE were identified and validated by twelve experts. The details of these experts are mentioned in Section 4.

3.1. Technological Immaturity

The lifecycle stage of innovation is usually essential for its adoption and diffusion [51]. While blockchain technology can transform the CE into a developed ecosystem by providing product traceability, assurance, and incentivization, the relative immaturity of the technology [20,48,52] and scarcity of commercial applications [19] can act as a barrier to blockchain adoption in the CE. Firms attempting to explore and potentially implement blockchain-based CE solutions may encounter the dilemma of determining the tangible advantages to the business and providing the value of blockchain in their CE activities. In this regard, Erol et al. [53] highlighted that blockchain implementation in the renewable energy sector is still in its infancy in Turkey. Shojaei et al. [54] also argued that the technology is promising to enable the CE in the build environment sector. However, the usage of the technology remains limited. Therefore, blockchain can be viewed as an emerging innovation surrounded by technological uncertainty and immaturity, which arise from a lack of awareness of its practicality in the CE transition. The slow rate of blockchain adoption can magnify the level of risk and uncertainty of managers, lowering or hampering the wide-scale implementation of the technology in the CE.

3.2. Scalability Issues

Scalability represents the capability of an information system to maintain its equilibrium condition with increased storage volume [55]. In the context of CE, blockchain scalability is one of the most critical barriers to adopting the technology [53]. This issue originates from increasing the number of transactions and the shortcomings of consensus protocols [19]. According to [19], communication malfunctions among network participants, linear transaction records, and data storage are all examples of scalability issues. Additionally, Erol et al. [53] noted that blockchain may not possess the necessary level of robustness regarding latency and data throughput, which poses a serious problem with an integrated ecosystem like the solar photovoltaic energy sector. CE practices adopted by firms may result in a huge volume of business transactions and consequently slow down the blockchain performance to some degree. Therefore, poor scalability may raise questions of blockchain viability in the CE [20]. Hence, design and architectural considerations are crucial to making the ledger lightweight and ensuring satisfactory performance.

3.3. Security Risk

Blockchain can underpin the CE transition by allowing continuous and fine-grained product traceability. However, there are concerns related to the security of blockchain that stores and deals with lots of sensitive business data. In this context, Esmaeilian et al. [19] contended that public blockchains are vulnerable to 51% attacks, wherein a group of participants controls most of the network's computing power and the ledger. Böckel et al. [52] found that security issues associated with blockchain deployment in the CE were highly discussed in the research, with 27% of reviewed studies highlighting them. The authors further noted that in practice, false information can still be entered into a blockchain, which makes the validation and certification process outside of the blockchain an imperative. Esmaeilian et al. [19] stated that the mechanisms for verifying data uploaded on the blockchain are required to ensure that the link between digital records and physical entities is properly established and that the information uploaded on the blockchain is accurate. In addition to human-related security loopholes, double spending and the improper mechanism for protecting private keys impel CE stakeholders to apply more secure consensus algorithms to strengthen security and system resistance against cyber attacks [19]. Security needs to be maximized while linking disparate systems connected to different CE stakeholders accessing blockchain [15].

3.4. Privacy Risk

Blockchain technology provides a decentralized platform, brings transparency to the supply chain, and empowers firms to transit toward a CE. While the current development of blockchain advocates the anonymity of users' identities through digital signatures, transactional confidentiality via cryptography remains challenging [19]. Privacy issues can be raised in inter-firm contexts to manage and control CE-related data in a blockchain. Moreover, information related to assets and resources may be regarded as confidential and sensitive for firms; thus, sharing data through blockchain may be risky [56]. Privacy and the unwillingness to disclose critical information urge firms to prefer private (permissioned) blockchains over public ones [57]. However, this renders the main functions and advantages of transparency and visibility limited. Therefore, privacy is considered a subset of security, which requires increased control over information access. In other words, privacy needs to be constantly audited and revisited in blockchain systems. For example, this can be achieved by establishing concrete policies to protect legitimate CE activities and prevent malicious participants and potential misbehavior [56].

3.5. Interoperability Issues

Interoperability represents the capability of various information systems, applications, and devices to connect in an integrated manner within and across firm boundaries to access, share, and jointly utilize data among stakeholders [58]. The challenging process of integrating blockchain with existing legacy systems constitutes one of the most critical barriers to deploying the technology in the CE [49]. The lack of alignment between the systems of different CE stakeholders could limit the value of blockchain and hamper its adoption [59]. Additionally, the combination of blockchain with current legacy systems is costly to achieve and time-consuming. The lack of common information infrastructure and inconsistent data format can create striking discrepancies between firms involved in the CE. Therefore, high interoperability is required to achieve connectivity, modularity, and compatibility [12,60]. The full benefits of blockchain can only be achieved if the platforms used by firms are interoperable, thereby reducing the time between CE processes, speeding up the ordering, transfer, payment, and guaranteeing time and efficient movement of products [48,53].

3.6. High Energy Costs

One downside of implementing blockchain is the significant cost needed to power blockchain [33]. By nature, existing blockchain protocols are computational-intensive [19]. Blockchain is a prodigious consumer of electricity. For example, Esmaeilian et al. [19] argued that if Bitcoin pursues the similar adoption pattern of other broadly deployed technologies, carbon emissions from Bitcoin are sufficient to increase global warming above 2 °C. Therefore, this contradicts the goals of the CE to benefit the environment, reduce energy consumption, and promote renewable energies [61,62]. Böckel et al. [52]

found that a significant number of studies assessed the necessary amount of energy for operating a blockchain system and concluded that the technology is inefficient in terms of energy consumption; Truby [63] claimed that the first application of blockchain, Bitcoin, has been developed without considering the possible implications on the environment. The leveraging of this blockchain type can increase environmental degradation through high electricity consumption rates and emissions, thus preventing firms from adopting blockchain in the CE.

3.7. Conversion to a New System

A tough problem encountering firms during their adoption of blockchain in the CE is the involvement of employees and supply chain partners in novel systems and organizational structures that may entail using the technology. Integrating blockchain in the CE may require firms to configure their business models and revisit how they provide products and services [22]. Moreover, firms need to modify their legacy systems and develop rules for data authentication [54]. In recent research, Abreu and Coutinho [64] stated that several legacy systems lack direct interfaces to blockchain and necessitate considerable reconfiguration when integrating blockchain-based functionalities and data with legacy systems. Esmaeilian et al. [19] noted that it is hard to write all possible scenarios in CE business settings as computer codes in smart contracts. The infancy of blockchain and its continuous development poses significant issues for integrating blockchain with legacy systems [20,65]. Moreover, the high complexity of blockchain makes conventional practices for managing the CE process inappropriate, leading to challenges related to process delays, ease of use, and unwillingness to adapt to the new environment of the blockchain [66,67]. Consequently, the conversion to a new blockchain-based CE system is a complicated issue that must be addressed wisely to encourage the active involvement of employees, enhance awareness, and prevent the failure of the adoption procedure.

3.8. Investment Cost

The adoption process of blockchain technology comprises several phases, including design, development, implementation, migration, and maintenance. Despite the long-term benefits of blockchain, investment costs could discourage firms from adopting circular digital technologies [13]. The development cost necessary to manage a blockchain system could be quite high [49]. The upfront costs involved in adopting blockchain technology could outweigh the benefits of the technology [22]. As a result, managers should be aware of the development costs both within their firm and with their business partners. Magrini et al. [36] argued that the cost of blockchain and IoT systems should be assessed, including the initial investment cost in designing and purchasing sensors and the operating costs, such as energy and maintenance. Consequently, the investments in blockchain for CE activities should be justified with reasonable returns on investment [57].

3.9. Reluctance to Change

Several scholars argued that reluctance to change or adopt novel technologies could be pervasive in many firms [68–70]. In the CE context, the adoption of blockchain may be considered a risky decision since the technology is relatively untested in several CE activities [57]. For example, Shojaei et al. [54] found that change resistance among key stakeholders in the construction industry plays a critical role in hampering blockchain implementation. This hesitancy could be explained by the immaturity of the technology, which makes the performance outputs not large to judge the utility of blockchain for the CE transition [49]. Furthermore, the likelihood of operationally unexpected issues reduces the acceptance of the technology in CE activities. Therefore, adopting blockchain may be a frustrating and tedious effort that requires innovativeness, openness, willingness to take risks, and a clear organizational strategy.

3.10. Lack of Knowledge and Management Support

Firms consider blockchain adoption an arduous task requiring a sufficient level of knowledge and understanding of blockchain and its integration in the CE. The authors of [71] highlighted that emerging technologies strongly influence supply chain operations and require new skills, knowledge, and labor management across different actors. Considering its immaturity, a few people possess excellent knowledge and competencies of how blockchain can be effectively adopted in the CE [34]. Consequently, firms should upgrade their knowledge base and technical assistance to ensure the successful implementation of blockchain.

Besides lack of knowledge, top management support constitutes one of the main determinants for effectively implementing new technologies. However, some managers fail to afford the necessary support to integrate new technologies and CE principles [53]. The implementation of blockchain in the CE requires knowledge and management support [48]. According to [49], the lack of experience with large-scale applications in the CE could challenge the adoption of blockchain as the supply chain involves several partners and activities that differ from each other, thus making the experience of integrating blockchain more difficult. Therefore, firms are impelled to develop expertise and software on blockchain programming [22]. The intervention of managers is primordial to success in implementing blockchain and CE principles. Similarly, sufficient knowledge and expertise about the technology are necessary to achieve CE goals [53]. Thus, sufficient managerial commitment can improve blockchain adoption and warrant the mobilization of adequate resources. Likewise, a strategic perspective that stresses top management support is necessary to facilitate blockchain deployment in the CE.

3.11. Organizational Policies

Integrating blockchain in the CE necessitates new organizational mechanisms, policies, and procedures as elements of a firm's overarching strategy. As per [72], the absence of organizational policies constitutes a key barrier to blockchain deployment. The possibilities of capitalizing on blockchain in CE activities can thus be fully achieved if the factors of its adoption are backed by supportive organizational policies and strategies [53]. For instance, Chanson et al. [73] demonstrated the importance of organizational practices to identify how blockchain users can circumvent, detect, and avoid security issues. Furthermore, there is an exigency to change existing organizational mechanisms (e.g., changes in goals, responsibilities, practices, decision-making processes, systems) and policies to benefit the CE transition. Therefore, it is essential to adapt blockchain to the existing organizational practices and policies [74,75]. In this regard, CE stakeholders are required to support a wide variety of activities (product traceability and monitoring, data collection, quality control) that should be guided by organizational mechanisms and policies to develop more efficient processes and gain operational excellence.

3.12. Organizational Culture

Organizational culture has a significant impact on the success of blockchain adoption in the CE. Kouhizadeh et al. [72] pointed out that the deployment of blockchain in sustainable supply chains can be hampered by issues in changing corporate culture, while Ada et al. [65] also stated that some firms find it challenging and time-consuming to shift the entire corporate culture toward the CE transition since circular business models demand a culture inclined to cooperation and collaboration along the supply chain. Similarly, Nandi et al. [76] noted that an organization's ability to digitize CE activities depends on its readiness to create an adequate corporate culture toward blockchain-driven digital transformation. The fundamental shift in corporate culture brought by blockchain can considerably impact CE performance (e.g., via green operations, material reuse, waste management) and the sustainability of firms involved [56]. Even though the technology can encourage a culture of trust through its immutable recording capability [19,48,57], blockchain adoption in the CE creates many challenges on a more human level. Relatedly, Kurpjuweit et al. [77] suggested that the successful deployment of blockchain is determined by a favorable culture that motivates managers and employees to take risks and accelerate the implementation process of the technology.

3.13. Lack of Collaboration, Coordination, and Cooperation

Collaboration is a critical requirement for enhancing circular supply chain networks [53,78]. Collaboration, communication, and coordination play a vital role in minimizing logistics costs and boosting CE stakeholders' involvement in detecting and eliminating waste throughout the supply chain. As a result, a lack of collaborative approaches can hamper blockchain implementation in the CE [65]. Contradicting priorities, goals, and incentives among CE stakeholders may result in many consistency issues, inefficiencies, and additional costs (e.g., inventory costs, production costs, high lead times) [13,41,59]. In spite of the manifold opportunities of blockchain, Yadav et al. [67] pointed out that firms may be unwilling to collaborate and participate in consortia development. Potential causes for this conduct include acquiring individual benefits from blockchain implementation and a lack of desire to collaborate with rivals. It is vital to remove these hurdles as collaboration is no longer a choice but a requirement that allows firms to harness blockchain strategically and capitalize on its collaborative potential for the CE.

3.14. Cultural Differences

Researchers have reported that cultural differences could increase transactions and reduce collaboration [79]. Cultural differences can significantly impact CE implementation [46,65], which influences CE operations such as reuse, remanufacturing, recycling, and waste management [80]. Regarding blockchain adoption, cultural differences of supply chain stakeholders regarding sustainability and technology are found to yield different mindsets and attitudes that can hinder blockchain adoption in supply chain management [72]. For example, Hew et al. [74] demonstrated that countries with a conservative culture, such as Malaysia, are reluctant to take up new technologies like blockchain. Another study, Qian et al. [81], underlined the necessity to promote a culture of cooperation to speed the transition from conventional to blockchain-enabled supply chains. Therefore, the push for blockchain-based CE business models can be hampered by cultural differences.

3.15. Lack of Regulatory Support

In general, CE implementation necessitates an understanding of the diverse expectations of different stakeholders and clear regulatory standards [65]. Because of the recent emergence of blockchain, no specific and defined regulations exist for implementing the technology [49]. Steenmans et al. [35] pointed out that regulations could be a barrier to using blockchain for better resource management and waste management. The authors further argued that caution should be exercized when designing regulations, rules, and standards to govern blockchain and smart contracts. The legislation and policy development should balance the ecological and economic objectives to establish CE business models that protect the environment and maximize returns on investments using blockchain [35]. In a blockchain ecosystem, smart contracts are based on rules defined by coders and software engineers who determine architecture, applications, and network design [19]. Thus, this may result in several issues in ensuring compliance with regulation and industry standards. The inability to adapt to changing CE stakeholders' preferences of smart contracts to connect to the physical world and validate information recorded on blockchain poses legal challenges to blockchain platforms [19]. Overall, the lack of regulatory support is expected to constrain the diffusion of blockchain in the CE.

3.16. Usage in Illicit Activities

Although organizations should comply with legislation and take responsibility for environmental preservation and sustainability, they may be engaged in illegal practices and behaviors such as corruption, bribery, and child labor. In addition to these problems, firms could use blockchain to avoid paying taxes and fund criminal activities through cryptocurrencies. To confirm this development, Upadhyay et al. [22] stated that blockchain could stimulate money laundering, illicit trade, human trafficking, and risky activities undetected by the authorities. Given the insufficient level of regulation, blockchain technology may allow criminal activities and irregularities to thrive in the CE since malicious entities can manipulate records and disseminate false information to other entities involved in the CE network [34].

This section will review the academic literature to ascertain the barriers to blockchain adoption in the CE. Additionally, expert feedback was gathered to validate the barrier list. Table 1 summarizes these issues based on the available literature and expert consultations. In general, the majority of experts agree that interoperability concerns and reluctance to change are the primary barriers to blockchain adoption in the CE. Additionally, experts agree on the importance of a lack of knowledge and management support and scalability issues.

Table 1. Barriers to blockchain adoption in the CE according to the academic literature and experts.

No.	Barriers	Reference	No. of Experts Agreeing on the Barrier
1	Technological immaturity	[19,48,52]	7
2	Scalability issues	[19,20,53]	7
3	Security risk	[19,52]	3
4	Privacy risk	[19,56,57]	4
5	Interoperability issues	[12,48,49,53,59]	10
6	High energy costs	[19,33,52]	3
7	Conversion to a new system	[19,22,54]	5
8	Investment cost	[13,22,49]	6
9	Reluctance to change	[49,54,57]	9
10	Lack of knowledge and management support	[34,48,53]	8
11	Organizational policies	[53,72,74]	4
12	Organizational culture	[48,56,65,72]	4
13	Lack of collaboration, coordination, and cooperation	[53,65,78]	4
14	Cultural differences	[65,72,80]	3
15	Lack of regulatory support	[35,49,65]	5
16	Usage in illicit activities	[22,34]	2

4. Methodology

This study employed the fuzzy Delphi method to evaluate the importance of the barriers to blockchain adoption in the CE. Additionally, the best-worst method (BWM) was applied to rank these barriers effectively. Twelve experts participated in the data collection process, with their details shown in Table 2. Data were gathered from experts operating in diverse industrial contexts, and who met the required criteria. This process was problematic since there exist few experts with a high level of in-depth knowledge, particularly individuals with real-life experience in the implementation of blockchain in the CE. Our criteria required that experts should possess a good knowledge of blockchain and should have had experience of adopting the technology in the CE. Experts should also have demonstrated neutrality by not preferring a particular blockchain solution or promoting certain software vendors. The group of experts were sourced from the professional networks of the author team via email and LinkedIn. These experts were engaged in blockchain research and adoption projects. These specialists had been involved in previous and ongoing blockchain projects within supply chain management, retailing, healthcare, and information technology sectors.

Table 2. Background of experts.

No. of Experts	Specialty	Years of Experience
1	Supply chain traceability software	27
2	Engineering	35
3	Digital health, data commons, and interoperability	30
4	Supply chain and operations management	35
5	Blockchain	25
6	Blockchain	20
7	Retail	24
8	Supply chain finance	20
9	Digital development and food, land, and water systems research	25
10	Geospatial science, resources	30
11	Operations management	30
12	Supply chain management	30

Given their expertise and positions within their organizations, the experts were consulted to collect their feedback regarding the barriers and their level of importance, from "very low" to "very high". Then, BWM was used to identify the preferences for each barrier. This method is recognized for its effectiveness in research with a limited number of experts [82]. For example, previous research work had samples of three, six, and twelve experts [83–85]. Details related to the BWM approach are described in the following subsections. Figure 1 depicts the research framework used in this study. The framework consisted of three stages for analyzing barriers to blockchain adoption in the CE. The steps followed in this process are detailed in the next sections.

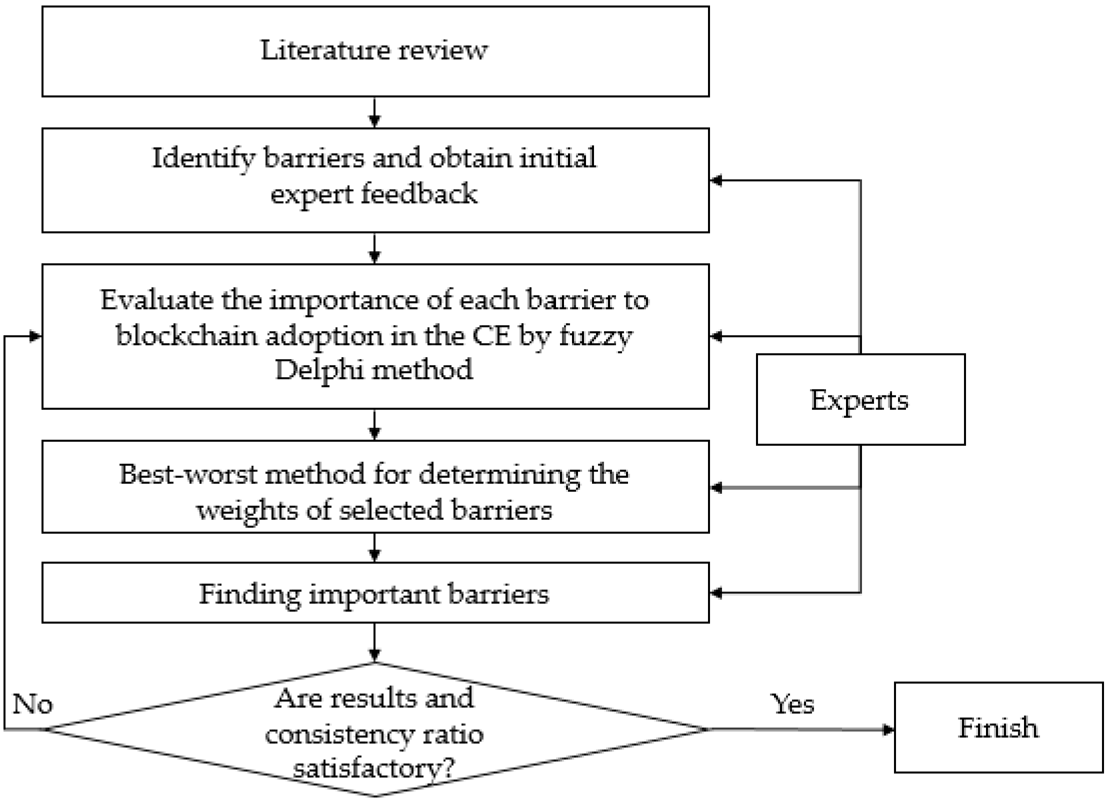

Figure 1. The research framework.

4.1. Fuzzy Delphi Method

The fuzzy Delphi method (FDM) represents a formal communication technique or strategy initially envisioned as a methodical, interactive, and predictive procedure based on an expert panel [86,87]. The FDM is an expert opinion survey technique that includes three main aspects: anonymous response, iteration and controlled feedback, and ultimately statistical group response [88]. Experts' opinions cannot be accurately translated into quantitative values [88]. As such, crisp values are inadequate to model real-world systems because human thinking, preferences, and judgments are vague, imprecise, and subjective [89]. Thus, to overcome this issue, Zadeh [90] proposed fuzzy set theory to handle the uncertainty of human thought and behavior in making decisions [91]. This study used FDM to examine the important barriers detected in the literature review. FDM combines fuzzy set theory and the Delphi approach [92]. The necessary steps of FDM are detailed as follows.

- Step 1: Identification of barriers to blockchain adoption in the CE. Initially, a detailed literature review identified the possible barriers to blockchain implementation in the CE.
- Step 2: Collection of expert opinions utilizing decision group. Once barriers were determined, n number of experts (i.e., decision-makers) from industry and academia were contacted to judge the importance of barriers via a questionnaire and employing linguistic variables listed in Table 3. This research employed fuzzy triangular numbers for assessing the barriers. In addition, a geometric mean model [93] was used to determine the group decision of experts.
- Step 3: Determination of important barriers. The final step in FDM aimed to identify the important barriers by comparing each barrier's weight with the threshold α. The TFN $\tilde{\tau}_j$ was determined as follows for each barrier.

$$\tilde{a}_{ij} = (a_{ij},\ b_{ij},\ c_{ij})\ \text{for } i = 1 \ldots n;\ j = 1 \ldots m.$$

$$\tilde{\tau}_j = (a_j,\ b_j, c_j) = \left(\min\{a_{ij}\},\ \left(\prod_{i=1}^{n} b_{ij}\right)^{\frac{1}{n}},\ \max\{c_{ij}\}\right)$$

In the previous equations, the index i corresponds to the expert and index j corresponds to the criterion. The notation $\tilde{a}_{ij}$ represents the fuzzy value of each criterion received from every expert. The fuzzy average value of each criterion is illustrated by $\tilde{\tau}_j$. Moreover, the fuzzy average value of each criterion is defuzzified into crisp value, which is equal to:

$$Crisp\ value = \frac{a + b + c}{3}$$

After calculating the abovementioned value, if the crisp value of $\tilde{\tau}_j$ is higher than the threshold α, the criterion j is accepted and taken for the next research stage. If the crisp value of $\tilde{\tau}_j$ is less than the threshold α, the criterion j is rejected.

Table 3. Linguistic variables.

Linguistic Term	Fuzzy Number
Very low	(0, 0, 0.25)
Low	(0, 0.25, 0.5)
Medium	(0.25, 0.5, 0.75)
High	(0.5, 0.75, 1)
Very high	(0.75, 1, 1)

4.2. Best-Worst Method

BWM represents the recent multicriteria decision-making methodology (MCDM) suggested by [82]. The premise of this technique is to weigh the criteria by pairwise comparisons such as the analytic hierarchy method (AHP) and the analytic network method (ANP) [94]. Compared to AHP and ANP methods, BWM has two main benefits; a higher consistency ratio and less pairwise comparisons. Due to its simplicity and flexibility, several scholars used BWM in their studies. For example, Shojaei et al. [95] utilized an integrated approach of Taguchi loss function, BWM, and VIKOR to evaluate Iranian airports. Gupta and Barua [85] used BWM to examine the enablers of technological innovation for micro, small and medium businesses in India, while Wan Ahmad et al. [96] also applied BWM to identify the most critical factors influencing the sustainable gas supply. The authors revealed that economic and political factors are the most important ones. Finally, Annema et al. [97] utilized BWM to analyze politicians' viewpoints on transport policy assessment.

The steps related to BWM are described below:

1. Identify the group of decision criteria $\{c_1, c_2, \ldots, c_n\}$ by experts.
2. Specify the best and the worst criterion: In this step, experts select the best and the worst criterion among the criteria determined in the first step. The best criterion is the most important criterion, and the worst criterion represents the least important or desirable criterion to experts.
3. Identify the preference of the best criterion over the other criteria: In this step, experts have to point out the preference of the most important criterion over the other criteria, utilizing a number ranging from 1 to 9, where 1 represents equal importance, and 9 indicates that the best criterion is much more important than the criterion in question, leading to a best-to-others vector, $A_B = (a_{B1}, a_{B2}, \ldots, a_{Bn})$.
4. Identify the preference of the criteria over the worst criterion: In this step, experts should indicate the preference of all other criteria over the criterion chosen as being the least desirable or important, utilizing a number ranging from 1 to 9, where 1 corresponds to equal importance, and 9 illustrates that the criterion in question is a lot more important than the least important criterion. This results in the others-to-worst vector, A_W, which is presented as follows.

$$A_W = (a_{1W}, a_{2W}, \ldots, a_{nW})^T$$

5. Find the optimal weights $(w_1^*, w_2^*, \ldots, w_n^*)$: To obtain the optimal weights of the criteria, it is required to minimize the maximum absolute differences $\{|w_B - a_{Bj}w_j|, |w_j - a_{jW}w_W|\}$ for all j. This can be described as follows [82]:

$$\min \max_j \{|w_B - a_{Bj}w_j|, |w_j - a_{jW}w_W|\}$$

$$s.t.$$

$$\sum_j w_j = 1,$$

$$w_j \geq 0, \text{ for all j.}$$

This model can be solved by transferring it into the following linear programming formulation [82]:

$$\min \xi$$

$$s.t.$$

$$|\mathbf{w_B} - \mathbf{a_{Bj}w_j}| \leq \xi, \text{ for all j}$$

$$|\mathbf{w_j} - \mathbf{a_{jW}w_W}| \leq \xi, \text{ for all j}$$

$$\sum_{j} \mathbf{w_j} = 1,$$

$$\mathbf{w_j} \geq 0,\ \textbf{for all j}.$$

5. Findings

As previously discussed, the FDM was utilized to select the most important barriers from the ones identified in the literature. The results of FDM are presented in Table 4.

Table 4. Output of FDM.

No.	Barrier	L	M	U	Defuzzified	Decision
1	Technological immaturity	0.25	0.66	1	0.636	Accept
2	Scalability issues	0	0.55	1	0.518	Accept
3	Security risk	0	0.55	1	0.516	Accept
4	Privacy risk	0	0.47	1	0.488	Reject
5	Interoperability issues	0	0.71	1	0.570	Accept
6	High energy costs	0	0.44	1	0.480	Reject
7	Conversion to a new system	0	0.67	1	0.557	Accept
8	Investment cost	0	0.56	1	0.520	Accept
9	Reluctance to change	0.25	0.76	1	0.671	Accept
10	Lack of knowledge and management support	0.25	0.77	1	0.674	Accept
11	Organizational policies	0	0.48	1	0.494	Reject
12	Organizational culture	0	0.56	1	0.520	Accept
13	Lack of collaboration, coordination, and cooperation	0	0.57	1	0.524	Accept
14	Cultural differences	0	0.00	1	0.333	Reject
15	Lack of regulatory support	0	0.00	1	0.333	Reject
16	Usage in illicit activities	0	0.00	1	0.333	Reject

As per the FDM outputs and experts' opinions, the barriers to blockchain adoption in the CE were finalized and listed in Table 5.

Table 5. Accepted barriers to blockchain adoption in the CE.

Index	Barriers
C1	Technological immaturity
C2	Scalability issues
C3	Security risk
C4	Interoperability issues
C5	Conversion to a new system
C6	Investment cost
C7	Reluctance to change
C8	Lack of knowledge and management support
C9	Organizational culture
C10	Lack of collaboration, coordination, and cooperation

Consistent with the steps of BWM stated above, the experts were asked to select the best and the worst barriers among the indicators (Table 5). Subsequently, the decision panel was asked to prioritize the best criterion among other criteria and determine the preference of other criteria over the worst criterion. The inputs of each expert resulted in best-to-others and others-to-worst vectors presented in Tables 6 and 7, respectively.

Table 6. Best-to-others vector.

Expert Number	Best Criteria	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
1	C8	3	4	2	3	3	3	2	1	3	3
2	C8	3	2	2	2	2	3	2	1	3	2
3	C8	5	5	5	2	3	3	2	1	5	3
4	C7	5	8	9	9	4	9	1	5	8	6
5	C7	9	9	9	5	7	9	1	7	8	9
6	C8	3	7	7	3	3	4	6	1	9	7
7	C1	1	3	2	2	4	4	4	4	4	4
8	C8	2	3	4	3	3	3	2	1	3	4
9	C8	3	3	3	2	2	2	2	1	3	3
10	C8	3	4	4	4	4	4	2	1	2	6
11	C1	1	3	3	5	9	7	6	6	6	6
12	C8	4	6	4	3	3	4	2	1	3	3

Table 7. Others-to-worst vector.

Expert Number	1	2	3	4	5	6	7	8	9	10	11	12
Worst criteria	C2	C6	C3	C3	C3	C9	C6	C3	C3	C10	C5	C2
C1	3	2	3	9	9	9	4	3	2	4	9	4
C2	1	3	2	7	9	5	3	2	2	3	9	1
C3	3	2	1	1	1	5	4	1	1	3	8	3
C4	3	3	5	5	9	9	3	3	3	4	6	5
C5	3	3	4	9	9	9	2	3	3	4	1	5
C6	2	1	3	4	9	8	1	2	2	3	4	4
C7	3	3	5	9	9	5	2	4	3	5	5	5
C8	4	3	5	9	9	9	2	4	3	6	5	6
C9	2	2	3	7	9	1	2	3	2	5	4	4
C10	3	3	4	9	9	5	2	2	2	1	5	5

The final weights of criteria were determined using the linear model of BWM. The optimal weights and the optimal value of ξ* (consistency ratio) were identified for each expert by solving the BWM linear model. Afterwards, the arithmetic mean of the criteria's weights for each expert was calculated to obtain the final weights of the criteria. Table 8 and Figure 2 display the results of BWM.

Table 8. BWM results.

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	Consistency Ratio ξ*
1	0.083	0.042	0.125	0.083	0.083	0.083	0.125	0.208	0.083	0.083	0.026
2	0.071	0.106	0.106	0.106	0.106	0.047	0.106	0.176	0.071	0.106	0.035
3	0.056	0.056	0.036	0.141	0.094	0.094	0.141	0.231	0.056	0.094	0.022
4	0.097	0.061	0.024	0.054	0.121	0.054	0.351	0.097	0.061	0.081	0.026
5	0.062	0.062	0.025	0.111	0.079	0.062	0.39	0.079	0.069	0.062	0.031
6	0.125	0.053	0.053	0.125	0.125	0.093	0.062	0.288	0.022	0.053	0.016
7	0.233	0.093	0.14	0.14	0.07	0.047	0.07	0.07	0.07	0.07	0.029
8	0.128	0.085	0.043	0.085	0.085	0.085	0.128	0.213	0.085	0.064	0.026
9	0.076	0.076	0.051	0.114	0.114	0.114	0.114	0.19	0.076	0.076	0.038
10	0.095	0.071	0.071	0.071	0.071	0.071	0.142	0.234	0.142	0.031	0.017
11	0.309	0.133	0.133	0.08	0.025	0.057	0.066	0.066	0.066	0.066	0.017
12	0.071	0.03	0.071	0.095	0.095	0.071	0.143	0.232	0.095	0.095	0.018
Final weight	0.117	0.072	0.073	0.1	0.089	0.073	0.153	0.174	0.075	0.073	
Rank	3	10	9	4	5	8	2	1	6	7	

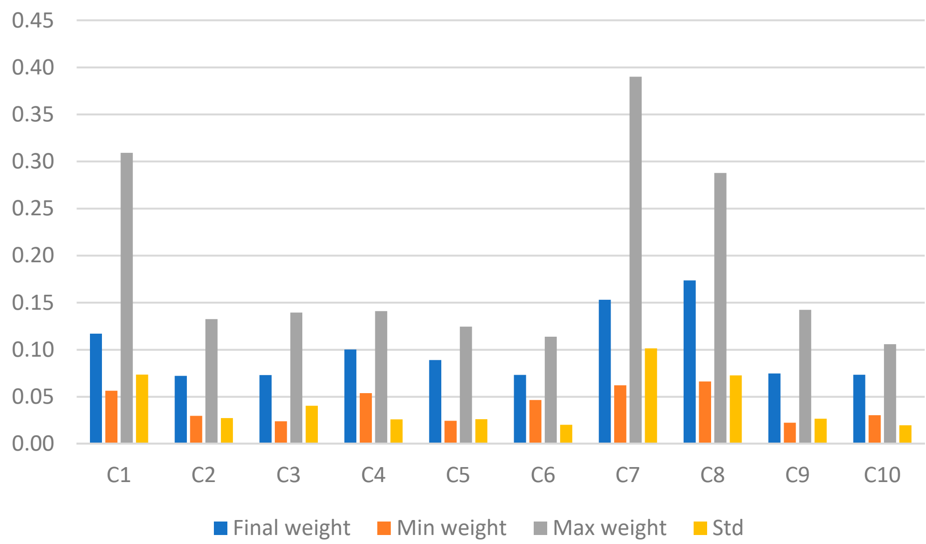

Figure 2. BWM results.

As can be observed from the application of BWM, lack of knowledge and management support (C8), reluctance to change (C7), and technological immaturity (C1) are the most important barriers, while investment cost (C6), security risk (C3), and scalability issues (C2) are the least important barriers to blockchain adoption in the CE. According to Table 8, the comparisons indicate a very high consistency since the value ξ^* is close to zero.

6. Discussion

Researchers agree that new technologies such as blockchain can play a critical role in CE realization [22,52,57]. The capabilities of the technologies in terms of democratization and transaction transparency have attracted organizations striving to implement CE practices. Because information can be securely maintained and updated without a central authority, blockchain provides proof of transaction between different CE stakeholders. Blockchain is a key enabler for overcoming several pressing CE challenges, including developing a secure payment system and the requirement for transparent transactions to maintain materials and products in the circulation loop for longer periods [1,22]. Blockchain strengthens collaboration and integration of transaction processes and cleaner production in the supply chain, thereby reducing inefficiencies and waste [34,45].

Moreover, a tamper-proof and secure decentralized ledger can usher in new sustainable, democratic, and cyclical CE business models that enable firms to collaborate closely with larger CE stakeholder networks, notably with customers [22,98,99]. By allowing the design of incentive schemes, blockchain can motivate green consumer behavior, improve transparency, optimize operational efficiencies, and facilitate performance control and reporting [19,52]. Realizing the CE is a common objective of many organizations and governments, requiring collective decision-making considering inputs from diverse actors. As such, the adoption of blockchain can be an effective solution to large-scale collective decision-making processes [100]. Furthermore, the technology offers incentives for supporting a novel trading and pricing resources system between CE stakeholders at lower transaction costs and increased visibility [17,20]. Blockchain enables reliable and decentralized data, process transparency, traceability, and optimal supply chain performance [17].

Additionally, with blockchain, platforms like those designed for shared leasing can be established, and organizations can coordinate and redistribute their excessive assets and resources [57,101]. The visibility of transactional information enabled by blockchain also strengthens intra- and inter-firm communication [17,102] and facilitates the formulation of CE strategies. The deployment of blockchain could further prevent waste and create environmental benefits through sustainable product designs, encouraging customers to utilize products for longer periods and return them after use at optimal points in the product lifecycle [76].

Finally, the development of an economic system based on tokens with the help of blockchain can ultimately dismantle the relationship between economic growth and environmental deterioration and allow organizations to explore new opportunities for value creation and engage consumers in value co-creation [20]. Besides these economic and environmental benefits, blockchain can boost the social dimension of sustainability by promoting social welfare and equity [103].

Despite the tangible benefits of the technology, the wide-scale implementation of blockchain in the CE remains uncertain. This study investigated potential barriers to blockchain adoption in the CE. The barriers identified in this research are temporary in nature due to the novelty of the technology. As blockchain develops over time, it is expected that these barriers will be overcome [104]. This study aims to determine barriers hampering the effective integration of blockchain in the CE, stimulate future academic research, and assist in developing more successful blockchain systems tailored to CE activities. Overall, sixteen barriers were identified from the literature and validated by twelve experts. While we do not pretend to be inclusive in our review, the proposed research framework can provide a comprehensive set of hurdles that slow down the CE transition. Next, the FDM outcomes included ten important barriers.

Even though the academic literature and the experts validated barriers such as privacy risk and lack of regulatory support, they have been disallowed to be viewed as important barriers to blockchain adoption in the CE due to user anonymity in permissioned blockchains [19,52] and the readiness of government to support blockchain adoption [105]. This finding contradicts previous studies that highlighted the importance of regulations to blockchain application for better resource management, waste initiatives, and conflict prevention [22,35,57]. The selected ten barriers were further analyzed and ranked using BWM. The application of this hybrid approach has led to several interesting findings. For instance, the lack of knowledge and management support is identified as the most important hindering the adoption of blockchain in the CE. This result corroborates the findings of several studies [48,53,76,106].

Recently, Karuppiah et al. [107] found that the lack of knowledge about blockchain technology represents one of the top five challenges encountered by firms operating in the leather garment manufacturing industry. The lack of knowledge could exacerbate resistance to implement the technology [108] and lead to unsuccessful adoption [109]. Moreover, the results documented by the experts indicated that reluctance to change is the second most important inhibitor of blockchain adoption, which is in line with the research conducted by [110,111] and confirms the role of organizational resistance to change in prolonging the process of blockchain–CE integration. In addition, this outcome illustrates that the move towards new blockchain-based CE business models is perceived as a risky decision that may aggravate corporate uncertainties and losses.

Technological immaturity and interoperability issues were ranked the third and fourth most important barriers, respectively. The immaturity of blockchain may create different expectations regarding its use in various cases and implementation advantages in the CE. Uncertainties arising from the infancy of blockchain and the limited number of experienced people with the technology pose challenges in using and adapting blockchain to the CE. Moreover, the existing blockchain systems are still generally at the experimentation phase [48,54]. The significant ranking of interoperability issues signifies that existing legacy systems used for CE activities should be able to operate with blockchain. This finding supports previous studies, highlighting the need to develop fully decentralized systems that could interconnect without intermediaries and achieve high performance [52,53,60].

Consequently, firms are required to devise effective strategies to prevent problems (e.g., system incompatibilities, lack of data integration, inefficient communication, etc.) that may happen during the transition to a blockchain-enabled CE. Furthermore, the reason behind the lack of real-world blockchain applications in the CE could be due to the difficulty of converting to a new system (C5), organizational culture (C9), and the lack of collaboration, coordination, and cooperation (C10). During an unprecedented technological transformation, firms are required to prioritize the adaptation of their system infrastructure to ensure the success of their CE.

The findings are consistent with those of [112], which found that organizational culture was among the most critical success factors for blockchain adoption in freight transportation. Thus, firms need to have systematic thinking and an effective approach in terms of organizational culture to facilitate blockchain's role in reducing environmental impacts of resources at the end of their lifecycle. A supportive organizational culture can provide a favorable operational setting to incubate blockchain. Similarly, the adoption of blockchain extends beyond the individual firm to a larger set of CE stakeholders. Eventually, it causes radical changes in the firm's role in the CE ecosystem. This coincides with the views of [113,114], which stated that integration of "system-changing" innovations requires new collaborative initiatives with multiple actors.

Finally, this study suggests that investment cost (C6), security risk (C3), and scalability issues (C2) were the least important barriers to blockchain adoption in the CE, thereby requiring less attention from managers. While blockchain technology is not costly to operate [115], a recent study suggested that investment costs represent the most significant obstacle in integrating blockchain into energy management [49]. In contrast to our study findings, [19] argued that security risks and scalability are among the major limitations of blockchain that need to be addressed to ensure the wide adoption and implementation of the technology in the CE.

7. Conclusions

The purpose of this article was to examine the significance of barriers to blockchain adoption in the CE. Experts' opinions were used to validate a pool of barriers to blockchain application for the CE extracted from the academic literature, which was then refined using FDM. The significant barriers to blockchain adoption in the CE were then ranked using BWM.

7.1. Research Implications

This study makes a number of theoretical and management inferences. The findings indicate that ten potential barriers are critical for decision-makers, necessitating the adoption of several best or good practices and adaptation efforts during blockchain implementation in the CE. The study's contribution to the existing body of knowledge cannot be overstated, as it is one of the few attempts to prioritize and rank blockchain barriers in the context of CE. Additionally, the complementarity of FDM and BWM paints a clear picture of the barriers that must be addressed (or removed) immediately in order to mitigate potential risks and uncertainties associated with blockchain integration in the CE. Additionally, the findings also support the view that corporate knowledge, training, and communication are critical to blockchain adoption in circular supply chain management. This study responds to academics who have emphasized the importance of examining the relationship between sustainable supply chain management and blockchain [116–118]. In the context of sustainable supply chain management, our findings indicate that a reluctance to change and technological immaturity continue to be impediments to the deployment of blockchain. As a result, technological maturity is necessary because it enables integration and the capture and disclosure of information needed in the circular supply chain. Consistent with previous studies [116,118,119], this study indicates that blockchain technology has the potential to enhance the security, trust, traceability, and transparency of sustainable supply chains. In general, this is the first study to comprehensively identify, evaluate, and rank barriers to blockchain adoption in the CE. The barriers to technology adoption in the CE were analyzed as multifaceted issues that affect relationships between organizations and stakeholders in sustainable supply chains [116]. Additionally, the technological barriers related to blockchain implementation were found to be less significant, as they primarily stem from the technology's infancy. Organizational barriers to blockchain adoption require greater attention in future research and workable solutions to increase organizational readiness to adopt blockchain in sustainable and circular supply chains. Additional empirical studies are necessary to investigate the factors that contribute to technology acceptance. From an integrative approach, this research sought a close alignment of the CE and blockchain concepts and examined the barriers that must be overcome in order for a blockchain-enabled CE to succeed.

The findings of this study inform CE stakeholders and managers about the barriers to blockchain adoption on which they must focus their resources and efforts. Organizations should be encouraged to participate in blockchain-enabled CE initiatives that promote sustainable and efficient processes by sharing information and resources. Blockchain adoption in the CE is critical in today's dynamically competitive markets. As a result, managers should budget specifically for this technological advancement in the CE system. To avoid technical issues during blockchain implementation, businesses must establish dedicated research and development units where IT staff can acquire expertise and training. Specifically, software professionals' knowledgeable about blockchain will have a positive impact on businesses as they transition toward a blockchain-enabled CE.

Technological change is more challenging in the CE from the technical and financial perspective because a highly intricate network structure features this paradigm based on information, product, and capital flows. Therefore, for the achievement of the CE, governments may grant additional subventions and support organizations to thrive in competitive marketplaces. Finally, interoperability, one of the barriers most critical to blockchain, needs to be taken seriously to ensure effective system integration in CE activities. Moreover, CE stakeholders must be persuaded of the potential of blockchain for the CE transition; thus, the hesitance in this respect should be erased. As a result, all sorts of reluctance undermining the adoption of blockchain should be followed closely, and the required precautions should be considered in this regard. The strategies used to reduce reluctance may vary according to actual conditions and individual qualities. More specifically, the human aspect is the main cause of the reluctance to shift to blockchain systems. Thus, employees should be taught more about blockchain barriers to ensure successful technology adoption in the CE.

7.2. Research Limitations

Despite the significant contributions of the current study, it is worth noting that the findings were biased toward experts' opinions in academia and industry. Moreover, the lack of peer-reviewed academic literature on the nexus of blockchain and the CE is another limitation of the study. The theoretical nature of the research can also be considered a concern. However, we believe that the recent conceptual development of this knowledge domain and the scarcity of theoretical studies on the barriers to blockchain adoption in the CE make our study a worthy and valuable scientific contribution.

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