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Expert perspectives on blockchain in the circular economy: A Delphi study with industry specialists

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ABSTRACT

The burgeoning interest in both the circular economy and blockchain technology has spurred numerous proposed integrations. Despite this enthusiasm, empirical research examining the practical feasibility and critical assessment of blockchain's potential within the circular economy remains limited. This study engages with eleven distinguished blockchain experts to critically analyze the prospects of technology integration across various facets of the circular economy, aiming to predict potential outcomes. Utilizing the Delphi method, this research seeks to attain a consensus on the experts' visions and opinions. The findings suggest a nuanced perspective: while certain integrations in the circular economy may face challenges and are unlikely to succeed, others could prove effective in the long term, provided specific conditions are met. When appropriately designed Tokenomics are in place, and the necessary level of digitalization is achieved, blockchain technology can significantly incentivize circular economy practices. However, the complete disintermediation of circular practices through blockchain is viewed as less feasible, owing to its reliance on external data providers.

1. Introduction

"*A systematic assessment of advantages and disadvantages of blockchain for a circular economy is lacking for different use cases and contexts … we argue that critical dialogue led by industry is essential*" (Böckel et al., 2021). The integration of blockchain technology within the circular economy (CE) has garnered significant attention, yet a systematic assessment of its advantages and disadvantages across various use cases remains elusive. Böckel et al. (2021). highlight the need for a more technical and critical analysis led by industry experts, emphasizing the predominance of general statements rather than systematic approaches in current literature.

The concept of the circular economy traces its origins back to the 19th century, when workers in the textile industry suggested utilizing newly introduced machinery to recycle old materials rather than producing new ones from scratch (ARR-VE). This nascent idea was later formalized by Walter Stahel, who introduced the concept of the closed-loop economy. Stahel posited that extending the life of products is essential for transitioning towards a sustainable economy (StahelSusan Grintor Orr, 1984). Subsequently, other distinguished experts expanded upon this foundation, further elaborating on related concepts such as recycling and reusing. At its heart, the circular economy aims to indefinitely delay the disposal of goods and raw materials (Stahel, 2016), (Johnson, 2013). In this quest for a closed-loop economy, machinery, and technology play crucial roles. Consequently, emerging technologies such as blockchain are currently under exploration for their potential contributions to the CE.

The pivotal rationale for considering blockchain as a beneficial technology within the circular economy stems from its inherent immutability and transparency (Centobelli et al., 2022), (Hatzivasilis et al., 2021). These attributes confer a high level of confidence and reliability on the data recorded on the blockchain, enabling precise traceability of information. As highlighted by Kouhizadeh et al. (2019), a significant obstacle to the circular economy is the scarcity of information, which complicates the traceability of products and waste. Consequently, the emergence of blockchain technology presents a logical basis for exploring its integration with circular economy principles to facilitate the transition towards a more sustainable economic model (Wang et al., 2020), (Rejeb et al., 2023).

A consistent body of research in fact, advocates for the integration of blockchain technology as a means to transparently trace records in supply chains with a higher degree of certainty. Enhanced transparency is sought in both forward and reverse logistics to improve recycling and reuse processes (Lo et al., 2018), and to facilitate the return of components (Kouhizadeh and Sarkis, 2018a). Further studies suggest that implementing blockchain in logistics processes can indirectly contribute

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to cleaner production by reducing waste and material loss, while also preventing overproduction and the bull-whip effect by reducing information asymmetry (Younis et al., 2020), (Yildizbasi, 2021), (Paul et al., 2022). Transparency in production can also be leveraged to provide data on emissions, working conditions, and the quality and safe use of chemicals, which are critical in industries such as fashion (Upadhyay et al., 2021a), (Bhubalan et al., 2022), (Shou and Domenech, 2022), (Tian, 2017), (Venkatesh et al., 2020). A reduction in information asymmetry also aims to improve cooperation between stakeholders and enhance supplier selection (Saberi et al., 2019a). If supplier information is transparent, clients with a major regard for green production can better benchmark their performance (Upadhyay et al., 2021b), (Rejeb et al., 2022), (Böhmecke-Schwafert et al., 2022). Similarly, as in the financial sector, several studies advocate for the implementation of blockchain in waste management, and oil and energy production to reduce costs and the number of intermediaries. In the energy sector, for example, the goal is to overcome centralization by embracing a peer-to-peer structure (Centobelli et al., 2022), (Montakhabi et al., 2021), (Akinade and Oyedele, 2019). Leveraging tokenization and cryptocurrencies, numerous proposals involve using blockchain to incentivize circular behavior (Farizi and Sari, 2021), (Gong et al., 2022), (Grati et al., 2023). For instance, 'Plastic Coin' is a notable application that incentivizes recycling of plastic bottles by issuing a specific token through the Ethereum blockchain (Cluchet et al., 2019). Additionally, a significant number of articles support the integration of blockchain for traceability and authentication of products (Shou and Domenech, 2022) (Centobelli et al., 2022) (Saberi et al., 2019b). In the context of a circular economy, this feature would be critical for ensuring authenticity among different stages of reusing and recycling (Casado-Vara et al., 2018) (Upadhyay et al., 2021b) (Yildizbasi, 2021).

While existing studies advocate for these integrations, there remains a notable gap in research dedicated to examining the technical mechanisms that actualize these benefits (Weber et al., 2016), (Agrawal et al., 2018). The hype surrounding blockchain often harbors misconceptions and inflated expectations, particularly regarding its capacity to monitor external states and serve as a unique source of truth (Caldarelli, 2020a), (Sharmaa), (Song). Such misconceptions can lead to biases in theory and research, especially in the context of real-world applications.

In alignment with Böckel et al. (2021)'s call for a transparent and unbiased approach, this study aims to investigate the assumptions surrounding blockchain in the CE through the lens of leading experts in blockchain technology. Employing the Delphi methodology, adapted specifically for this research, a literature review has been conducted to develop the framework for the study and extract the required items. Experts were then engaged in direct interviews to evaluate and discuss these items, culminating in a final survey to achieve consensus. Further investigation, using sentiment analysis and association rules, offers additional insights into the data collected through the Delphi study.

The findings of this research thanks to the Experts' technical insights and examples provide a comprehensive understanding of how blockchain can incentivize green practices. Additionally, the study delineates unsupported assumptions about blockchain integration, shedding light on whether these are rooted in misconceptions, technological limitations, or conceptual flaws. Expert recommendations further contribute to a detailed list of CE applications likely to benefit from blockchain integration.

This paper aims to:

1) Provide a foundational understanding of blockchain technology pertinent to research on real-world applications like the CE, as advocated by Böckel et al. (2021)
2) Investigate the literature on both blockchain and the circular economy to identify the main areas of integration.
3) Explore the specific limitations and boundaries of each integration, with insights from blockchain industry experts.
4) Develop a list of applications where blockchain is poised to enhance CE practices, highlighting those that are less likely to benefit from the technology.

The structure of the paper is as follows: Section Two offers a background on Blockchain technology and the CE, laying the groundwork for understanding their real-world applications. Section Three describes the methodology, including its adaptation for this study and the expert panel composition. Section Four presents the quantitative results, while Section Five delves into the qualitative aspects, outlining expert concerns and recommendations for each topic. Section Six discusses the results, while Section Seven summarizes the study and suggests directions for future research.

2. Theoretical background

This section explores the foundational aspects of the circular economy and blockchain technology, initially examining each independently before considering their integration. Furthermore, in line with Böckel et al.'s (Böckel et al., 2021) recommendation to bridge the research-practice gap, the background of blockchain technology is deconstructed into its fundamental concepts. This approach aims to highlight its practical implementation within the context of the circular economy more effectively.

2.1. Circular economy

The CE concept, emerging as a sustainable development paradigm, aims to address the limitations inherent in the traditional linear 'take-make-dispose' model. At its core, the CE recognizes the finite nature of resources and endeavors to establish a regenerative and restorative system. It emphasizes reducing material consumption and waste generation while maximizing resource utility through recycling, refurbishing, and remanufacturing strategies (Cheng and Chou, 2018). This model seeks to decouple economic growth from resource consumption and environmental degradation (Murray et al., 2017).

The CE has gained considerable attention in academic and practitioner circles, becoming a central topic in discussions about sustainable development. Its benefits span environmental, economic, and social dimensions. Environmentally, it promises to lessen the strain on natural ecosystems, curtail greenhouse gas emissions, and conserve finite resources (Geissdoerfer et al., 2017). Economically, the integration of circular practices is seen as a catalyst for innovation, resource efficiency, and job creation (Dey et al., 2022). Socially, it advocates for a shift in consumer behavior towards sustainable consumption, emphasizing the value of durability, repairability, and product longevity over disposability (Shevchenko et al., 2023), (Ghisellini et al., 2016).

Despite its potential, the practical implementation of the CE faces significant challenges. A primary obstacle is the lack of comprehensive information throughout the product lifecycle, which hinders the effective application of circular principles. Many experts posit that blockchain technology could address this critical data gap, facilitating the transition to a more circular economic model (Kouhizadeh et al., 2019), (Wang et al., 2020), (Rejeb et al., 2023), (Verma et al., 2022), (Baralla et al., 2023).

2.2. Blockchain technology and its characteristics

Blockchain technology, fundamentally a distributed ledger system, operates through a consensus mechanism where data is added in sequential 'blocks'. The characteristics and applications of blockchain are diverse and multifaceted. Typically, blockchains are categorized based on access type, delineating public, private, and hybrid (or consortium) blockchains (Erol et al., 2021), (Kouhizadeh et al., 2020). Additionally, they are often distinguished by their ecosystems, such as Bitcoin, Ethereum, or Hyperledger, each with unique characteristics

(Centobelli et al., 2022), (Damianou et al., 2019).

However, categorizing blockchain merely by access type or ecosystem may not sufficiently illuminate its real-world application potential, particularly in contexts like the CE. Such a narrow focus can lead to misconceptions about the technology's integration capabilities. For instance, basing sustainable supply chain solutions on the characteristics of Bitcoin, and then attempting to apply these solutions using alternative blockchain platforms, can create false expectations due to the differing features and capabilities of these platforms.

To better understand and effectively link blockchain technology with real-world CE applications, an approach centered on the 'blockchain trilemma' is deemed suitable. This concept efficiently encapsulates the strengths and weaknesses of blockchain technology, offering a more comprehensive understanding of its capabilities and limitations in practical scenarios. The author acknowledges the existence of various formulations of the blockchain trilemma, including the well-known interoperability trilemma (Bhuptani). However, for the sake of clarity and to minimize complexity, this study specifically refers to the blockchain trilemma as introduced by Vitalik Buterin during the launch of Ethereum, because it is considered the most intuitive and suited to a broader audience (Buterin), (Crooks).

2.2.1. Blockchain trilemma

The concept of the 'blockchain trilemma' is pivotal in understanding the inherent trade-offs in blockchain technology. Notable distributed ledgers like Bitcoin exemplify a high degree of decentralization and security, but at the cost of scalability. In comparison to traditional financial systems like Visa and Mastercard, Bitcoin's transaction processing capacity is significantly lower (Cluchet et al., 2019). This limitation arises from Bitcoin's design choice to prioritize decentralization and security over throughput.

On the other hand, alternative blockchain platforms such as Ethereum or Tron attempt to offer greater scalability, but this often comes with reduced levels of decentralization and security. The central premise of the blockchain trilemma posits that it is technically challenging to simultaneously maximize decentralization, security, and scalability within a single blockchain architecture. Enhancing one of these aspects typically necessitates compromises in the other two dimensions (Buterin), (Raheman et al., 2021), (Fujihara, 2020), (Belchior et al., 2023).

This trilemma presents a paradox when considering the integration of blockchain with real-world applications, which often have specific technical requirements. For instance, an application demanding high scalability may necessitate compromises in blockchain's security and decentralization aspects. If the primary goal of integrating blockchain is to bolster security and decentralization, the resulting implementation may fall short of these objectives. Thus, it's crucial to acknowledge that the integration of blockchain into existing business processes doesn't necessarily imply enhancements in decentralization, security, or scalability across the board. Fig. 1 provides a graphical representation of the trilemma, illustrating these trade-offs.

2.3. Consensus and real-world data on the blockchain

Bitcoin's robust consensus mechanism underpins its decentralization and security. Adding a block to the Bitcoin blockchain necessitates solving a cryptographic puzzle, demanding significant hardware and energy investments (Antonopoulos, 2017). If the authenticity of this process is verified by other users, the miner who adds the block is rewarded with newly issued bitcoins. This ensures ledger security, as producing a block that is not recognized as valid results in no reward and forfeits the mining cost incurred. This process, known as proof-of-work (PoW), entails wealth consumption regardless of the block's validity. An alternative, proof-of-stake (PoS), involves agents staking their wealth as a guarantee of their block's validity. Here, wealth is consumed only if the block is deemed invalid, serving as a punitive measure (Antonopoulos and Woods, 2018).

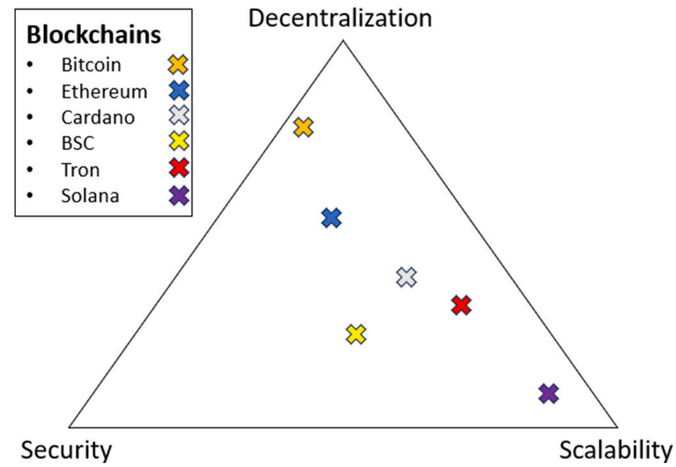

Fig. 1. Blockchain Trilemma
*Author elaboration.

It is crucial to understand that the blockchain's consensus mechanism only verifies data essential for adding a new block. For instance, in Bitcoin, the data verified and deemed secure relates solely to bitcoin cryptocurrency transactions (Antonopoulos, 2017). If the Bitcoin blockchain is utilized to register data like academic transcripts, credentials, or traceability information, its consensus mechanism does not authenticate this data, as it is unrelated to bitcoin transactions (Bistarelli et al., 2019), (BitMex-Research). This limitation extends to other blockchains, regardless of their consensus mechanisms, highlighting that they cannot inherently guarantee the authenticity of all data stored.

To bridge this gap, there is ongoing research and development of systems known as 'oracles,' designed to ensure the reliability of real-world data transferred onto the blockchain. These systems attempt to mimic blockchain consensus mechanisms but, due to the complexity of the issue, robust oracle solutions remain elusive (Caldarelli, 2020b), (Caldarelli, 2021). Some oracles ensure data integrity during the transfer process but not at the source (D-Nice). Others leverage crowd wisdom for data validation, effective for widely accessible information like weather or election results (Peterson et al., 2015). However, verifying less accessible or private data remains a challenge. The development of robust oracles necessitates a dual approach that encompasses both philosophical considerations and practical methodologies, owing to the intricate mechanics involved. One line of inquiry delves into the fundamental concepts of trust and truth that oracles must embody in their responses, alongside the design of an optimal incentive system to ensure their reliability (Hassan et al., 2023), (Sztorc), (Xiao et al., 2023). Conversely, another research direction prioritizes practical interoperability, exploring seamless integration among heterogeneous blockchains as well as between blockchains and other technologies (Belchior et al., 2022), (Kayıkcı and Subramanian, 2022), (Zhu et al., 2023).

Simply integrating blockchain into applications such as waste traceability or carbon emission monitoring, therefore does not inherently enhance data authenticity or reliability (Kumar et al., 2020), (Gaggioli et al., 2019). A comprehensive approach, potentially involving other technologies like IoT, is necessary for effective data acquisition and verification (Caldarelli et al., 2023). To illustrate, blockchain technology is anticipated to enhance the quality of digital twins, thereby improving the reliability and security of data. Digital twins serve as digital representations of physical objects, tracking their entire lifecycle up to disposal. From a circular economy perspective, this capability is particularly advantageous for products like batteries, which require secure tracing and monitoring to ensure safe disposal or recycling (Baralla et al., 2023). While it is indeed feasible to create digital twins on the blockchain, for instance, through NFT technology, and to safeguard their data using robust consensus mechanisms, the efficacy of blockchain oracles in reliably gathering data for real-time detection remains a topic of ongoing debate (Hunhevicz et al., 2022), (Sadri et al., 2023), (Zhou and Yang, 2022). Table 1 provides a summary of the information discussed in this section.

3. Methodology

In light of the study's objectives, the Delphi method was selected as the primary research approach (Dalkey and Helmer, 1963) (Hsu and Sandford, 2019). Renowned for its efficacy in consolidating expert opinions on specific subject matters, the Delphi method has been extensively used not only in healthcare but also in information systems research (Addison, 2003), (Keil et al., 1998), (Brancheau and Wetherbe, 1987). This method involves a series of iterative surveys designed to aggregate and refine expert opinions, ultimately leading to a consensus.

Recent advancements in the application of the Delphi method have introduced various modifications and adaptations from its original form (Taylor, 2020). Typically, the initial round involves an open-ended survey, allowing experts, often organized into panels, to freely express their views on the topic at hand (Keeney et al., 2001). A notable modification in this approach is the inclusion of predetermined questionnaire items (Eubank et al., 2016), (McKenna, 1994). These items, derived from a thorough literature review, serve to guide the first round in gathering additional insights, clarifying redundancies, or addressing specific issues related to each statement (Keeney et al., 2001), (Banayan et al., 2015). While this approach might introduce a certain degree of bias by potentially constraining the scope of discussion, it is a widely accepted practice, given its foundation in comprehensive literature analysis.

An alternative adaptation involves replacing the initial open-ended survey with semi-structured interviews (Taylor, 2020). This approach allows for a deeper level of engagement with the experts, yielding more elaborate qualitative data. The semi-structured format provides flexibility, enabling experts to expand upon their responses, thus enriching the data pool for the study.

Given the substantial amount of qualitative and quantitative data obtained through a Delphi study, several studies have combined the outputs from Delphi rounds with additional methodologies to further validate the robustness of the results (Sahal and Yee, 1975), (Murray et al., 1985), (Chang et al., 2000).

Table 1
Concepts to be aware of when evaluating real-world blockchain integrations[a].

Concept	Description	Reference
Blockchain Trilemma (by Vitalik Buterin)	Blockchain technology inherently seeks a balance among scalability, security, and decentralization. Maximizing one attribute often entails constraints on the others.	(Buterin), (Raheman et al., 2021), (Fujihara, 2020)
Consensus	The consensus mechanism in blockchain technology is designed to verify only the information essential for the generation of a new block.	(Antonopoulos, 2017), (Antonopoulos and Woods, 2018)
Real-world data on a blockchain	Like traditional databases, blockchain technology is capable of storing virtually any form of real-world data. However, it does not inherently apply quality criteria to the extrinsic data being uploaded.	(Bistarelli et al., 2019), (BitMex-Research), (Caldarelli, 2023)
Secure Oracles	Highly secure oracles are pivotal in ensuring the integrity of transmitted data and can provide critical information. Yet, as of now, they fall short of being infallible arbiters of truth.	(D-Nice), (Peterson et al., 2015), (Sztorc), (Delphi)

[a] Author elaboration.

3.1. Our Delphi study

The methodology employed in this research for the modified Delphi study unfolds in three distinct phases. Building on (Eubank et al., 2016), (McKenna, 1994), the initial step involved conducting a comprehensive literature review in order to find relevant items to include in the Delphi study. The review process, was performed using the Scopus academic database and to ensure a broad scope, the search was limited to the keywords 'blockchain' and 'circular economy.' This search, conducted on June 7, 2023, yielded 227 entries. From this sample, 54 articles were excluded due to unavailability, language differences, or for being clearly unrelated. The remaining 173 articles were downloaded and scrutinized for their relevance to the study. In the review process, it was found that some articles delved into sector-specific blockchain applications within the Circular Economy (CE). However, considering that blockchain experts might not have detailed knowledge of certain sectors, such as plastic processing, articles with a narrow focus were excluded. The goal was to keep the analysis broad, including sector-specific examples only when they were broadly applicable. Ultimately, articles that did not contribute relevant information for this research, specifically lacking assumptions that experts could evaluate, were excluded. This process resulted in the further exclusion of 91 articles, yielding a final sample of 82 articles.

Each article of the final sample was meticulously analyzed, and assertions pertaining to blockchain applications in CE were recorded in a separate document. Subsequently, these claims were methodically compared and categorized, with an aim to eliminate duplicates and identify both recurring and unique proposals. This step, admittedly, introduces a degree of subjectivity, as different researchers might extract varying topics or articulate them differently. Nonetheless, it is hypothesized that such variations in item formulation or categorization are unlikely to significantly skew the study's outcome or validity. This is premised on the assumption that the overarching themes and insights would remain consistent despite potential heterogeneity in item presentation. Regarding thematic saturation, it is influenced by a key constraint: the length of the interview. With an average discussion time of 5 min per item and an overall interview duration of approximately 50 min, the study could only accommodate a maximum of ten items. Consequently, related themes were grouped into macro categories, enabling a broader range of themes to be encompassed within the study's scope.

The distinct assumptions and proposals identified were summarized and utilized as items for the second phase of the study. Table 2 enumerates these research items.

The second phase of the study entailed conducting direct, semi-structured interviews with blockchain experts. Prior to these interviews, experts were invited via email and provided with study materials, including the scope and content of the questions. This allowed experts to gauge their familiarity and competence with the topics under discussion. These interviews, averaging an hour in length, were divided into two parts. Initially, experts rated their agreement with the items found in the first phase of the study with the literature review using a 4-point Likert scale (ranging from 1 = strongly disagree to 4 = strongly agree). Experts also had the option to abstain from providing an evaluation on a specific topic if they were unable to predict the outcome of an item. Subsequently, they were encouraged to elaborate on their ratings and provide rationale for their choices. Specifically, when opting to abstain, they were encouraged to articulate the reasons that hindered speculation on particular outcomes. It is important to clarify that the experts' opinions on these statements, though inspired by academic literature, are not intended as evaluations of the quality of the cited studies themselves.

Replacing the traditional first round of a Delphi study with a literature review, these interviews served as the initial stage of opinion

Table 2
Research items extracted from the literature review.

Items	Description	Sources
Improve logistic processes	Blockchain technology enhances the traceability of transactions in supply chains, allowing stakeholders to optimize inventory efficiency, minimize loss of products and materials, and make a positive impact on waste production and resource utilization	(Younis et al., 2020), (Yildizbasi, 2021), (Paul et al., 2022), (Rejeb et al., 2022), (Castañer and Oliveira, 2020)
Facilitate reverse logistics	Blockchain is envisioned to ensure comprehensive traceability within supply chains, thereby facilitating stakeholders in effectively monitoring reverse logistics processes for waste reuse, refurbishment, and the return of components and unsold products.	(Kouhizadeh et al., 2019), (Wang et al., 2020), (Lo et al., 2018), (Kouhizadeh et al., 2020), (Kouhizadeh and Sarkis, 2018b)
Improve supplier selection	The transparency of data on a blockchain can aid in supplier selection by documenting the historical performance of suppliers. Such transparent records of past performance can bolster trust in supply chains, reduce opportunistic behavior, and enhance collaboration among stakeholders.	(Wang et al., 2020), (Paul et al., 2022), (Saberi et al., 2019b), (Ciardiello et al., 2020) (Upadhyay et al., 2021b) (Rejeb et al., 2022) (Böhmecke-Schwafert et al., 2022) (Grati et al., 2023)
Minimize transaction costs by reducing intermediaries.	Blockchain technology, by directly connecting buyers and sellers, has the potential to reduce transaction fees and streamline the exchange of goods, services, or resources. Furthermore, its data transparency can support peer-to-peer (P2P) marketplaces, allowing stakeholders from diverse supply chains to freely exchange waste without intermediaries.	(Akinade and Oyedele, 2019) (Montakhabi et al., 2021) (Upadhyay et al., 2021b) (Böhmecke-Schwafert et al., 2022) (Pay and Lombard-platet, 2021) (Centobelli et al., 2022)
Incentive circular behavior	Blockchain-based systems can introduce incentives, like tokens or cryptocurrencies, to promote and reward behaviors that align with CE principles.	(Cluchet et al., 2019) (Farizi and Sari, 2021) (Gong et al., 2022) (Grati et al., 2023) (Böhmecke-Schwafert et al., 2022)
Manage green production.	Blockchain technology can be utilized to gather and maintain data on green products, such as monitoring gas emissions to verify a product's environmental friendliness, auditing the usage of chemicals, water, and land, and tracking workplace conditions, including factors like light, humidity, temperature, and working hours.	(Upadhyay et al., 2021b) (Bhubalan et al., 2022) (Shou and Domenech, 2022) (Venkatesh et al., 2020) (Tian, 2017)
Enhance product share and sharing economy.	Blockchain technology may facilitate networks for product sharing among different users, enabling companies to share idle resources, thereby reducing costs and carbon emissions.	(Esmaeilian et al., 2020) (Bekrar et al., 2021) (Böhmecke-Schwafert et al., 2022) (Sharma et al., 2021) (Te Wu et al., 2018) (Alexandris et al., 2018) (Yildizbasi, 2021) (Rejeb et al., 2022)
Guarantee authenticity of reused/recycled products.	Through the traceability offered by blockchain, consumers can gain assurance regarding the origin of products, their authenticity, and their status post-reuse and recycling.	(Casado-Vara et al., 2018) (Upadhyay et al., 2021b) (Yildizbasi, 2021) (Shou and Domenech, 2022) (Centobelli et al., 2022) (Saberi et al., 2019b)
Prolong product life	Blockchain can be deployed to accumulate data on the lifecycle of products/components, usage phases, maintenance and repair cycles, and geo-localization. In CE assets composed of modular components, blockchain and IoT systems could be instrumental in predicting equipment malfunctions, thereby streamlining repair or recycling procedures.	(Grati et al., 2023) (Hatzivasilis et al., 2021) (Rejeb et al., 2022) (Magrini et al., 2021) (Grati et al., 2023)
Enable Digital Product Passports (DPP) on the blockchain.	Blockchain is considered a suitable platform for storing digital product passports, owing to its transparent, immutable, and permanent record-keeping capabilities.	(Bhubalan et al., 2022), (Li and Wang, 2021)

convergence (Taylor, 2020). Contrary to the suggestion in (McKenna et al., 2001), participants were not prompted to propose new items for the questionnaire to avoid potential biases as highlighted in (Keeney et al., 2006). However, additional insights and ideas offered by experts during the interviews were incorporated into the study's findings. A distinctive feature of this Delphi study is that items failing to reach consensus are not simply omitted or discarded. Instead, they are subject to further exploration in the qualitative segment of the research. This approach aims to illuminate the underlying causes of confusion and heterogeneity, which contribute to the absence of consensus among experts.

Drawing from (Ilbery et al., 2004), the experts' comments will inform the discussion phase of the study, where their perspectives will be analyzed in the context of the results. Their insights are expected to clarify the rationale behind their selections and distinguish between proposals grounded in technological feasibility and those based on misconceptions or false assumptions. Expert recommendations are anticipated to guide future research directions effectively.

In the third phase, experts received a report summarizing the first round's responses along with another survey featuring items that did not achieve consensus. Following the approach in (Thomson et al., 2009), the second survey included explanatory notes on item classification and feedback (both quantitative and qualitative) from the first survey. Once responses to the second survey were collected, a final report was compiled and shared with the participants. To maintain the integrity of the Delphi method, individual responses and comments were anonymized, preventing direct influence among participants and ensuring confidentiality. While the list of experts is transparent, their individual responses remain confidential throughout and after the study's conclusion.

Interviews were systematically recorded and subsequently transcribed into eleven separate Word documents, one for each interview conducted. The transcriptions were meticulously edited to remove any redundant sentences, enhancing clarity and conciseness. The content from each interview was organized according to the discussed items and summarized. Notably, certain statements from experts that were deemed particularly insightful and self-explanatory were highlighted and preserved in their original form.

To facilitate a more straightforward comparison, the content was restructured into ten distinct files, each corresponding to a specific item discussed across the interviews. This reorganization allowed for the inclusion of relevant comments from all eleven experts for each item, streamlining the analysis process. Upon reviewing the transcribed content, recommendations and conditions expressed by the experts were extracted and systematically organized into specialized tables for each item discussed. This organized content then underwent a detailed examination, structured around the evaluation and agreement levels associated with each item, enabling a coherent discussion of the findings.

To further substantiate the results obtained from qualitative and quantitative data, this research employs two additional methodologies. Sentiment analysis was applied to quantitatively assess the emotional tone and subjective content of expert opinions, enhancing the understanding of consensus and highlighting areas of disagreement. The analysis presents the sentiment on the topic using two indicators: polarity and subjectivity. Polarity ranges from −1 to 1, where −1 indicates extremely negative sentiment and 1 indicates highly positive sentiment about a specific subject. Subjectivity, on the other hand, ranges from 0 to 1. Values closer to 0 suggest that opinions are primarily based on facts, whereas values closer to 1 indicate opinions grounded predominantly in personal beliefs. This approach allows for an understanding of how a certain topic is perceived by the expert panel and what the overall sentiment is, regardless of the extent of consensus reached.

In contrast, association rule analysis was employed to reveal potential correlations among research items. The analysis assesses the probability that an expert who evaluates one item will assign similar evaluations to other items. To ensure the robustness of the results, a 100% confidence level was chosen, indicating that every association rule identified occurs consistently, 100% of the time. The underlying assumption for implementing this type of analysis is that if experts evaluate different items similarly, whether positively or negatively, it is reasonable to hypothesize that the likelihood or uncertainty of their success is perceived dependent on similar factors. Both sentiment analysis and association rule analysis have been executed using Python, utilizing the TextBlob and mlxtend libraries, respectively.

Fig. 2 offers a schematic overview of the Delphi study process.

3.2. Respondents profile

The careful selection of experts is paramount to the success of this study. In an effort to differentiate this research from prior work in the field and to minimize potential biases, a deliberate choice was made to include experts renowned in the blockchain domain, but not actively engaged in blockchain integrations for the CE. This approach aims to avoid conflicts of interest and ensures impartiality in their assessments.

To fulfill the methodological requirements and ensure a comprehensive perspective, experts were selected based on their diverse backgrounds, without imposing geographic, academic, or professional limitations. However, a minimum of five years of experience with a preference of ten in the blockchain field was deemed necessary. Preference is also given to experts with renowned experience in the oracles' field. This criterion aligns with the findings from (Caldarelli, 2020a), (Caldarelli, 2020b), (Caldarelli, 2022), (Antonopoulos, 2019), which suggest that misunderstandings about blockchain integrations often stem from a lack of consideration for oracles and real-world interactions. Oracles are employed to trace both tangible and intangible real-world assets (RWAs) in numerous real-world blockchain integrations, including those in the circular economy. Consequently, a deep understanding of how they operate is considered essential for a more informed evaluation of the topics discussed in this study (Caldarelli, 2020a), (Kumar et al., 2020), (Al-Breiki et al., 2020). Therefore, a significant portion of the experts chosen for this study possess specialized knowledge in the field of oracles. The initial selection of experts began with a targeted approach, directly reaching out to individuals who met the above-mentioned criteria. Subsequently, a snowball sampling method was employed, where additional experts were recommended by the initial participants. To ensure a diverse range of perspectives, from the pool of suggested names, individuals who offered distinct characteristics compared to those already interviewed were invited to contribute. This process continued until the sample reached the desired number.

Furthermore, although the study drew insights from blockchain

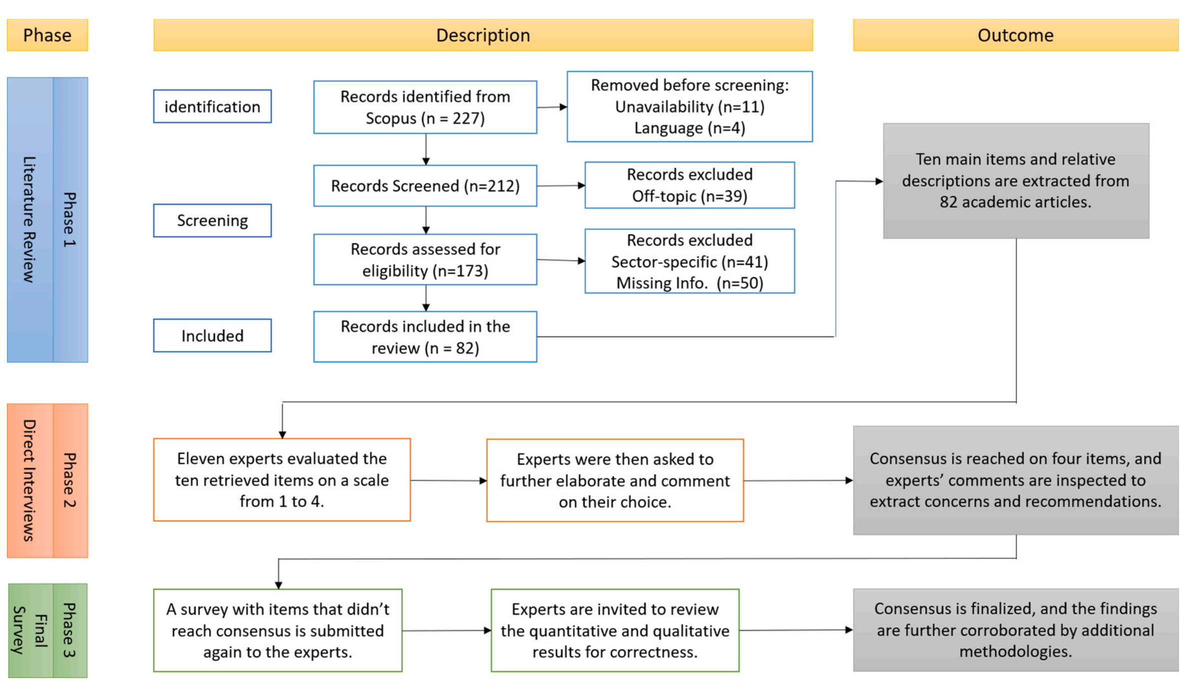

Fig. 2. Overview of the Delphi study.

industry experts, it aimed to maintain a balanced composition of its expert panel, given its focus on the circular economy. Special attention was given to including professionals from computer science, economics, management, and other disciplines to provide a multifaceted perspective on the underlying subject matter. Additionally, in accordance with Delphi study protocols, each expert was sent an invitation email before their interview. This email outlined the research objectives and the specific topics to be discussed, a preparatory step taken to ensure that the panel consisted of distinguished figures in blockchain technology, capable of making significant contributions to the circular economy.

Regarding optimal panel size, the literature suggests varying ideal sizes based on the qualifications of the professionals involved (Taylor, 2020). For panels composed of highly qualified experts, a smaller group size is generally preferred, with four members already considered sufficient (Skinner et al., 2015). However, as noted by (Hogarth, 1978), an optimal panel consisting of qualified experts typically includes 8 to 12 members with Taylor et al. (Taylor, 2020) recommending a panel of eleven members to maximize reliability. This panel size was then selected to balance a diverse range of insights with manageability and depth of analysis. The complete list of participating experts, along with their roles, background, and main areas of expertise, is detailed in Table 3.

3.3. Consensus

In determining the appropriate consensus level for this study, guidance was taken from (Keeney et al., 2006), which suggests that for topics not of critical urgency, such as in healthcare, a consensus level fairly below 100% is acceptable. Existing literature on Delphi studies indicates varying consensus thresholds, typically ranging between 51% and 80%, depending on the subject matter. Notably, a consensus level above 70% is often favored for its balance of inclusivity and decisiveness, as recommended in (McKenna et al., 2001), (Loughlin and Moore, 1979), (Green et al., 1999).

Accordingly, for this study, the desired consensus level was set at a minimum of 8 out of 11 respondents (approximately 73%) agreeing on either a positive (ratings 3–4) or negative (ratings 1–2) stance regarding a specific item. However, a consensus level above 51% will also be acknowledged as significant, albeit representing a weaker agreement. It's important to note that while respondents have the option to remain neutral (i.e., express no opinion), such neutrality does not impact the threshold for determining significance. This is because neutrality could potentially dilute the strength of the consensus on certain claims compared to others.

To streamline the study and minimize the burden on the participating experts, the decision was made to limit the Delphi process to two rounds. This approach implies that not all items may reach the set consensus level, aligning with the practical constraints and scope of the study.

4. Findings from the second and third phases

The findings of the study are derived from two phases of the Delphi process, as well as from the outcomes of the sentiment analysis and association rule analysis. The first survey round, constituting the second phase of the study, commenced on September 21, 2023, with the interview to Nicholas Fett and concluded on November 02, 2023, with the interview to Shayan Eskandari. Post-interview analysis revealed that 4 out of 10 topics achieved a complete consensus (72.72%) and were subsequently excluded from the second survey round. Additionally, two items exceeded a 51% consensus threshold, warranting their inclusion in the third phase to either confirm or enhance the level of agreement.

The second survey round, marking the third phase of the study, was conducted between November 07 and December 09, 2023. The detailed outcomes of this round are presented in Table 4. Notably, no new items reached a consensus in the second round, with minimal changes in voting patterns. However, one item transitioned from a weak to a strong consensus. Overall, six out of ten items achieved at least a weak consensus (>51%). Sentiment analysis and association rule analysis were instead performed in 2024, following definitive feedback from the expert panel.

Analysis of the results indicates that consensus was not reached for forward and reverse logistics, likely influenced by a nearly 30% abstention rate. It is important to clarify that the abstention rate in this study does not equate to a lack of responsiveness, as the response rate was 100% in both rounds. An expert is considered to have abstained when they express discomfort in providing either a positive or negative opinion on an item. Reasons for abstention include perceptions of the technology's immaturity for application in the specified field, the presence of conflicting results from pilot projects, or a self-acknowledged lack of expertise in a particular area by the experts. A qualitative analysis of expert comments further elucidates the reasons behind their decisions to abstain.

Forward logistics, compared to reverse logistics, received a more negative perception (average rating of 1.6 with 45.45% agreement). In contrast, supplier selection garnered a strong positive consensus in the first round (average rating of 3.375 with 72.72% agreement). The reduction in transaction costs, while viewed positively, did not achieve consensus (average rating of 3.4 with 45.45% agreement). The item regarding incentivizing CE behavior attained the highest positive

Table 3
List of participants in the Delphi study.

PARTICIPANTS[a]	BACKGROUND	POSITION (ACTUAL OR PAST)	YEAR INTO BLOCKCHAIN	MAIN EXPERTISE/SKILLS
Nicholas Fett	Economics	CTO/Founder at Tellor	2013	Oracles, Game Theory
Saša Milić	Computer Science	Researcher, Founder at API3	2018	Statistics, Programming languages
Edmund Edgar	Philosophy	Founder at Reality Eth.	2011	Mechanism Design
Chhay Lin Lim	Philosophy	Lecturer, Founder at Heartland Finance	2011	Payment methods, blockchain ethics
Daniele Pinna	Physics	Lecturer, Head of Research at KEOM	2011	Dynamic systems, Quantitative modeling.
Benjamin Senn	Econometrics	Blockchain and smart contract developer	2011	Macroeconomics, Smart Contracts
Abdul Osman	Business Administration, Computer science	CEO/Founder at Gora	2013	Real-world blockchains, Business Analytics
Thomas Bertani	Computer Science	Founder at Oraclize, Cofounder at Cross-chain alliance.	2012	Oracles, Cross-Chain protocols
David Minarsch	Economics	CEO/Founder at Valory	2013	Game Theory, Artificial Intelligence
Clément Lesaege	Computer Science	CTO/Founder at Kleros	2013	Dispute resolution, Cryptoeconomics
Shayan Eskandari	Computer Science	Researcher, CTO at Ether Capital	2012	Information Security, System Architecture

[a] Experts are ordered by chronological participation in the interviews.

Table 4
Outcome of the second-round survey and sentiment analysis.

Item	Mean 1-2 (%)	Mean 3-4 (%)	N° Abst. (%)	Avg. Polarity	Avg. Subjectivity
Improve logistic processes	1.6 (45.45%)	3 (27.27%)	3 (27.27%)	-0.021	0.476
Facilitate reverse logistics	1.5 (36.36%)	3.25 (36.36%)	3 (27.27%)	0.017	0.386
Improve supplier selection	1.5 (18.18%)	3.375 (72.72%)**	1 (9.09%)	0.13	0.507
Minimize transaction costs by reducing intermediaries.	2 (36.36%)	3.4 (45.45%)	2 (18.18%)	-0.034	0.485
Incentive circular behavior	2 (9.09%)	3.75 (72.72%)**	2 (18.18%)	0.088	0.524
Manage green production.	1.25 (72.72%)**	3.5 (18.18%)	1 (9.09%)	-0.139	0.572
Enhance product share and sharing economy.	1 (36.36%)	3.3 (27.27%)	4 (36.36%)	0.02	0.875
Guarantee authenticity of reused/recycled products.	1.83 (54.54%)*	3.3 (27.27%)	2 (18.18%)	-0.027	0.565
Prolong product life	1.1 (81.81%)**	/	2 (18.18%)	-0.156	0.464
Enable Digital Product Passports (DPP) on the blockchain.	1.75 (72.72%)**	3.5 (18.18%)	1 (9.09%)	-0.096	0.433

*≥51% weak consensus, **≥72.72% strong consensus. Consensus reached on positive opinions is marked in Green while negative is marked in Red.

consensus (average rating of 3.75 with 72.72%), while prolonging product life achieved the highest consensus but with the lowest evaluation (average rating of 1.25 with 81.81%). Negative consensus was reached for supporting green production and digital product passports, with average ratings of 1.25 and 1.75, respectively. The item on supporting the sharing economy saw nearly 40% abstentions, indicating unpredictability in current understanding, while authentication support garnered negative opinions but only a weak consensus (average rating of 1.83 with 54.54%).

The sentiment analysis provided valuable insights into the overall sentiment held by the expert panel on each topic, irrespective of the final consensus reached. Although polarity values are expected to range between −1 and 1, the analysis revealed values close to 0 for several reasons. Firstly, sentiment analysis is highly sensitive to words like “awful” or “superb,” which were predictably absent from the more moderated language used by the panel of experts. Consequently, the absolute values of each sentence rarely reached extreme polarities. Moreover, to maintain the anonymity of the experts’ interview content, the polarity values were averaged, which naturally led to values closer to 0 when positive and negative values were combined. Additionally, to mitigate biases caused by variations in response length among experts, a polarity value was calculated for each expert’s opinion before deriving the overall average.

The highest positive polarity was observed for the use of blockchain in improving supplier selection, followed by the incentivization of circular behavior, values that suggest a relative enthusiasm for these topics compared to others. Other topics with positive values include the use of blockchain to facilitate reverse logistics and enhance the sharing economy. However, these values are very low, almost neutral, and notably, the integration in the sharing economy received the highest subjectivity value. Overall, the subjectivity balance indicates that experts based their analyses on a mix of facts and personal beliefs. In the case of the sharing economy, however, personal beliefs predominated over facts, suggesting that the topic might be under-explored or that blockchain’s relevance to it is not perceived as strong.

Apart from these three, all other topics displayed negative polarity, ranging from values close to zero, as in the integration in logistic processes, to −0.156 for prolonging product life. The negative polarity that emerged from this analysis corroborates the negative consensus observed in the Delphi rounds on some of these topics and supports the view that most of these integrations are viewed with skepticism or limited enthusiasm.

Association rule mining was performed with a 100% confidence level to identify rules of the highest significance. Table 5 provides an overview of the rules found. A minimum support threshold of 20%, requiring at least three experts to make the same selections on highly evaluated topics, was set. The analysis yielded four rules with complete confidence. Experts who positively evaluated blockchain in logistic processes also favorably assessed reverse logistics, likely following similar

Table 5
Outcome of the association rules mining.

Lhs	Rhs	Frequency	Support	Confidence	Lift
Association of topics with high evaluations ≥ 3					
Item 1	Item 2	3	0.27	1	2.75
Item 8	Item 3	3	0.27	1	1.38
Item 7	Item 3	3	0.27	1	1.38
Item 4, Item 5	Item 3	3	0.27	1	1.38
Association of topics with low evaluations ≤ 2					
Item 6	Item 9	8	0.73	1	1.22
Item 10	Item 9	8	0.73	1	1.22
Item 10, Item 6	Item 9	7	0.64	1	1.22

assumptions. Additionally, there were correlations between positive evaluations of blockchain for the authentication of recycled products and improving supplier selection, as well as between blockchain for the sharing economy and supplier selection. Furthermore, experts who positively evaluated the use of blockchain to reduce transaction costs and encourage circular behavior also positively assessed supplier selection.

Surprisingly, negative evaluations revealed a higher number of rules, with 852 identified under the same criteria as positive evaluations. This finding allowed for an increase in the minimum support level to 60%, meaning that for the three rules identified, at least seven out of eleven experts concurred when negatively evaluating an item. There was a significant correlation among negative evaluations of blockchain's use in managing green production, prolonging product life, and enabling DPP. These integrations are most likely perceived to rely on similar blockchain properties or characteristics that are deemed unsuitable for these purposes. Lastly, lift value is a metric used to measure the strength of an association between items in a dataset. It helps in understanding how likely items are to be selected together more than just by chance. A lift greater than 1 indicates that the rule is better at predicting the outcome than guessing based on the items of the individual probabilities alone, suggesting a positive association. Within this specific dataset, despite the increase in minimum support, the lift ratio remains consistently above one, indicating strong significance among the identified rules.

The experts' comments were instrumental in shedding light on the rationale behind these quantitative results. A comprehensive overview of their insights and interpretations of the results is provided in the subsequent paragraphs.

5. Experts' comments, concerns, and recommendations

This section delves into the experts' comments, which are systematically organized according to the items discussed in the study. The commentary is presented for each item, regardless of whether a consensus was reached. Given the nascent stage of the sector, the limited availability of related research, and the significant expertise of the distinguished experts involved, as outlined in our methodology, we have included all provided comments and opinions. This includes insights not directly linked to items that achieved consensus, underscoring our commitment to a comprehensive and inclusive analysis. This comprehensive approach aims to elucidate the underlying reasons behind the experts' perceptions of specific blockchain integrations within the CE. It also seeks to explore the diversity of opinions and the factors contributing to ongoing debates where consensus is lacking.

For ease of reference and to enhance comprehension, the items are presented in the same sequence as they appear in Table 2. This alignment facilitates a direct comparison between the consensus results and the qualitative insights offered by the experts. Table 6 through 15 provide a detailed account of the experts' concerns and recommendations pertaining to each research item. These tables serve as a crucial resource for understanding the nuances of expert opinions and the implications of their perspectives for future research and practical applications. Adjacent to the title of each subsection discussing items that have reached consensus, quantitative data detailing the evaluation and level of agreement will be presented. This strategy is designed to enable readers to distinguish between comments reflecting positive or negative consensus and those resulting from indecision.

5.1. Improve logistic processes

Experts exhibit a heterogeneous stance on the application of blockchain in logistic processes, although the sentiment analysis is slightly negative. A minority with positive views highlight its potential in global trade scenarios, where multifaceted transactions and extensive paperwork are involved across numerous countries (Kouhizadeh et al., 2020). They suggest that blockchain could harmonize the accounting system by adding a third, immutable ledger where all data and signatures are transparently stored (Schmitz and Leoni, 2019). However, substantial concerns are raised about utilizing blockchain to enhance traceability and inventory efficiency for reducing material loss and waste production. Improved traceability is attributed not to blockchain itself but to oracles and the '*stapling problem*,' which pertains to the challenge of reliably linking a physical product to a blockchain record (Eskandari et al., 2021). As an example, it's difficult in practice to ensure that a received shipment precisely matches its blockchain registration (Kumar et al., 2020).

Concerning the fact that blockchain is often recommended in absence of trust, an expert emphasizes the existing trust within business relationships, remarking, '*Most of the time when you do business, there is already some trust involved ….the supply chain is still phone calls and handshakes, even faxes. This blockchain optimization is superfluous*'. Echoing this sentiment, another expert describes such blockchain implementation as '*overengineering*', arguing that achieving transparency can be accomplished by simply publishing data (Andolfatto, 2018), (Ivanitskiy).

The consensus among experts is that supply chain inefficiencies are not predominantly due to a lack of trust but rather to other factors such as digitalization shortfalls. In terms of inventory management, inefficiencies are often internal organizational issues, where a standard database is deemed sufficient. An expert comments, '*Order or inventory tracking is not a problem as incorrect inventory entry ….human mistake, thefts or accidents can cause products and material loss. Blockchain cannot prevent those*'.

Another expert shifts focus to implementation challenges, asserting that '*There are bigger challenges on the implementation rather than usefulness.*' This includes issues like data interoperability, the complexity of establishing a universally accepted source of truth, and the development of privacy-preserving smart contracts (Carminati et al., 2018). Furthermore, the expert points out that the high setup costs of blockchain make it a viable option for supply chain applications only if the technology is already being used in the company for other purposes, thus questioning the additional benefits of its implementation.

Table 6
Experts concerns and recommendations over blockchain integration for forward logistic processes.

Concerns
There are bigger challenges in the implementation rather than usefulness.
Most of the blockchains are not suitable for logistic processes.
For real-world assets, blockchain doesn't equal ownership.
The same result is achievable by just publishing data.
It's still challenging to attach a physical product to the blockchain (Stapling problem)
Blockchain is recommended in the absence of trust, while there is always some sort of trust involved in businesses.
Products and material loss are not perceived as related to a lack of trust but to a lack of digitalization and human mistakes that blockchain is unlikely to prevent.
Conditions and Recommendations
Given the high setup costs, blockchain should only be implemented for internal logistic processes if it is already used for other processes.
In the case of global trade, blockchain can simplify the paperwork and signature handling.
Blockchain can be suitable to harmonize multiple accounting systems.
Certain scenarios necessitate actors to adopt a common platform standard; in such cases, blockchain technology can be effectively leveraged.

5.2. Facilitate reverse logistics

The consensus and the sentiment among experts regarding the application of blockchain in reverse logistics is more favorable compared to forward logistics, albeit with some reservations. Reverse logistics introduces an additional participant, the entity responsible for sending items back, necessitating an extra layer of verification. This aspect theoretically justifies the utility of blockchain due to the involvement of multiple actors (Centobelli et al., 2022), (Bekrar et al., 2021). However, its practical implementation is not without challenges and skepticism.

A segment of the experts believes that blockchain might be an overextended solution for reverse logistics, arguing that a conventional database could adequately serve the purpose. They suggest that even a regular database, when distributed across multiple computers and servers, can achieve the degree of decentralization required for this scope. The real-time updating of reverse logistics information via blockchain is acknowledged as potentially beneficial, but this advantage is contingent on whether the blockchain is already in use for other processes within the organization, considering the significant setup costs involved.

One expert, who is particularly optimistic about this implementation, nonetheless perceives it as impractical in the current business context. He argues that reverse logistics is typically a process companies strive to minimize, except in cases where there is a regulatory or market-driven need to recollect certain types of waste, such as batteries (Grati et al., 2023). In such scenarios, the expert posits, the efficacy of blockchain hinges on the existence of a decentralized identification service (Kerner), underscoring the conditional nature of its utility in reverse logistics.

5.3. Improve supplier selection [3.375 (72.72%)]

The application of blockchain in supplier selection garners broad consensus and optimistic expectations among experts. The central premise is that storing a company's reputation on a decentralized database can foster transparency, positively influencing supplier behavior, enhancing collaboration, and reducing fraud (Battah et al., 2021). One expert encapsulates this view, noting, *'It's a marketing thing. If other entities know you are more reliable, they are more likely to get it from you'*. This application differs from logistics processes in that sharing data with others is crucial, making blockchain a valuable tool in this context.

Experts recognize the potential risk of historical data manipulation in competitive supplier environments. Blockchain's immutable nature ensures data integrity, preventing such tampering. The prospect of decentralized reputation systems holds significant appeal, as experts underscore the importance of preventing centralized control over such data. While there is consensus on the inadequacy of centralized databases, given the requisite trust, it is also acknowledged that blockchain may not be the sole or optimal solution. An alternative suggestion includes the use of timestamps and data hashes, though blockchain natively integrates these features.

Regarding private blockchains, they are seen as potentially suitable, albeit with implementation challenges. One expert highlights the difficulty in finding skilled professionals and the necessity of building tools from scratch, along with concerns about system interoperability. Despite these challenges, on which recent studies and projects are contributing to overcome, a private blockchain's traceability feature of data reordering or reorganization is viewed as beneficial (Guo et al., 2024), (Brandín and Abrishami, 2024).

The infamous 'Oracle problem' and the potential for collusion in a blockchain context are acknowledged (Caldarelli, 2020b), (Egberts, 2017), (Douceur, 2002). However, experts opine that the risks are mitigated by the inherent traceability of data entries and the long-term benefits of maintaining a trustworthy reputational score (Truong et al., 2021). A more critical view suggests that supplier review data should be accompanied by signatures from involved parties as proof of transaction, adding, *'You want to have more than just what the buyer/seller said'*.

One dissenting expert expresses skepticism about the long-term viability of this blockchain application. The concern is that even though supplier data on the blockchain is immutable, transparent, and non-erasable, it does not preclude the possibility of entities selling their reputations, a phenomenon observed in current web2 platforms (Olsen). This perspective underscores a limitation of blockchain systems in preventing certain types of reputational manipulation.

5.4. Minimize transaction costs by reducing intermediaries

The topic of blockchain's role in reducing transaction fees did not achieve consensus among experts, although their opinions were not markedly divergent and polarity was slightly negative. Some experts expressed skepticism about the claim that blockchain can lower transaction fees. One expert pointedly remarked, *'We should just look at the evidence. Has blockchain made anything cheaper? … Blockchain is more expensive than running a database, so the costs will more likely increase'*. This view challenges the common perception of blockchain as a cost-effective alternative to traditional databases (Te Wu et al., 2018), (Roeck et al., 2019).

Table 7
Experts concerns and recommendations over blockchain integration for reverse logistics.

Concerns
An ordinary database would suffice. Decentralization is guaranteed by hosting copies by multiple actors.
Reverse logistics is not something that companies wish to improve but to prevent.
Conditions and recommendations
Blockchain can be helpful to obtain real-time data on returns.
It is recommended when it's already used for other processes.
Its integration is conditional on decentralized identity.
Recommended for markets where reverse logistics is mandatory (i.e., batteries, chemicals)

Table 8
Experts' concerns and recommendations over blockchain integration to improve supplier selection.

Concerns
Reputation can be sold, as happens on web2. Blockchain cannot prevent this type of behavior.
A private blockchain may be more suitable, but we lack the infrastructure, skills, tools, and interoperability with legacy systems.
Conditions and recommendations
If a blockchain cannot be implemented, a timestamp with a hash at data checkpoints should provide a similar outcome.
Above the suppliers' review, all the data and signatures should be stored to certify the genuineness of occurred transactions.

Table 9
Experts concerns and recommendations over blockchain integration to minimize transaction costs by reducing intermediaries.

Concerns
There will probably not be a reduction in fees. Maybe an increase.
Operations in meatspace cannot be disintermediated with blockchain.
The switching costs of learning the new technology may surpass the exiguous reduction in transaction costs.
Conditions and Recommendations
Prioritize the use of blockchain for transactions and operations that can be entirely digitized (i.e., do not need an intermediary that operates in the real-world)
Leverage dispute resolution mechanisms, when disintermediating real-world operations.

Others who are more inclined to believe in blockchain's potential to reduce transaction fees limit this benefit to the financial sector, particularly in reducing the need for financial intermediaries (Fisch, 2019), (Caldarelli and Ellul, 2021). They suggest that blockchain, coupled with smart contracts, could function efficiently in roles traditionally held by lawyers, financial institutions, and centralized markets, such as in initial public offerings (IPOs). However, extending blockchain's application to intermediate non-financial markets is met with considerable skepticism. An expert notes, *'We should be concerned with markets where there is no need for a central intermediary. The electricity market, for example, cannot benefit from blockchain since you will always need a centralized authority to measure electricity consumption and production'*.

Another expert expands on this, highlighting the limitation of blockchain in *'meatspace'* scenarios, where real-world operations by actors or intermediaries are involved. In developer jargon, 'meatspace' humorously refers to the physical world, contrasting with 'cyberspace' to denote the realm outside of digital and online environments (Vincente). Blockchain's digital nature precludes it from directly influencing or guaranteeing these real-world actions (Song), (Frankenreiter, 2019). This expert elaborates, *'In theory, you can have the perfect blockchain that can make the perfect streamline of uncensored transaction between purchaser and supplier and then you can have unexpected mid actors that preclude buyer to have access to their resources. And blockchain cannot help there at all!'*

However, a more optimistic viewpoint is presented by an expert who sees the potential for blockchain in resolving disputes over transactions involving real-world activities. For instance, discrepancies in energy meter readings managed by multiple entities could be addressed through blockchain-based dispute mechanisms (Kadioglu, 2022).

The general consensus, however, is that blockchain does not significantly reduce fees or enhance efficiency for transactions occurring in the 'meatspace'. Another point raised by an expert concerns the switching costs associated with adopting blockchain technology. Despite potential cost savings, the complexities involved in setting up and learning to use blockchain systems might outweigh these benefits (Harwick and Caton, 2020). Citing the example of a project named OpenBazaar, the expert emphasizes, *'It was not about the saving in transaction cost but the mental cost of using it, running the software, manage the wallet, be the p in p2p'*, highlighting the non-monetary costs involved in transitioning to blockchain (Hochstein).

5.5. Incentive circular behavior [3.75 (72.72%)]

Experts' opinions on blockchain's potential to incentivize circular behavior are largely positive, though they come with various conditions and recommendations, some of which are contradictory. The majority view is that issuing tokens for green actions, like recycling, could encourage CE practices (Cluchet et al., 2019). An expert illustrates this concept: *'In a competitive fashion, people can use tokens to draw and pull resources from other sectors of the economy, as a sort of vampire attack ….as it pulls resources from the polluting sectors and puts them into the green sectors'*. This 'vampire attack', performed by drawing away customers from a platform offering the same service at a lower cost or higher reward, though often seen as malpractice in the crypto space, could be beneficial for environmental goals (Shah).

Some experts advocate for the use of micro-communities issuing their own tokens as incentives for specific actions, albeit with inherent uncertainties due to the trust required in these communities, in charge of issuing and managing the tokens (Mukhametov, 2020). An expert proposes the micro-community because he sees the management of token issuance and resource supervision as extremely unfeasible on a broader scale.

There is a general consensus that an overseeing authority, either centralized or a decentralized autonomous organization (DAO), is necessary to monitor operations, as blockchain and smart contracts alone are insufficient (Wang et al., 2019). Blockchain as a technology is not even necessary to enable the issuance of tokens and recycling processes, but the idea is that it will speed up procedures and provide more transparency.

Despite general agreement on the concept, experts diverge on its practical implementation. The complexity of designing an incentive system that is compatible for all participants is highlighted as a significant challenge. As an expert comments: '*If one can design an incentive compatible for all participants that allows these actors to participate in such a circular economy, I would agree more, but I don't know if someone could create that. It is technically feasible but economically difficult'*. Concerns

Table 10
Experts' concerns and recommendations over blockchain integration to incentive circular behavior.

Concerns
The incentive is hypothetical since an authority will always be needed to make sure a certain action is rewarded.
Token issuance and the economics of the incentive system are seen as hard to design
Blockchain and Smart contracts cannot enable these mechanisms alone.
There is skepticism in the use of community tokens (XYZ) as a payment system. A global one such as (BTC, ETH) is seen as more appropriate.
Non-zero monetary incentives are insufficient to boost circular behavior.
The higher the incentive, the higher the chance for the system to be manipulated.
Recycling is complicated to incentivize with blockchain due to the lack of digitization.
Conditions and Recommendations
Circular economies should be organized in micro-communities so that behavior can be more efficiently monitored.
An authority, whether centralized or in the form of a DAO is required to supervise these operations.
A community token may prevent the value from being cashed out from the system, still, a global token allows more fungibility of value for different actions performed, facilitating transactions.
Products should have embedded the amount of money rewarded for their recycling.
Blockchain can be leveraged to enable refunds for unused resources, incentivizing efficient resource usage.
Donations can be incentivized by issuing tokens through a blockchain that identifies the source of the donation.

also arise regarding the type and use of tokens. Some experts argue against using well-known cryptocurrencies like BTC or ETH for rewards, fearing constant cash-outs from the system. In contrast, community-specific tokens could also encourage users to retain value within the system further supporting and incentivizing circular practices (Cluchet et al., 2019). However, another expert although keen on the coexistence of different community tokens, used also as a reward, sees as impractical their use as a global payment system. Every action would create then different revenue streams, eventually increasing transaction costs. As he suggested: "*I see a good incentive in paying people with crypto that should be the most fungible such as BTC, ETH or DAI*"

There is also skepticism regarding the effectiveness of the incentive amount. An expert argues that substantial rewards are needed to promote green actions as a non-zero incentive is seen as insufficient. Per his experience: '*They give me some points for recycling, which makes my shopping a little bit cheaper ….I suppose it could be an NFT or a token, but I don't see any benefit … it's such a small incentive!*' In contrast, other experts promote caution against high incentives, fearing increased vulnerability to fraud (Gong et al., 2022).

The challenge of digitizing and tracing items like old clothes or compost is also noted as a barrier to effective implementation (Bhubalan et al., 2022), (Taylor et al., 2020). An expert argues: '*How can I prove that I recycled or reused them? How can I prove that I am recycling compost? Should I weigh it every time? Should we have a smart garbage collector? It would just require such a big change!'*. An innovative solution to this issue involves embedding rewards directly on product packaging, which would reduce the potential for systemic manipulation. If tokens are embedded in the product package, no authority is needed to manage the rewards and no 'honey pot' is created since the reward pool is decentralized. Lastly, experts explore the idea of rewarding donors for contributions to circular projects with badges that signify donation sources without compromising anonymity (Cheikosman). This mechanism aims to provide recognition and further incentives for participation in CE initiatives.

5.6. Manage green production [1.25 (72.72%)]

Expert commentary on the application of blockchain technology for managing and monitoring green products and production predominantly leans towards skepticism. Only two experts view this application favorably, contingent upon the assumption that IoT devices function correctly and are not under the control of the producing company. Additionally, one of these experts presupposes the involvement of an external Oracle provider to ensure the integrity of data transmission (Vári-Kakas et al., 2021).

This reliance on IoT systems for data gathering is a primary concern, as most experts express doubt about the feasibility of guaranteeing impartiality and preventing IoT malfunctions (Rejeb et al., 2023). One expert succinctly observes, *'With blockchain, you are just using a different database for accounting, not monitoring, these things. There is always an authority that decides how to collect this data and where to put it*'. The trustworthiness of systems reliant on sensors is questioned, especially in high-value transactions, due to the relative ease of tampering with these devices (Albizri and Appelbaum, 2021).

The practicality of implementing independent sensors is also challenged. An expert highlights the impracticality of such an approach: *'We should give everyone the possibility to crawl to the chimneys and put the data on the blockchain, which is just not feasible.'* These comments underscore a common misconception regarding blockchain's ability to independently monitor external states, a function more suited to other technologies not characterized by decentralization, trustlessness, and transparency (Caldarelli, 2020b), (Egberts, 2017).

A more plausible, yet still unlikely, proposition by some experts involves using blockchain as a decentralized database for uploading independently collected data on products and production by various stakeholders, including companies, employees, private citizens, and IoT devices. This approach, leveraging the 'wisdom of the crowd' similar to prediction markets, could potentially yield more reliable real-time information (Pastore et al., 2013). One expert suggests that blockchain could serve as *'a sort of diary for workers that remains immutable'*, with data agreed upon by all parties to safeguard against disputes.

However, even with this approach, preventing collusion or manipulation by central authorities remains a challenge. Finally, an expert proposes an alternative use of blockchain, not for monitoring green production directly but for tokenizing proofs of green production or emission reduction. This expert points to ongoing experiments in the tokenization of carbon credits (Haritonova), which enhance their fungibility and enable a broad spectrum of use cases, including integration into decentralized finance (DeFi) platforms (Kouhizadeh et al., 2019), (Elghaish et al., 2023). Such tokenized credits could facilitate the creation of 'green bitcoins', whose clean origin is verifiable on-chain, appealing to hedge funds and other entities focused on green investments.

Table 11
Experts' concerns and recommendations over blockchain integration to manage green production.

Concerns
Blockchain cannot monitor external state.
IoT data is easy to manipulate.
It's unfeasible to extract data such as emissions or pollution in an independent way.
Conditions and Recommendations
IoT systems should be trusted, reliable, and not under the control of a central authority.
Blockchain can be used as a database to store real-time data coming from independent data sources.
Instead of using blockchain to monitor green production, it can be used to tokenize proof of emission reduction (e.g., carbon credits).

Table 12
Experts' concerns and recommendations over blockchain integration to enhance product share and sharing economy.

Concerns
We still don't have the necessary scalability.
Blockchain is not strictly needed.
Conditions and Recommendations
Blockchain can be used to facilitate the use of crypto in the sharing economy.
Digital products can be more easily shared.
It can be used as a common standard for sharing resources (i.e., a decentralized warehouse database)
Automated insurance for shared products can be enabled.
A sharing economy DEX is feasible with blockchain.
It can facilitate green investments and initiatives by sharing the cost over many individuals.

5.7. Enhance product share and sharing economy

Opinions on the potential of blockchain to enhance the sharing economy are varied, reflecting a balanced distribution of positive, negative, and neutral perspectives. The diversity of views underscores the complexity and unpredictability of blockchain's integration in this area. Some experts are outright skeptical or indifferent, especially regarding the involvement of physical products in the sharing economy. An expert succinctly puts it, *'Apart from the chance of using cryptocurrencies, I don't see how blockchain can improve the sharing economy, especially if we talk about physical products.'* Conversely, there is more optimism for the sharing of digital assets, though the technology's scalability remains a concern, as one expert notes, *'It will happen once we have the scalability to do it.'*

Among the experts holding positive views, their rationale varies. One expert envisages blockchain as a unifying technological standard that could lower registration and login costs. This expert imagines a scenario where resources from different companies registered on a shared blockchain could be redistributed more efficiently. Another suggests blockchain's utility in enabling insurance services for shared products, offering protection against malfunctions (Wan et al., 2018). A third expert proposes the concept of a decentralized exchange for shared products, where users can bid for services. While acknowledging that blockchain is not indispensable for this service, the expert points out its potential to enhance openness and transparency.

Moreover, blockchain technology is posited as a facilitator for tokenizing and sharing large-scale projects, like recycling plants, which typically require substantial capital investment (Baber, 2019). This application is particularly relevant where green investments are not viable for multinational corporations or the public sector. Blockchain could enable private individuals to collectively fund such projects in their local areas, democratizing investment in green initiatives.

5.8. Guarantee authenticity of reused/recycled products [1.83 (54.54%)]

Expert opinions on using blockchain for product authentication and traceability are heterogeneous, with a majority expressing reservations although the negative sentiment is not as low as for other integrations. The predominant concern is the 'stapling problem', the challenge of physically linking a product to its digital representation on the blockchain (Caldarelli et al., 2023), (Eskandari et al., 2021). One expert highlights, *'Anyone can remove that tag and put it to something else …. these systems work with the package, not with the content, so it is hard to imagine a working system for products that get manipulated and transformed during the supply chain'*. This concern extends to the recycling and reuse phases, where the risk of manipulation further undermines the feasibility of reliable tracking. Regarding the recording of traceability information, the prevailing sentiment is skepticism about the necessity of blockchain. However, two experts propose a scenario where blockchain could be advantageous: in cases where a company goes bankrupt, blockchain-stored data could preserve product identification throughout its lifecycle, offering particular benefits for collector's items, provided the blockchain tag remains unaltered.

Another expert views the application positively, not for blockchain's intrinsic value but as an added hurdle for counterfeiters (Caldarelli et al., 2020). This expert also notes the need for a certification body to ensure data accuracy. However, they acknowledge the possibility of corruption but suggest that blockchain could track such actions, marking compromised data as untrustworthy. This approach is deemed viable mainly for high-value products, where additional security measures would not significantly impact cost.

A unique perspective considers products composed of parts from various suppliers. In such cases, the diversity of stamps from different companies reduces the likelihood of replication, although component manipulation or substitution remains feasible. An expert notes, *'The swap is not completely free because if you swap a product, you need to have a similar one. You can just swap products; you cannot invent them'*. This implies that while tags can be manipulated, the total number of products registered on the blockchain cannot increase artificially, making the introduction of counterfeit goods more detectable.

Building on this, another expert discusses items like artificial diamonds or high-quality counterfeits of designer products, which are difficult to distinguish from originals (Gordon et al., 2023), (Steven). They suggest that the accompanying certificate of authenticity, potentially managed as a non-fungible token (NFT) on the blockchain, could confer value and authenticity to the product. This application of blockchain, leveraging NFT technology, could provide a viable solution for certifying the authenticity of hard-to-differentiate items.

5.9. Prolong product life [1.1 (81.81%)]

Except for a few neutral experts, there is a broad consensus that blockchain is unlikely to present a compelling use case for prolonging the life of products. This skepticism largely stems from misconceptions about blockchain's data-gathering capabilities (Egberts, 2017). Experts clarify that blockchain itself does not facilitate data collection; this task is typically performed by IoT devices, which currently do not offer the requisite level of reliability for such operations (Powell et al., 2022). An expert points out, *'the problem is that IoT devices are not trustless yet. The closest we have are TEEs, but if you have physical access to them, they are not that secure'*. The Trusted Execution Environment (TEE), as referenced by the expert, constitutes a secure enclave within the main processor. It is engineered to guarantee that sensitive data is stored, processed, and safeguarded within a secluded and secure compartment (Sabt et al., 2015). Within the realm of blockchain oracles, the TEE acts as a 'trusted path,' safeguarding the integrity of data from its origin to the designated smart contract, ensuring it remains unaltered during transmission (Al-Breiki et al., 2020).

The fundamental necessity of blockchain in this context is therefore questioned. Predicting component failure is more effectively achieved using AI and statistical models, particularly when large volumes of data

Table 13
Experts concerns and recommendations over blockchain integration to guarantee authenticity of reused/recycled products.

Concerns
It's challenging to ensure a stable link with a physical product to the blockchain over time (Stapling Problem).
An intermediary (certification body) is needed to make sure that the data is true. The authority can get corrupted and become unreliable.
It's impossible to prevent manipulation in the recycle/resale process.
The system works with the package, not with the product itself.
Considered of low utility for products of exiguous value.
Conditions and Recommendations
For long-term purposes, traceability data can be available forever on a chain.
The product should be properly branded, and the tag should not be cloned.
More viable for products of high value, given the costs of tags and blockchain fees.
Valid, for modular products whose parts are made by different producers
For products that are difficult to distinguish from their copies. The authenticity certificate gives value to the underlying product.

Table 14
Experts' concerns and recommendations over blockchain integration to prolong product life.

Concerns
Blockchain cannot gather data. It is the IoT that is used for this purpose.
IoTs are easy to manipulate if there is direct access to them.
Components are owned by the company, and the data they provide cannot be trustless.
IoTs cannot initiate transactions as a direct link with the blockchain is hard to establish.
Fees would be high due to the considerable amount of data collected by the sensors.
Predictions are more associated with AI and statistical models.
Conditions and recommendations
Appliances with already integrated sensors may be more suitable for this integration (i.e., smartphones)
An open blockchain where all product data from many companies can be used as a database for statistical model purposes.
Although impracticable, a peer-to-peer marketplace storing all the product data and previous ownership can be helpful in this integration.

from multiple sources are collected and shared in an open database. This approach allows for the calculation of failure probabilities conditional on various factors (Li et al., 2018).

A decentralized marketplace for sharing information about a product's previous usage instead could theoretically aid in predicting its lifecycle, however the feasibility of such a system is viewed as minimal.

An expert acknowledges the theoretical value of blockchain in managing products with multiple integrated sensors, such as cars or high-end smartphones (Zhang et al., 2021). However, practical implementation challenges are highlighted by another expert with experience in the high-quality smartphone sector. The difficulty in initiating blockchain transactions via sensors and the economic viability of managing the costs associated with storing large volumes of data are key concerns. This expert argues that centralized servers are more efficient for these purposes. A parallel is drawn with the approach used for ink cartridges, where chips are embedded in products to communicate with servers, providing updates on product conditions and indicating when parts need replacement.

5.10. *Enable digital product passports (DPP) on the blockchain [1.75 (72.72%)]*

The proposal to implement digital product passports (DPP) on the blockchain is met with limited enthusiasm among experts, with only two expressing favorable opinions. Interestingly, the experts' reservations are not grounded in technical limitations of the blockchain, as NFT technology could feasibly enable the storage of DPP on the blockchain (Bhubalan et al., 2022). One expert acknowledges, *'Technically, it is possible to store those digital passports on-chain. It is something that is currently done with many documents, but I don't think they'll achieve what they want to with that'*. The skepticism is primarily rooted in conceptual rather than technical issues.

A primary concern involves the credibility of the information within the digital certificate; experts argue that storing it on the blockchain does not inherently enhance its trustworthiness (Caldarelli, 2020b), (Gaggioli et al., 2019), (Albizri and Appelbaum, 2021). Additionally, the challenge of selecting an appropriate blockchain platform is significant. Open blockchains like Bitcoin or Ethereum are deemed impractical due to the large data volume and associated high fees, coupled with funding challenges for these expenses. This leads to a debate over whether the information should be globally accessible or restricted to certain stakeholders, which would necessitate a private blockchain and shared maintenance costs (Lai and Lee Kuo Chuen, 2018), (Sharmab).

Beyond these practical concerns, philosophical questions are raised about whether DPPs can truly promote recycling, a behavior more influenced by human actions than information availability. When considering the technical application of blockchain for DPPs, issues such as immutability, which cannot be guaranteed by any blockchain, data privacy, and transaction fees come to the forefront. Some experts propose using a regular distributed database across EU states as a cost-effective alternative.

One expert suggests a community-driven database model akin to Wikipedia, instead of a blockchain, where all members can contribute. A final thought-provoking comparison is made with digital human passports. While these are accompanied by unique digital signatures to verify the link between the person and the document, a physical, inanimate product cannot provide such a signature (Li and Wang, 2021), (Ghazal and Saleh, 2018). This limitation significantly undermines the potential and utility of DPPs on the blockchain in facilitating CE practices.

6. Discussion

Blockchain technology, heralded for its potential to revolutionize digital transparency and security is increasingly scrutinized for its practical applicability across a range of circular economy applications. Despite the enthusiasm surrounding blockchain capabilities, expert analysis reveals consistent themes of overestimation of its utility, implementation barriers and significant contextual limitations that often undermine its effectiveness. In logistics and supply chain management, blockchain is often advocated for its ability to enhance transparency and ensure the integrity of transactions. As advocated in existent research (Saberi et al., 2019a), (Kouhizadeh et al., 2020), (Costa et al., 2022), (Henríquez et al., 2021), (Harris) experts particularly recognize its potential in global trade, where complex transactions and extensive documentation are prevalent.

However, as further studies in this area show, the actual implementation reveals substantial challenges, including the high costs of blockchain adoption and the inherent complexity of integrating it with existing digital systems (Kouhizadeh et al., 2021), (Caldarelli et al.,

Table 15
Experts' concerns and recommendations over blockchain integration to enable digital product passports on the blockchain.

Concerns
Blockchain cannot guarantee the authenticity of data provided with digital product passports.
It would be unfeasible to leverage open blockchains due to the high costs of fees.
It's unclear if transparency or privacy is to be prioritized.
If the objective is to guarantee the immutability of certificates, then not all blockchains are non-modifiable and secure.
DPPs lose their advantages when used for physical products since, unlike humans, they cannot provide proof of their existence through a signature.
Conditions and recommendations
Multiple parties should verify the DPP.
It should be done by a family of products or lots of production to reduce the amount of data to be stored.
A community-driven database or a distributed database can also work well.

2021), (Steenmans et al., 2021), (Alves et al., 2022). Integrating blockchain into specific applications, such as waste management, therefore faces significant hurdles. Although the literature includes several studies on this topic (Farizi and Sari, 2021), (Gong et al., 2022), (Baralla et al., 2023), (Taylor et al., 2020), (Castiglione et al., 2023), future research could further explore this integration, taking into account the specific insights of experts.

Equally crucial is the so-called 'stapling problem,' which refers to the difficulty of securely attaching digital records to physical products (Eskandari et al., 2021). This issue is particularly emphasized in the sectors of recycled product authentication and green production management.

This issue reflects a broader limitation of blockchain for its ineffectiveness in handling interfaces between digital records and physical realities. For example, ensuring the authenticity of recycled products or monitoring green production processes requires reliable data from physical assets, which blockchain alone cannot verify without robust and secure IoT systems.

Although this specific study focuses on the circular economy and, therefore discusses the authentication of recycled products and emissions monitoring, the same limitations apply to the authentication of newly produced products and the measurement of any other real-world data using blockchain. Despite the existence of a few articles addressing these issues (Caldarelli, 2020b), (Kumar et al., 2020), (Egberts, 2017), (Frankenreiter, 2019), (Powell et al., 2022), the literature on the circular economy, as well as on real-world blockchain implementations, generally lacks a thorough analysis of how the 'stapling problem' could affect blockchain integrations.

The use of blockchain to enhance the reliability of data in the supplier selection process is seen as less problematic. The actual benefit is conditional on the existing digital infrastructure and the availability of specific skills. However, experts' opinions are highly positive and largely confirm what the academic literature advocates on this matter (Mogos and Fragapane, 2022), (Rusch et al., 2023), (Orji and Ojadi, 2022), (Kouhizadeh et al., 2022), (Schöggl et al., 2023).

Different is the theme of blockchain implementation to reduce transaction costs and intermediaries that actually reveals a paradox. Although theoretically capable of reducing fees by eliminating intermediaries, the reality, as discussed by experts, often shows an increase in costs due to the technical and operational expenses associated with blockchain systems. This is particularly evident in non-financial sectors where traditional systems/intermediaries are already efficient, and the additional layer of blockchain technology may not necessarily result in cost savings. The available literature indeed effectively supports the possibility of integrating blockchain in sectors such as energy production and water management (Yildizbasi, 2021), (Montakhabi et al., 2021), (Erol et al., 2021), (Zhu et al., 2020), (Poberezhna, 2018). However, further analysis is needed to also prove its cost-effectiveness.

In agreement with the current literature, a broad consensus emerges in favor of using blockchain technology to incentivize circular behavior (Cluchet et al., 2019) (Farizi and Sari, 2021) (Gong et al., 2022) (Grati et al., 2023) (Böhmecke-Schwafert et al., 2022). Experts acknowledge significant constraints in the process, such as identifying the proper economic model, managing the system, and combining technologies effectively (e.g., Blockchain, IoT, Artificial Intelligence). However, they confirm the potential of blockchain in providing valuable incentives for circular practices. Remarkably, only a few works in the literature delve into its practical implementation (Gong et al., 2022), (Cluchet et al., 2019), (Verma et al., 2022), (Wankmüller et al., 2023), (Katz, 2019).

The potential of blockchain to prolong the life of products and manage green production, similarly, encounters skepticism from experts who highlight the technology's limitations in direct interaction with physical processes. The reliance on external devices like IoT for data collection introduces points of failure that blockchain cannot rectify. Thus, while blockchain may serve as a reliable repository of information, its role is fundamentally auxiliary, dependent on the accuracy and security of data inputs it receives.

Experts' opinion supports, in fact, works of literature that specify the need for blockchain to interact with reliable IoT systems to perform these tasks (Hatzivasilis et al., 2021), (Rejeb et al., 2023), (Paul et al., 2022), (Damianou et al., 2019), (Sharma et al., 2021). Ad hoc studies should, however, clarify the exact role and the specific advantages of integrating blockchain in support of these activities.

Lastly, the proposal of uploading digital product passports (DPP) on the blockchain encapsulates the overarching challenges of applying blockchain. While storing digital certificates on a blockchain could enhance their security and longevity, the practical benefits are constrained by the costs of blockchain operations and the challenge of ensuring the credibility of the stored information. The scarcity of available works of literature on this matter reflects its novelty (Bhubalan et al., 2022), (Li and Wang, 2021), (Schöggl et al., 2023), and experts opinion obtained within this study, may push further research in the right direction.

7. Conclusion

This paper has delved into the potential of integrating blockchain technology with CE practices, employing the Delphi technique to critically evaluate specific topics. Items for the Delphi study were derived from a comprehensive review of academic literature, and their evaluation was enriched by extensive comments from experts. After two rounds, consensus was reached on five key items. The experts recognized significant potential in using blockchain to incentivize CE practices through token issuance and to facilitate green supplier selection by ensuring the transparency, immutability, and independence of historical performance data from central authorities. Conversely, skepticism was expressed regarding the utility of blockchain in monitoring green products and production, prolonging the life of modular products, and implementing digital product passports. Expert commentary has also shed light on additional blockchain implementations that may support or hinder CE practices, summarized in Table 16.

These findings offer valuable insights into the practical assumptions and potentials of blockchain as depicted in academic literature, providing guidance for managers in developing CE integrations and investors seeking clarity on promising projects. This study aligns with Bockel et al.'s advocacy for bridging the gap between research and practice, offering a robust foundation for future studies (Böckel et al., 2021). However, this research is not without limitations. To mitigate biases and conflicts of interest, the experts selected were not involved in CE initiatives at the time when the research was made, which might have limited their awareness of the latest advancements in the field. The results are based on the opinions and experiences of these experts and not on specific use cases, suggesting that certain applications may prove effective despite negative sentiments, and vice versa. Furthermore, the aggregation of potential integrations into broader macro categories, aimed at simplifying the interview process, may have inadvertently compromised the precision of research items. For instance, the concept of asset tokenization for environmental sustainability, while strongly supported by one expert, did not receive comprehensive endorsement from the entire panel due to its inclusion in a broader category, indicating a need for further investigation. Additionally, these applications may benefit from a more thorough analysis that incorporates diverse perspectives. For instance, while blockchain may not be suitable for reducing intermediaries or costs in green energy production, it could have applicability in other aspects of this sector, such as tokenizing proof of electricity production.

Table 16
Potential contributions and limitations of blockchain technology for the Circular Economy as delineated by expert comments and evaluations.

Blockchain may
Incentivize circular behavior through the issuance of tokens or badges.
Facilitate the selection of green suppliers, guaranteeing the transparency and immutability of related feedback.
Facilitate reverse logistics for material that requires safe disposal or recycling by enabling authentication and transparency of multiple agent's signatures.
Facilitate green investments by enabling crowdfunding at reduced transaction costs.
Be leveraged to constitute a DAO to manage green initiatives.
Be used to Tokenize proof of green production or reduction of emissions (i.e., carbon credits).
Help harmonize accounting systems (i.e., sustainability accounting) by enabling a triple entry accounting.
Be utilized to establish a platform standard, thereby enhancing collaboration among various stakeholders
Blockchain is unlikely to
Help track and authenticate products after recycling due to manipulation and the stapling problem.
Prevent material loss and minimize waste caused by human mistakes.
Constitute a convenient platform to store digital product passports due to the high volume of data and transaction fees required.
Reduce intermediaries and fees for activities in the meatspace, such as green energy production, water management, etc.
Extend product life and facilitate the repairing cycle for the inability to gather and process high data volumes.
Monitor green products and productions, being unable to monitor external states efficiently.

Future research should empirically validate these expert expectations through real-world integrations, further substantiating the robustness of this study's findings. Items that did not reach consensus warrant additional investigation. Furthermore, it is evident that the list of proposed integrations explored in this study represents only a fraction of the myriad possibilities that could be conceived in the future. Periodic replication of this study is recommended to stay abreast of evolving trends and applications in this dynamic field.

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CRediT authorship contribution statement

Giulio Caldarelli: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

I, as the sole author of this research, declare on my own responsibility that I have no competing interests related to the execution of this study. I am not affiliated with any company or project that applies blockchain technology in the circular economy. To the best of my knowledge, this also applies to the experts who participated in the research. Their involvement in the study was purely voluntary, and they did not receive any form of payment or benefit from any institution for their contributions.

Data availability

Data will be made available on request.

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