Journal of *Risk and Financial Management*

*Article*

# Blockchain Technology in the Environmental Economics: A Service for a Holistic and Integrated Life Cycle Sustainability Assessment

**Sanja Tišma [1,*] and Mira Mileusnić Škrtić [2]**

[1] Institute for Development and International Relations IRMO, 10000 Zagreb, Croatia
[2] Faculty of Organization and Informatics, 42000 Varaždin, Croatia
* Correspondence: sanja.tisma@irmo.hr

**Abstract:** The application of blockchain technology in the field of environmental economics is still in its inception so it is not sufficiently used in a holistic and integrated life cycle sustainability assessment (HILCSA). The capability of the blockchain to provide a verifiable and transparent record can make it a good tool in environmental economics for an agile reflection in doing business and production. The research is focused on the advantages and challenges in the inclusion of blockchain technology into a holistic life cycle assessment. Based on the existing possibilities of using blockchain technology in environmental economics and life cycle assessments (LCAs), a framework and a model for applying the blockchain in the holistic life cycle sustainability assessment are proposed. A Design Science methodology was used as a research strategy. Particular emphasis in this paper is put on risk management when integrating blockchain methodologies through environmental economics into the life cycle sustainability assessment (LCSA) in order to use all the advantages of the blockchain technology optimally.

**Keywords:** blockchain; distributed ledger technologies; environmental economics; life cycle assessment; life cycle sustainability assessment; risk identification; bioeconomy



**Citation:** Tišma, Sanja, and Mira Mileusnić Škrtić. 2023. Blockchain Technology in the Environmental Economics: A Service for a Holistic and Integrated Life Cycle Sustainability Assessment. *Journal of Risk and Financial Management* 16: 209. https://doi.org/10.3390/jrfm16030209

Academic Editor: Shigeyuki Hamori

Received: 1 March 2023
Revised: 13 March 2023
Accepted: 15 March 2023
Published: 22 March 2023



## 1. Introduction

This paper presents the results of feasibility research, challenges, advantages, and risks of blockchain technology in the field of bioeconomy with a focus on the application of blockchain within the framework of environmental economics on the holistic life cycle sustainability assessment.

Blockchain technology has attracted the most attention in the application of digital currency. However, its basic network protocols and infrastructure can be used for documenting, checking, and sharing data in a number of fields studied by environmental economics. Blockchain is a kind of shared, distributed ledger that uses an agreed-upon encryption process in order to protect information from unauthorized access. The data in the blockchain can be trusted even without a centralised validity check by a third party. Blockchain is essentially an increasing list of data blocks forming a chain in which every new link, i.e., block, depends on the value of the previous link (Nakamoto 2008). The application of the blockchain in environmental economics for the evaluation of phenomena and processes in the environment, particularly in the holistic life cycle sustainability assessment, has not yet taken hold to the extent to which it could considering the possibility of its efficient application in storing personal identifiers and credentials, as well as providing new models of data ownership and management with inbuilt mechanisms of control and consent (Karaszewski et al. 2021).

Blockchain, by definition, is a widely distributed database of blocks of digital transactions that are executed and shared among nodes within the whole network for the purpose of transaction checking. Blockchain records transactions from the very beginning. Nodes can access any block in order to get insight into public information within the block, but they cannot change it. All participating nodes within a blockchain network are anonymous and the identity of all hidden transactions is included and based on the public key. Blockchain, as a linked list, uses hash pointers, which enable the recording of any unauthorised access. Therefore, the data chain shared on the network becomes a decentralised, trustworthy, secure, and unalterable distributed ledger (Kotha and Patel 2020). The data within the network are available to every node in the network. Since blockchain is a ledger of shared and unalterable records, everything created on a blockchain is transparent and the person responsible for certain transactions is responsible for his/her doings.

Using code to write smart contracts on the blockchain, scripts containing contract terms and business rules can be executed automatically. The conditions and clauses of the contract are approved by the network members. Due to the automatic execution of smart contracts human intervention is needless while efficiency is improved and business activity costs are reduced (Kouhizadeh and Sarkis 2018).

The blockchain development was iterative following interests and new ideas, which resulted in four generations in the development of blockchains: Blockchain 1.0, Blockchain 2.0, Blockchain 3.0, and Blockchain 4.0. Blockchain 1.0 for digital currencies was started in 2009 and it is important for the introduction of the first cryptocurrencies and refers exclusively to paying and its functionalities for cryptocurrency generating. Blockchain 2.0 has a practical application in creating various applications for specific fields. Some of its significant applications are in banking, finances, intellectual property, and medical documentation management, and, in several recent years, it has been applied in scientific research in the framework of environmental economics. Blockchain 3.0 is directed toward digital society and decentralised applications. Decentralised applications' research fields cover health, governance, IoT, supply chains, businesses, the environment, and smart cities. Blockchain 4.0 deals with the integration with industry and is directed to a public ledger and distributed databases in real time. It uses a smart contract, which eliminates the need for paper contracts and does the regulation within the network by consensus (Bodkhe et al. 2020).

Environmental economics deals with the analysis of the use and protection of planet Earth through efforts to reduce air pollution, preserve water quality, reduce solid waste amounts, and prevent further global warming with the ultimate aim of building a sustainable economy (Tišma et al. 2022). Concretely, environmental economics researches the efficient use of natural resources (Chen 2022). Within the framework of this scientific discipline, all activities related to services of ecosystems as a whole are studied as well (Diemer et al. 2020).

The advantage of the life cycle sustainability assessment (LCSA) is its systemic perspective and identification of potential compromises in the framework of environmental economics which lies among three pillars—social, environmental, and economic sustainability (Karaszewski et al. 2021).

The life cycle assessment method includes all impacts of individual activities on the environment that can emerge during production and it covers all stages related to a product, material, or service. The method tries to encompass all changes in the product or material and it is necessary to understand the sources, manners, rules, and consequences of the manufacturing, use, and disposal of some products. It is applied within the framework of environmental economics for the selection of adequate interventions in the systems of supply, production, logistics, use, maintenance, repair, resources recovery, reproduction, waste management, and also provides a survey of costs of different systems, thus enabling the comparison of the impacts on the environment. Therefore, in the framework of environmental economics it enables a recognition of main impacts and improves decision-making on the basis of information products and services (Rolinck et al. 2021).

Development of the life cycle assessment method in the framework of environmental economics included already well-established and internationally accepted standards such as ISO 14040-14044 (ISO 2006a, 2006b) with the application in a number of sectors, e.g., energy, construction, forestry, fishery, agriculture, etc. ISO 14040 prescribes a working framework for conducting LCA analysis, while ISO 14044 specifies demands and guidelines for the implementation of an LCA study.

Currently, institutions using a holistic life cycle sustainability assessment in the framework of the research in the field of environmental economics develop their own platforms and methods for the dissemination of information and data among their interested prospective clients and, if needed, among the general public. The use of blockchain in environmental economics provides new and more flexible ways of sharing data and information, as well as innovative tools for blockchain data storage, overcoming the difference between private limited information and fully open public information. Furthermore, services based on blockchain technology significantly differ from the previous commercial solutions made for use on the internet and they are particularly important for the development of the bioeconomy, especially in the analytical field through the application of the holistic life cycle sustainability assessment method. Information is the backbone of doing business, while data precision and the fast access possibility directly affect business performance. In that context, technologies such as blockchain, big data, and the Internet of Things (IoT) offer new opportunities to improve and increase life cycle inventory (LCI) data collection. Unfortunately, the potential of new technologies is not sufficiently exploited for research in the framework of environmental economics (Mieras et al. 2019). Blockchain application in the life cycle sustainability assessment in environmental economics has not taken hold to the extent it could, considering the possibility of its efficient application along with the control of users' identifiers and credentials, and its offering of new models of data ownership and management with the built-in mechanisms of control and consent (Lesavre et al. 2020). There are still issues that need further research, such as the risk of uploading incorrect data due to the occasional or intentional modification of data before uploading them into blocks of the blockchain (Zhang et al. 2020).

These new blockchain data technologies in the function of life cycle assessment could open the way to new forms of blockchain research where automated data gathering by means of blockchain could provide tools for further development of the environmental economics and, within that framework, also methods of holistic life cycle sustainability assessment.

The goal of this paper is to examine the role of blockchain technology in the holistic integrated life cycle sustainability assessment (HILCSA) of the bioeconomy and to analyse the advantages of its implementation in the field of environmental economics. The main research question is: how can blockchain technology improve environmental economics and how it can support the holistic integrated life cycle sustainability assessment from the aspect of risk recognition?

The authors have examined the literature and based on it they showed the possibilities of using blockchain technology in the environmental economics for the life cycle assessment, suggesting a framework and a model for the application of blockchain in the holistic life cycle sustainability assessment related to environmental protection. The results of the analysis of the research presented in this paper also provide guidelines for the use of blockchain's advantages in the environmental economics and particularly in the life cycle assessment, thereby considering the technological limitations and pointing out the potential directions of further research.

An all-encompassing model of holistic life cycle sustainability assessment (HILCSA) is selected for the analysis of blockchain applications, which is based on the life cycle assessment and life cycle sustainability assessment. This model is proposed in a paper by Zeug et al. (2021). A HILCSA model with a common scope, goal, functional units and variables, impact assessment, and accompanying interpretation can describe social, economic, and ecological risks, opportunities, synergy, and costs (Zeug et al. 2021). The achievement of bioeconomy sustainability is limited as long as sustainability is not the main goal of the economy in general, as well as of the total social relations towards the environment.

The main contributions of this research are a review of the literature on experiences in blockchain implementation in LCA, the management approach to perform LCA—risk management in particular, as well as the proposal of the holistic model for gathering blockchain technology, the Holistic and Integrated Life Cycle Sustainability Assessment (HILCSA) method and risk management.

This paper presents the following: (i) a definition of the research questions; (ii) a literature review; (iii) a methodology covering the research area as well as the Design Science (DS) framework (Holmström et al. 2009), focusing on the steps and processes involved in the analysis of problems, and solution design; (iv) results and discussion based on the DS process; and, finally, (v) the conclusion as well as research limitations and suggestions of future research.

## 2. Literature Overview

Problems related to the work with a large amount of data cover characteristics such as privacy, complexity, asymmetric distribution, and information demand. Data openness, sharing, and privacy issues are the main bottlenecks in data science development. Recognizing several possibilities of blockchain such as transparency, security, revision, and privacy used to supplement data science, many newly established enterprises, corporations, and governments accept its use in supply chains, electronic medical records, voting, energy, environment, property management, and critical civil infrastructures protection (Liu et al. 2020).

An example of a blockchain application that directly benefits the environment in several different ways is, for example, blockchain usage in monitoring the carbon footprint of a product, which can then determine the amount of tax on the carbon that should be paid. Furthermore, the impact of blockchain on supply chain management through its benefits for the environment as the side effect of its improvement of the organisation of global supply chains was observed (European Union and European Regional Development Fund 2021). Risks to big data analytics and blockchain adoption in supply chains in India were identified as 'supply chain visibility risks', 'infrastructure and development costs', 'demand forecasting and sensing risks', 'data privacy and security risks', 'policy and legality related risks', and 'supply chain resilience' (Narwane et al. 2021). Privacy and restricted access are required for supply chain blockchains. As different partners may require different levels of visibility and accessibility, blockchain should record and protect important data. Thus, through the interaction of supply chain partners and the related network architecture at the organisational level, smart contract and transaction validation rules at the operational level can be established through the blockchain-based traceability framework (Agrawal et al. 2021).

Concerning the role of blockchain in safeguarding agri-foods, the possibility of better agricultural food management through better product traceability and transparency by the use of decentralisation and distribution characteristics of blockchain technology is emphasised. An opportunity for the improvement of security and food quality is also seen in the digital monitoring of a product from farm to consumers. However, there is still room for further research and improvements in the increased adoption of blockchain technology for, as diverse as possible, the offer of agricultural and alimentary products considering numerous technical and regulatory challenges (Xu et al. 2020; Barbosa 2021; Mangla et al. 2021).

The willingness and efforts of forest farmers to reduce carbon emissions directly affect the cost decrease and the efficiency improvement. Due to the inclusion of the blockchain in the work processes, forest farmers can make a more precise forecast of the future benefits, enabling them to adjust the ratio of investments in order to maximise their benefits in an appropriate way (Sun et al. 2021). A holistic approach in understanding the application of blockchain technology in the transition of decarbonisation, decentralisation, and digitalization in the energy sector assumes the integration of user behaviour research, business model innovation, and regulatory experimentation for developing corporate strategy and public policy (Ahl et al. 2022).

The experience of applying blockchain is also noticeable in the field of fishery. In order to be fully sure that the fish is in good condition for consumption, it is necessary to know the entire value chain related to the fish and its derivatives—from fish capture to the final consumer, including transport, logistics, and industry. That chain involves many operators and companies and each of them controls its internal processes. To that purpose, the integrated process of all operators in a fish value chain using a smart contract on the Ethereum (2022) blockchain is implemented. The advantages of the proposed platform include improved communication and coordination between stakeholders, control of the quantity and the species of wild caught fish, marine diversity preservation, etc. The characteristic of traceability is stressed according to which each operator will have its own copy of the data, thus allowing all operators to work together even without fully trusting each other (Ferreira Cruz and da Cruz 2020). Blockchain, with its inherent characteristics of inalterability, security, and decentralisation together with the smart contract technologies, has potential for the improvement of efficiency and responsibility in the value chains of fishery. Understanding blockchain and its unique issues and requirements before adopting the technology is crucial for industry organisations (Pu and Lam 2020).

The role of the life cycle assessment in informing on the sustainable and circular economy can be seen through the limiting of the competition for land and biomass, diversification of the raw materials through the valorisation of waste and residual streams, low quality land exploitation, yields improvement, improved conversion efficiency, carbon cascading, etc., which are considered as significant potential options. Participating with producers of biomass through social life cycle assessment (S-LCA) and approaches of stakeholder validation can direct focus to biomass from local sources, related skills, and infrastructures (Sevigné-Itoiz et al. 2021).

Regarding the environmental economics and the life cycle assessment initiative, a challenge is emphasised concerning possible insecurities because the LCA tools can have different fundamental information, different levels of granularity, some missing data, and information that is inaccurate. The validity, reliability, and transparency of blockchain can reduce information uncertainty, providing better inputs and outputs for modelling LCA tools that can be used in the analyses in the environmental economics (Kouhizadeh and Sarkis 2018).

Foltynowicz and Kłos (2022) give the review of the activities of LCA/LCM related to the environmental economy in Poland. They explore the effects of the bioeconomy at the regional level. Comparing social effects on local communities with reference to the economic sector in the example of a production chain of laminated veneer lumber in central Germany, it was shown that the more transparent environmental implications of the economic activities are, the more positive the social dimension in terms of health and safety, equal opportunities, and appropriate remuneration for the organisations participating in the value chain is (Jarosch et al. 2020).

Based on the life cycle assessment methodology, the aim of the life cycle sustainability assessment (LCSA) is to combine or integrate social, ecological, and economic assessments. A practical framework for a holistic and integrated life cycle sustainability assessment (HILCSA) of the bioeconomy on regional and local levels is provided, which includes a set of indicators for the assessment of regional (product and territorial) bioeconomies, applicable with the current software and databases, life cycle inventory assessment (LCIA) methods, and methods of normalisation, weighting, and aggregation, which is rarely used in the analyses related to environmental economics. The implementation of HILCSA in openLCA enables an integrative LCSA through conducting all steps in a single framework with harmonized, aggregated, and coherent results. This framework can compensate some deficits of S-LCA, E-LCA, and economic assessments by integration, and it shows the main advantages in comparison to additive LCSA. HILCSA can solve 15 out of 17 sustainable development goals (Zeug et al. 2021). By means of HILCSA methodology, it is possible to quantify and qualify the social, environmental, and economic performance of bioeconomy product systems, to identify main focal points, and, when it is possible, compare this performance and the focal points with product systems (Zeug et al. 2021). It is especially important to highlight the step forward in connecting the HILCSA method with the openLCA software. However, considering that it is a method whose application is significant at the regional level, the application of blockchain would make its application and results more widely available.

Furthermore, the research on the application of life cycle sustainability (Valdivia et al. 2021) provides the pragmatic LCSA framework based on three techniques: LCSA = environmental life cycle assessment (LCA) + life cycle costing (LCC) + social life cycle assessment (S-LCA). Ten harmonised principles (10P) were presented: understanding the areas of protection, alignment with ISO 14040, completeness, considerations of stakeholders and product utility, significance of system boundaries, transparency, consistency, explicit compromise communication, and caution in impacts compensating (Valdivia et al. 2021). There are numerous examples in the literature of blockchain application in various areas of application of the LCA method. Still, there is a lack of a broader approach that would take into account the management of external processes, i.e., risk management, that could significantly affect the implementation and results of the LCA method.

## 3. Materials and Methods

The research design follows a qualitative approach based on abductive, analytical, and systematic approaches, aiming at a better understanding of the rich variety of aspects inherent in the holistic life cycle sustainability assessment and blockchain practice in the framework of environmental economics. Desk research and a literature review were used. Since the application of blockchain technology in holistic lifecycle sustainability assessment is still in its inception, the use of qualitative methods is a pragmatic approach in dealing with the current topic. At the same time, case studies on blockchain and holistic lifecycle sustainability assessment are research or pilot initiatives. A review of the literature on holistic life cycle assessment and blockchain was carried out, with special attention given to works directly related to environmental economics. The literature included published scientific papers, conference and workshop reports, current strategic and legal documents, official statistics, and other online texts. Desk research also included primary sources covering:

- Technical specifications of major blockchain implementations.
- Product technical specifications and their administrative structures, operations, and intellectual property agreements, published by vendors offering products built on blockchain technology.

A systematic literature review (SLR) has been conducted. The authors reviewed the literature in three steps:

1. The keywords „Blockchain in life cycle assessment", „Blockchain and SDG", „Blockchain, environmental economics, methods", „Life cycle assessment, data", and „Holistic and integrated life cycle sustainability assessment, SDG, data", were selected.
2. Databases EBSCOhost, IEEEXplore, Scopus, and Emerald were selected and searched. The search was limited to journal articles published in the years 2015 to 2023. The period was chosen because scientific articles on the use of blockchain with the LCA method are rather rare in the years before. In total, 65 journal articles were selected for further analysis.
3. Selected journal articles were analysed according to the topic of the paper and 35 journal articles were chosen for deeper analysis (all listed in the references).

Data collection was limited to the main features of holistic and integrated life cycle sustainability assessment (HILCSA) in environmental economics for the information available online for the 2015–2023 period.

Figure 1 shows the research methodology, including a systematic search of available online literature, a comparison of static and dynamic data storage, identification of risks and control mechanisms for static and dynamic data storage, and a linking of blockchain features to data, tools, and resources related to HILCSA. Design Science was used as the research strategy (Holmström et al. 2009). The identified problem encompassed a situation where a large part of the data used in the processes of the HILCSA method is of interest to the business of various organisations, such as data on specific products; production processes; indicators on social, environmental, or economic sustainability; as well as data on specific knowledge input from different disciplinary fields or various biobased resources. Therefore, data of common interest to organisations and stakeholders should be transparent, confidential, immutable, authentic, and easily shareable (Himeur et al. 2022). In this context, the challenge in the application of the HILCSA method is the selection of appropriate technology, management methodology, and the development of the holistic model.

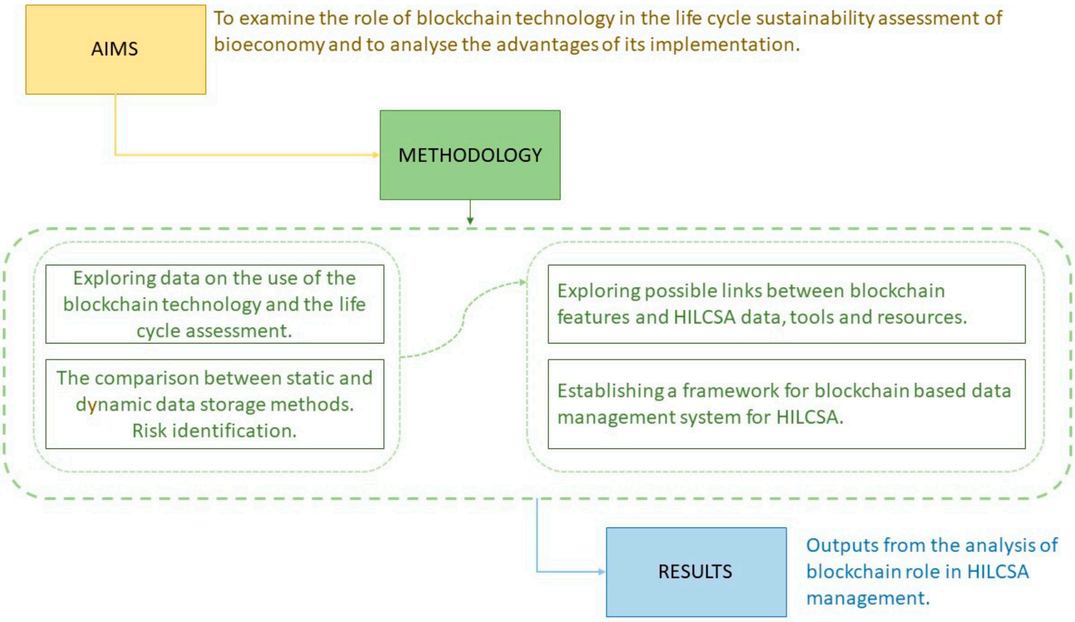


**Figure 1.** A flow chart summarising the aims–methodology–results path. Source: Authors.

Defined objectives were to improve the quality of the process in the application of the HILCSA method in the organisation in such a way as to enable fast and secure access to data, to automate the issuance of results after processing with the HILCSA method, to increase the transferability of assessment results to stakeholders, and to include risk management processes.

Design and development were added through the specification and development of the framework for blockchain implementation according to HILCSA method requirements.

Demonstration of the model was shown in prototyping the theoretical framework for managing risks, and supporting HILCSA with blockchain technology as a roadmap for practical use.

The risk identification methods that were used are the Ishikawa diagram and SWOT analysis. Observation, case control and intervention methods were included in the analysis. A comparison was made between static and dynamic data storage methods.

Social, environmental, and economic features of HILCSA were used for implementation in a blockchain-based data management system. HILCSA is an integrated approach that can be expressed as HILCSA = f (S-LCA, E-LCA, LCC), where S-LCA stands for social life cycle assessment, E-LCA means environmental life cycle assessment, and LCC means life cycle costing (Zeug et al. 2021) (Figure 2).

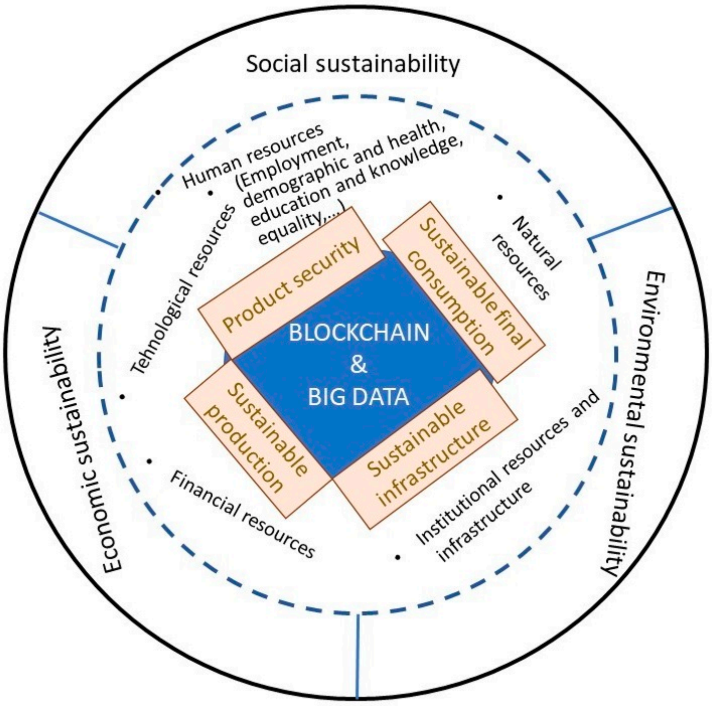


**Figure 2.** The framework for blockchain-based data management system for HILCSA. Source: Authors.

Limitations of this research include the risk identified as a lack of data analysis, which is very rare in the field of environmental economics due to the instability of the live environment. Not all research on blockchain applications will be considered in the holistic lifecycle sustainability assessment. This is because the technology is relatively new in the field and there are not many published studies of this kind. For the same reason, statistical data were not used.

## 4. Results

Analysis of the holistic life cycle sustainability assessment from the aspect of environmental economics and the inclusion of IT is carried out using the software applications and hardware support the organisations and individuals have at their disposal. A large part of data used in the HILCSA method processes can be useful for different organisations (Figure 2), which can be made accessible due to the data sharing characteristic.

The holistic model for gathering blockchain technology, the HILCSA method and risk management is dedicated to environmental, social, and economic objectives (Figure 2). Data availability, weighting and aggregation, and measuring a societal change are three main limiting factors in HILCSA (Zeug et al. 2021). Due to limited data availability, the first HILCSA application may result with fewer applicable indicators (Zeug et al. 2021). Data on technological resources for product security, natural resources for sustainable consumption, institutional resources for sustainable infrastructure, and financial resources for sustainable production can easily be added, tracked, and maintained on the blockchain. In conjunction with processes of risk management (risk identification, risk assessment, monitoring and controlling risk, and risk responses) HILCSA with blockchain support can improve its performance with complex sustainability assessments. In addition, blockchain is one of the enablers for fulfilling sustainable development goals (SDGs) as it plays a significant role in (1) building resilient and transparent supply chains, (2) creating stronger and more accountable public institutions, and (3) spurring responsible sourcing and consumption (Teh et al. 2020). Assessing a product or service's environmental impacts with the HILCSA method requires a large amount of data. Collecting and processing the data could be quite challenging for HILCSA as these processes could be rather difficult and time-consuming. Further difficulties could emerge in the form of missing data, inaccurate data, or even falsified data. Even with adopted blockchain technology, administrators can enter incorrect data by mistake, or data may be falsified to deceive the public about organisations' environmental performance. Besides technological integration, the framework for the blockchain-based data management system for HILCSA assumes the improvement of all processes included in the system in a way which will prevent data manipulation and to assure operational excellence for the organisations using HILCSA supported by blockchain. For example, the HILCSA method can deal with data on monitoring and controlling $CO_2$ emissions for measuring the environmental impact of products and processes.

The risk management process in the organisation plays the role of ensuring the optimal operation of the proposed model. In this case, the risk event is an incorrect entry of the $CO_2$ emission value that must have one or more responses to prevent, reduce, or avoid the risk. The $CO_2$ emission values obtained by the sensors can be automatically entered into the blockchain, which is an improved process to avoid data inaccuracies. Furthermore, performing a risk assessment on correct data reveals the nature and magnitude of health risks to humans and the environment from potential stressors at the specific site level. Risk management should be included for the optimal functioning of the blockchain and the HILCSA method, and after the obtained results, a risk assessment of the impacts on human health and the environment should be applied.

Generally speaking, the framework for a blockchain-based data management system for HILCSA with risk management processes is a model which each organisation tailors to its needs.

The structuring process should be conducted carefully, taking care that all necessary data and information are included, and accessibility rights for organisations and individuals are regulated. One of the advantages is that the existing local databases can be used as well and that a link can be made with the existing software that the organisations already use for the HILCSA. Furthermore, users enter new data according to the blockchain logic (Figure 3).

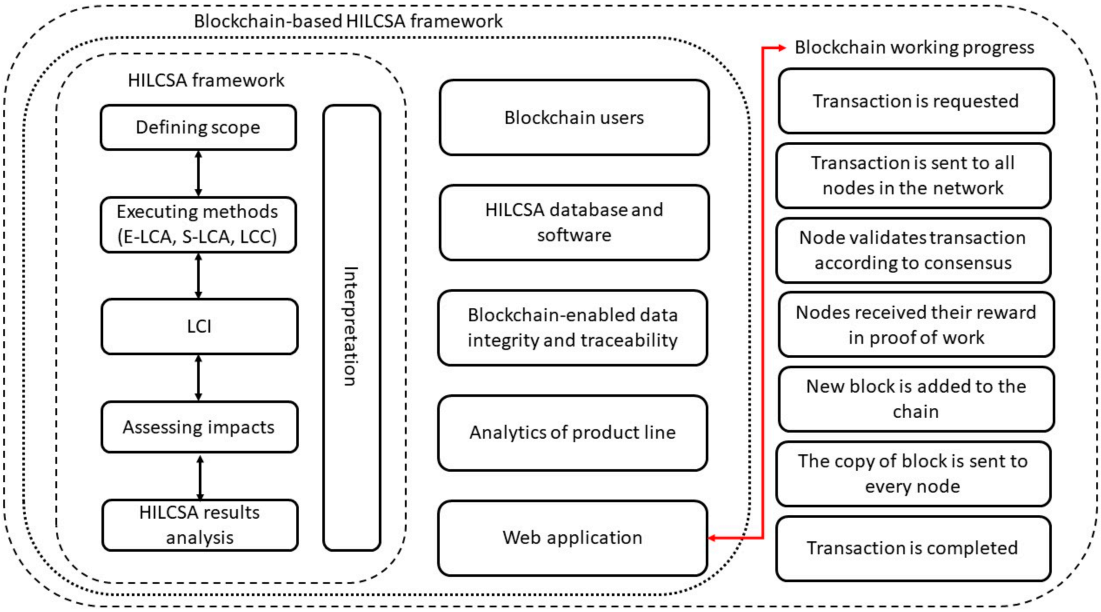


**Figure 3.** Blockchain-based HILCSA framework and blockchain working progress. Source: Authors.

Blockchain functions as a backend application while a plain user-friendly web application constitutes a frontend application through which users enter data and handle them according to the authorisations they have (Figure 3).

Some of the opportunities in connecting environmental economics, blockchain, and holistic life cycle sustainability assessment are data sharing, security and privacy, credibility and transparency, trustworthiness and integrity of data, data distributiveness, and data sovereignty protection.

The meaning of the characteristic of security and privacy in symbiosis with the HILCSA and blockchain is defined through work regulations in the HILCSA (Zeug et al. 2021) and by the blockchain logic (Smits and Hulstijn 2020). Thus, the maintenance of information is conducted through the blocks, and each block has a timestamp and hash value referring to the previous blocks in a chain. Hash values have unique cryptographic structures preventing information modification in a blockchain (Kouhizadeh and Sarkis 2018). Blockchain technology ensures data security and privacy through its decentralised system. In centralised systems, data are stored on centralised servers, which can cause data leakage and loss, while there is also danger from cyber attackers. However, there is decentralised data control in the blockchain, which makes it difficult for cybercriminals to access and modify data. The transaction data in the blockchain are open and transparent but the transaction address owner's identity is anonymous. Furthermore, blockchain uses an agreed-upon encryption process to ensure information protection from unauthorised access (Liu et al. 2020).

Credibility and transparency via blockchain for HILCSA are reinforced through the use of smart contracts. Blockchain technology provides an opportunity for the automatic execution of smart contracts, which, e.g., enables the users to transit to the next level in the process of holistic life cycle sustainability assessment. A smart contract enables automated data input in the blockchain and has the ability to initiate a programmed event when necessary. The direct benefit of this blockchain characteristic is manifested in the decrease of human intervention and redundancy. Identifying, collecting, and analysis of data have a key role in future predictions. Data related to the bioeconomy are stored in a blockchain through a holistic life cycle sustainability assessment, which contributes to wide possibilities of their future use for analyses in the environmental economics. In addition, blockchain can ensure trustworthiness and improve the integrity, access, and the repeated exchange of sensitive environmental data between entities in a network. In that way, the data are better integrated and as such they can be monitored, analysed, and optimized in real time. The distributed system of blockchain leads to enormous computing power, thus making possible a wide range of predictions and holistic approaches in the analyses based on the available information (Liu et al. 2020).

Data sharing as a characteristic of blockchain offers security in data storage. Blockchain has, to some extent, solved the security problem of data access. As a combination of distributed storage, the transfer from one point to the other, a consensus mechanism, and encryption algorithms, blockchain provides a solution for data sharing (Liu et al. 2020). Since a copy of the block is sent to each node in the network, in case of damage to one location, data loss cannot occur because the data are available on other nodes, which is not the case with centralised systems.

Considering data sovereignty protection, blockchain can additionally standardise data use and regulate the scope of authorizations to protect the relevant rights and interests of stakeholders (Liu et al. 2020).

Among threats in connecting blockchain and holistic life cycle sustainability assessment, the following stand out:

- Scalability;
- Consensus upgrade;
- Not clearly defined target users of the HILCSA results;
- Excessive energy consumption, as well as large memory usage can be caused by some consensus algorithms;
- Security attack.

Since the holistic life cycle sustainability assessment processes and analyses a large amount of data, there is a great need for data storage supporting high transactions throughout and high scalability, i.e., the capability of a system, network, or process to widen their potential according to the increase of workload. With the increase of the blockchain size, the time needed to copy data on new nodes on the network also increases. Optimisation at a certain algorithm level does not solve the problem of the scalability of a big decentralised system if there are schemes implemented within the chain, which collide with the blockchain decentralisation logic. In such cases, scalability is introduced through sharing, which can result in security problems. In that part, there is certainly still room for further research to find a more complete solution (Liu et al. 2020; Nurgazina et al. 2021).

Regarding the consensus upgrade, we start with the fact that blockchain data and information are unalterable. Unalterability means that the records could not be modified without the consent of the network members so all participants can be sure that the history of the records is reliable and unchanged. The consensus algorithm functions in such a way that it establishes a mechanism that forces multiple participants in the network to reach an agreement, considering that blockchain consists of decentralised nodes that have to reach a consensus on the validity of a transaction. The role of the consensus algorithm is to ensure that all nodes are in harmony with the protocol rules and that all transactions are conducted reliably. The challenge is to reach a consensus on one problem among multiple participants. Every update in a ledger demands consensus among network partners. Decentralised consensus is the core of blockchain, which uses different algorithms such as proof of work (POW) and proof of stake (POS) for the confirmation of the recorded transaction's reliability (Kouhizadeh and Sarkis 2018). Every organisation will modify the consensus mechanism according to its needs. In the case of the changes in organisations, e.g., changes in industry rules, the associated information on the blockchain will also change. The challenge is how to upgrade the consensus with the changes in the environment after all parties of blockchain have reached a consensus. This surely leaves room for further research on how to persuade stakeholders to revise their opinions (Liu et al. 2020).

Opportunities and threats, as a result of SWOT analysis and risk identification, are shown in a common probability and impact matrix (Figure 4) using positive definitions of impact for opportunities and negative impact definitions for threats. Descriptive terms very high (red colour), high (orange colour), moderate (yellow colour), low (light green colour), and very low (dark green colour) are used for probability and impact (Olson and Wu 2017).

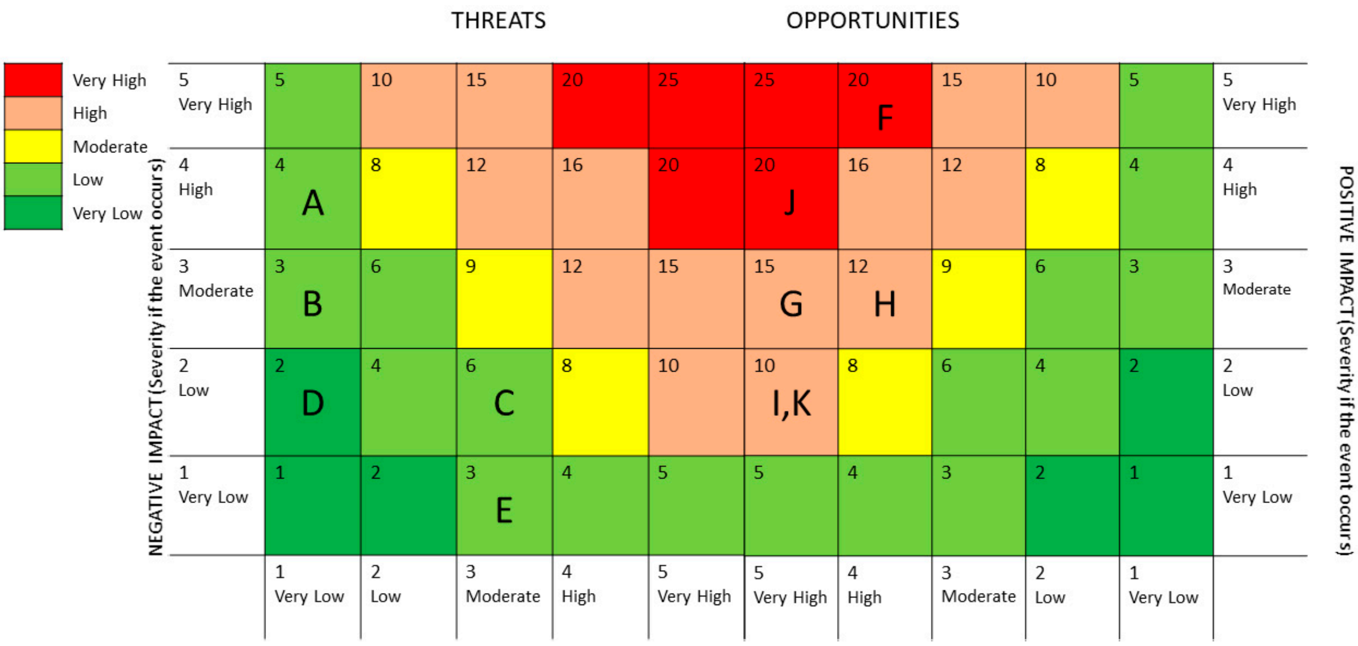


**Figure 4.** Tool for qualitative risk assessment: probability and impact matrix. Source: Authors.

Among the most significant threats for enabling the improvement of HILCSA with blockchain are: (A) scalability, (B) consensus upgrade, (C) lack of clarity in defining the target users of the HILCSA results, (D) excessive energy consumption and large memory requirements that can be caused by some consensus algorithms, and (E) security attack (Figure 4).

Among the most significant opportunities for enabling the improvement of HILCSA with blockchain are: (F) data sharing; (G) security and privacy; (H) validity, reliability and transparency; (I) data credibility and integrity; (J) distributiveness; and (K) data sovereignty protection (Figure 4).

On one hand, characteristics of blockchain—i.e., scalability, consensus upgrade, smart contracts, distributiveness, credibility, reliability and transparency, security, etc.—are advantages over other technologies and can improve work with the HILCSA method. However, on the other hand, if the organisation's business processes and HILCSA method processes are not taken into account, those characteristics can become issues because they will not fulfil our expectations completely. In the risk management context of blockchain inclusion in the HILCSA method, it is important to additionally assess all possible causes and consequences of any individual event.

Besides those, there are some open research challenges and open questions when blockchain is being integrated into the framework of HILCSA. Figure 5 shows some open questions, e.g., security (denial-of-service attacks, session hijacking, code injection, cross-site request forgery, and 51% attack) or consensus mechanisms that are surely interesting for further research.

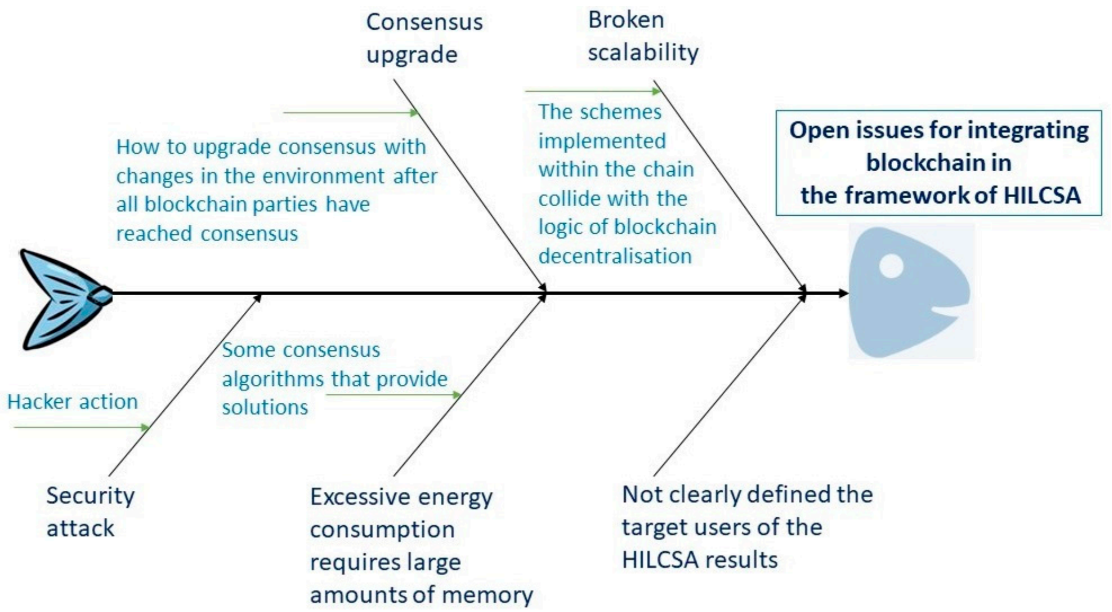


**Figure 5.** Ishikawa diagram—Open issues and research challenges. Source: Authors.

## 5. Discussion

The original contribution of this work is that, besides relating the existing HILCSA method processes and the way blockchain functions in the analyses concerning environmental economics, it stresses the risk management in implementing the proposed model in practice.

Based on the available literature, several studies have examined the potential of blockchain technology in the context of sustainable development, including environmental economics.

Zhang et al. (2020) emphasise a problem emerging before records are uploaded and converted into blocks. The enterprises can intentionally modify and edit data in their own database and then upload it into blockchains or accidentally upload wrong records which leads to the unreliability of data (Zhang et al. 2020). Processes management integrated into the business level of each organisation can prevent such or similar activities. Therefore, management through the introduction of new technology is very important.

The fundamental principles of blockchain are decentralisation, openness, and transparency. Handling such a large amount of data raises a trust issue in the digital economy despite the problem of data security within the internet environment actually being solved by the inclusion of blockchain technology (Liu et al. 2020).

Blockchain is an excellent solution in terms of collecting, processing, and providing reliable data in the situation when the reports on the conditions of the environment and environmental policies are being made, when interventions in the environment are being planned, or when enterprises develop their sustainability strategies demanding reports on the sustainability with a large number of indicators, i.e., water and energy consumption, use of chemicals, materials, and climate footprint (Benítez-Martínez et al. 2022).

Another study by Sunny et al. (2020) examined the potential of blockchain technology in supporting sustainable supply chain management. They argued that blockchain technology could enhance supply chain transparency, traceability, and accountability, which are critical for achieving sustainable development goals.

In comparison with these studies, the results presented in this article focus specifically on the implementation of blockchain technology in the context of holistic life cycle sustainability assessment (HILCSA) in environmental economics. This study emphasizes the potential of blockchain technology in addressing issues related to data availability, accuracy, and manipulation, which are critical for the effectiveness of the HILCSA method. The study also highlights the importance of risk management in ensuring the optimal operation of the proposed model.

Overall, the existing literature supports the potential of blockchain technology in enhancing sustainability in various domains, including environmental economics. The results presented in this paper contribute to this literature by providing a specific focus on the potential of blockchain technology in the context of HILCSA.

In dealing with challenges when including blockchain in HILCSA, the tendency is to first focus on the issues concerning digital disturbance, digital economics, knowledge industries, and the innovation system. This enables a full understanding of the digital disturbance context.

However, usually, it is not only digital technology that matters, i.e., social and economic drivers that create demand for technology (or a change as a response to it) can be equally if not even more important. The best functioning digital business models first understand people and only then the technology (Christensen et al. 2015). Therefore, the holistic approach to the inclusion of blockchain into HILCSA is of utmost importance for future analyses in the field of environmental economics.

Blockchain could facilitate application of the most recent scientific achievements in the production process to the organisations and public systems applying HILCSA. In addition, blockchain technology could enable a scientific and analytical foundation for the political decisions related to the environment and improve information accessibility for various stakeholders, as well as ensure procedural transparency. Eventually, it would promote good governance and sustainable development.

The ability of blockchain technology to create structures for data management where the users have increased ownership and control over the data could significantly reduce the costs of data management as well as the exposure to the responsibility stemming out from the issues related to data management.

The research on implementing blockchain in environmental economics has practical implications for businesses, governments, and researchers. The use of blockchain technology can improve the process of monitoring and evaluating environmental policies and sustainability predictions, leading to more efficient and effective decision-making processes. This can have a positive economic and commercial impact by reducing costs and increasing transparency and accountability. For example, businesses can use blockchain to track their supply chains and verify the sustainability of their products, which can improve their reputation and increase customer loyalty. The concrete impact of the research on society can be seen in the increasing adoption of blockchain technology in the environmental sector. For example, some companies are using blockchain to track the sustainability of their products, such as seafood and palm oil, which can help reduce deforestation and overfishing (Kechagias et al. 2023). Governments can use blockchain to improve their environmental policies and monitor compliance with regulations, which can lead to better protection of the environment and public health. Researchers can use blockchain to collect and analyse environmental data, which can improve the accuracy and reliability of sustainability assessments.

In terms of practice, the paper suggests that the use of blockchain technology in HILCSA could lead to significant workflow improvements and improved risk recognition, as well as improvements in data sharing, security, privacy, validity, reliability, transparency, credibility, data integrity, distributiveness, and data sovereignty protection. This could have a positive economic and commercial impact on businesses and organizations that implement blockchain technology for HILCSA by streamlining their business processes and improving their ability to predict sustainable development outcomes.

In terms of influencing public policy, the paper suggests that the use of blockchain technology in HILCSA could significantly improve the monitoring and evaluation of environmental policies and predictions of sustainable development. This could potentially lead to more effective and targeted policy interventions aimed at preserving and protecting the environment. The paper also highlights the need for further research into relevant regulatory methods.

Overall, the implications of the research suggest that the integration of blockchain technology into HILCSA could have significant benefits for both research and practice, as well as for society more broadly.

## 6. Conclusions

This paper first brings an overview of achievements in the fields of blockchain and holistic life cycle sustainability assessment in environmental economics. Secondly, the advantages and challenges in the inclusion of blockchain technology into holistic life cycle sustainability assessment with the application of risk management methodology are explored. Decentralized data processing represented by blockchain could improve work with the HILCSA method in environmental economics with continuous risk management, primarily from the aspect of improving the organisation's business processes, thus highlighting possible workflow improvements achieved through the use of a decentralized network, a distributed shared ledger, consensus, and data immutability and security, which can lead to a more optimized work process.

Blockchain applications in the protection and preservation of the environment are related to the holistic life cycle sustainability assessment in environmental economics. The explored examples of existing applications point out positive shifts in comparison to the use of exclusively centralised systems, as well as highlight the need for further development of blockchain applications and their combination with the already-existing IT systems and solutions that can be applied not only in business communities but in wider areas related to the environmental policies and good government.

In the analysis of HILCSA and blockchain processes within the field of environmental economics, several advantages of connecting the blockchain and holistic life cycle sustainability assessment have stood out, i.e., data sharing; security and privacy; validity, reliability and transparency; credibility; data integrity; distributiveness; and the data sovereignty protection.

The structure and completeness of the data in blockchains facilitate and improve their further analysis, which is very important in the predictions based on the HILCSA method application. Due to smart contracts provided by a blockchain, processes are automated which results in a decrease of human intervention and in the removal of redundancy. Processes in the framework of the HILCSA method use large amounts of data whose security and privacy are ensured by distributed storage, a consensus mechanism, and the encryption process.

Despite its results, this research has some limitations. The proposed model is a general framework that has to be tailored for each organisation specifically, so more research is needed for specific products or services. Limitations of this research include the risk of insufficient data analysis which is caused by the instability of the live environment. To provide a holistic understanding of blockchain implementation, future research needs to consider the views of all stakeholders to identify other critical challenges.

The most important challenges for enabling the improvement of HILCSA with blockchain are ensuring scalability, a consensus upgrade, not clearly defined target users of the HILCSA results, excessive energy consumption, the need for large amounts of memory required by some consensus algorithms, as well as the possibility of a security attack. There are several concrete limitations of blockchain technologies that should be considered when implementing them in various industries, including environmental economics. These limitations include:

1. Scalability: Blockchain networks can become slow and congested when many transactions are processed simultaneously. This can result in longer processing times and higher transaction fees.
2. Energy consumption: another significant limitation of blockchain technology is the excessive energy consumption required for the consensus process, which can contribute to environmental issues such as climate change.
3. Security vulnerabilities: although blockchain technology is designed to be secure, there is still a risk of security vulnerabilities such as 51% attacks, which can compromise the integrity of the blockchain.
4. Lack of regulation: the lack of regulatory frameworks surrounding blockchain technology can create legal and compliance issues, making it difficult for organizations to adopt blockchain-based solutions.
5. Limited adoption: despite the potential benefits of blockchain technology, its adoption is still limited, and many organizations may not have the necessary technical expertise to implement it effectively.
6. Complexity: Blockchain technology is a complex system that can be challenging to understand and implement. Organizations may need to invest significant resources in training and education to utilize blockchain technology effectively.

Overall, while blockchain technology has the potential to revolutionize various industries, it is essential to be aware of its limitations and carefully evaluate its suitability for specific use cases. These challenges leave room for further research in finding and improving solutions. The very process of the inclusion of blockchain into HILCSA as a new digital model of sustainable business, but also the development, monitoring, and evaluation of environmental policies, should be approached from a holistic aspect.

Holistic and integrated life cycle sustainability assessment in the field of environmental economics with the existing IT support can be combined with blockchain technology in order to improve the way data are processed and analysed. Thus, it would significantly improve the system and possibilities of monitoring, evaluation of the environmental policies, and predictions of sustainable development. The implications for research are significant, as the paper suggests that further research is needed to tailor the proposed model for specific products or services, and to consider the views of all stakeholders in identifying critical challenges.

It is recommended to include blockchain technology in holistic life cycle sustainability assessment in the field of environmental economics, pay attention to the research and analysis of security risks, and carefully monitor development trends as well as actively research relevant regulatory methods.

**Author Contributions:** Conceptualisation, M.M.Š.; methodology and formal analysis, S.T. and M.M.Š.; results and discussion, S.T. and M.M.Š.; investigation, M.M.Š. resources, S.T. and M.M.Š.; writing—original draft preparation, S.T., and M.M.Š.; writing—review and editing S.T., and M.M.Š.; visualisation, S.T. and M.M.Š. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research received no external funding.

**Institutional Review Board Statement:** Ethical review and approval were waived for this study, since the research was not a medical research on human subjects and did not include identifiable human material and data. It collected research participants' opinions and attitudes.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** Not applicable.

**Acknowledgments:** The authors wish to thank the editor and three anonymous reviewers for their constructive feedback for improving the manuscript.

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

## References

Agrawal, Tarun Kumar, Tarun Kumar, Rudrajeet Pal, Lichuan Wang, and Yan Chen. 2021. Blockchain-based framework for supply chain traceability: A case example of textile and clothing industry. *Computers and Industrial Engineering* 154: 107130. [CrossRef]

Ahl, Amanda, Mika Goto, Masaru Yarime, Kenji Tanaka, and Daishi Sagawa. 2022. Challenges and opportunities of blockchain energy applications: Interrelatedness among technological, economic, social, environmental, and institutional dimensions. *Renewable and Sustainable Energy Reviews* 166: 112623. [CrossRef]

Barbosa, Marcelo Werneck. 2021. Uncovering research streams on agri-food supply chain management. *Global Food Security* 28: 100517. [CrossRef]

Benítez-Martínez, Francisco Luis, Pedro Víctor Nuñez-Cacho-Utrilla, Valentín Molina-Moreno, and Esteban Romero-Frías. 2022. Blockchain as a Service: A Holistic Approach to Traceability in the Circular Economy. In *Blockchain Technologies for Sustainability. Environmental Footprints and Eco-design of Products and Processes*. Edited by Subramanian Senthilkannan Muthu. Singapore: Springer, pp. 119–33. [CrossRef]

Bodkhe, Umesh, Sudeep Tanwar, Karan Parekh, Pimal Khanpara, Sudhanshu Tyagi, Neeraj Kumar, and Mamoun Alazab. 2020. Blockchain for Industry 4.0: A Comprehensive Review. *IEEE Access* 8: 79764–800. Available online: https://ieeexplore.ieee.org/document/9069885 (accessed on 20 October 2022). [CrossRef]

Chen, James. 2022. Environmental economics: Definition, Importance and Example. Investopedia. Available online: https://www.investopedia.com/terms/e/environmental-economics.asp (accessed on 12 November 2022).

Christensen, Clayton, Michael E. Raynor, and Rory McDonald. 2015. What is disruptive innovation? *Harvard Business Review* 93: 44–53. Available online: https://hbr.org/2015/12/what-is-disruptive-innovation (accessed on 20 October 2022).

Diemer, Arnaud, Cécile Batisse, Ganna Gladkykh, and Thérèse Bennich. 2020. Role of Bioeconomy in the Achievement of Sustainable Development Goals. In *Partnerships for the Goals. Encyclopedia of the UN Sustainable Development Goals*. Edited by Walter Leal Filho, Anabela Marisa Azul, Luciana Brandli, Amanda Lange Salvia and Tony Wall. Cham: Springer, pp. 1–14. [CrossRef]

Ethereum. 2022. Available online: https://ethereum.org/en/ (accessed on 20 October 2022).

European Union, and European Regional Development Fund. 2021. Blockchains and Environment, Interreg, Central Europe, Chain Reactions. Thematic Brief Energy-Environment. Available online: https://bioeconomy.sk/en/wp-content/uploads/sites/2/2021/01/Thematic-brief-Blockchains-and-environment.pdf (accessed on 20 October 2022).

Ferreira Cruz, Estrela, and Antonio Miguel Rosado da Cruz. 2020. Using Blockchain to Implement Traceability on Fishery Value Chain. Paper presented at the 15th International Conference on Software Technologies (ICSOFT 2020), Paris, France, July 7–9; pp. 501–8.

Foltynowicz, Zenon, and Zbigniew Stanisław Kłos. 2022. Research Activities on LCA and LCM in Poland. In *Towards a Sustainable Future—Life Cycle Management*. Edited by Zbigniew Stanislaw Klos, Joanna Kalkowska and Jędrzej Kasprzak. Cham: Springer, pp. 289–303.

Himeur, Yassine, Aya Sayed, Abdullah Alsalemi, Faycal Bensaali, Abbes Amira, Iraklis Varlamis, Magdalini Eirinaki, Christos Sardianos, Magdalini Eirinaki, and Christos Sardianos. 2022. Blockchain-based recommender systems: Applications, challenges and future opportunities. *Computer Science Review* 43: 100439. [CrossRef]

Holmström, Jan, Mikko Ketokivi, and Ari-Pekka Hameri. 2009. Bridging practice and theory: A Design Science approach. *Decision Sciences* 40: 65–87. [CrossRef]

ISO. 2006a. *Environmental Management-Life Cycle Assessment-Principles and Framework*. ISO 14040:2006. Geneva: International Organization for Standardization.

ISO. 2006b. *Environmental Management-Life Cycle Assessment-Requirement and Guidelines*. ISO 14044:2006. Geneva: International Organization for Standardization.

Jarosch, Lena, Walther Zeug, Alberto Bezama, Matthias Finkbeiner, and Daniela Thrän. 2020. A Regional Socio-Economic Life Cycle Assessment of a Bioeconomy Value Chain. *Sustainability* 12: 1259. [CrossRef]

Karaszewski, Robert, Paweł Modrzyński, Gözde Türkmen Müldür, and Jacek Wójcik. 2021. Blockchain Technology in Life Cycle Assessment—New Research Trends. *Energies* 14: 8292. [CrossRef]

Kechagias, Evripidis P., Sotiris P. Gayialis, Georgios A. Papadopoulos, and Georgios Papoutsis. 2023. An Ethereum-Based Distributed Application for Enhancing Food Supply Chain Traceability. *Foods* 12: 1220. [CrossRef]

Kotha, Saransh, and Pearl Patel. 2020. Blockchain in Depth. *International Journal of Engineering and Computer Science* 9: 25029–38. [CrossRef]

Kouhizadeh, Mahtab, and Joseph Sarkis. 2018. Blockchain Practices, Potentials, and Perspectives in Greening Supply Chains. *Sustainability* 10: 3652. [CrossRef]

Lesavre, Loïc, Priam Varin, Peter Mell, Michael Davidson, and James Shook. 2020. *A Taxonomic Approach to Understanding Emerging Blockchain Identity Management Systems*; White Paper NIST CSWP 9. Gaithersburg: National Institute of Standards and Technology. Available online: https://nvlpubs.nist.gov/nistpubs/CSWP/NIST.CSWP.01142020.pdf (accessed on 20 October 2022).

Liu, Jiameng, Shaoliang Peng, Chengnian Long, Lijun Wei, Yunhao Liu, and Zhihui Tian. 2020. Blockchain for Data Science. Paper presented at the 2nd International Conference on Blockchain Technology, ICBCT'20, Hilo, HI, USA, March 12–14; pp. 24–28. [CrossRef]

Mangla, Sachin Kumar, Yigit Kazancoglu, Esra Ekinci, Mengqi Liu, Melisa Ozbiltekin, and Muruvvet Deniz Sezer. 2021. Using system dynamics to analyze the societal impacts of blockchain technology in milk supply chainsrefer. *Transportation Research: Part E* 149: 102289. Available online: https://dspace.yasar.edu.tr/bitstream/handle/20.500.12742/18500/1-s2.0-S1366554521000636-main.pdf?sequence=1&isAllowed=y (accessed on 20 October 2022). [CrossRef]

Mieras, Eric, Anne Gaasbeek, and Daniël Kan. 2019. How to Seize the Opportunities of New Technologies in Life Cycle Analysis Data Collection: A Case Study of the Dutch Dairy Farming Sector. *Challenges* 10: 8. [CrossRef]

Nakamoto, Satoshi. 2008. *Bitcoin: A Peer-to-Peer Electronic Cash System*. Austin: Satoshi Nakamoto Institute. Available online: https://nakamotoinstitute.org/bitcoin/ (accessed on 20 October 2022).

Narwane, Vaibhav S., Rakesh D. Raut, Sachin Kumar Mangla, Manoj Dora, and Balkrishna E. Narkhede. 2021. Risks to Big Data Analytics and Blockchain Technology Adoption in Supply Chains. *Annals of Operations Research*. [CrossRef]

Nurgazina, Jamilya, Udsanee Pakdeetrakulwong, Thomas Moser, and Gerald Reiner. 2021. Distributed Ledger Technology Applications in Food Supply Chains: A Review of Challenges and Future Research Directions. *Sustainability* 13: 4206. [CrossRef]

Olson, David L., and Desheng Dash Wu, eds. 2017. Risk Matrices. In *Enterprise Risk Management Models*. Springer Texts in Business and Economics. Berlin and Heidelberg: Springer, pp. 17–29. [CrossRef]

Pu, Shuyi, and Jasmine Siu Lee Lam. 2020. Blockchain adoptions in the maritime industry: A conceptual framework. *Maritime Policy and Management* 48: 777–94. [CrossRef]

Rolinck, Maximilian, Sebastian Gellrich, Christoph Bode, Mark Mennenga, Felipe Cerdas, Jens Friedrichs, and Christoph Herrmann. 2021. A Concept for Blockchain-Based LCA and its Application in the Context of Aircraft MRO. *Procedia CIRP* 98: 394–99. [CrossRef]

Sevigné-Itoiz, Eva, Onesmus Mwabonje, Calliope Panoutsou, and Jeremy Woods. 2021. Life cycle assessment (LCA): Informing the development of a sustainable circular economy? *Philosophical Transactions of The Royal Society A Mathematical Physical and Engineering Sciences* 379: 20200352. [CrossRef]

Smits, Martin, and Joris Hulstijn. 2020. Blockchain Applications and Institutional Trust. *Frontiers in Blockchain* 3: 5. [CrossRef]

Sun, Rui, Dayi He, Jingjing Yan, and Li Tao. 2021. Mechanism Analysis of Applying Blockchain Technology to Forestry Carbon Sink Projects Based on the Differential Game Model. *Sustainability* 13: 11697. [CrossRef]

Sunny, Justin, Naveen Undralla, and V. Madhusudanan Pillai. 2020. Supply chain transparency through blockchain-based traceability: An overview with demonstration. *Computers & Industrial Engineering* 150: 106895. [CrossRef]

Teh, David, Tehmina Khan, Brian Corbitt, and Chin Eang Ong. 2020. Sustainability strategy and blockchain-enabled life cycle assessment: A focus on materials industry. *Environment Systems and Decisions* 40: 605–22. [CrossRef]

Tišma, Sanja, Anamarija Farkaš, Anamarija Pisarović, Marina Funduk, and Iva Tolić. 2022. *Economics, Ecology, and Policy for the Bioeconomy: A Holistic Approach*. London and New York: Routledge.

Valdivia, Sonia, Jana Gerta Backes, Marzia Traverso, Guido Sonnemann, Stefano Cucurachi, Jeroen B. Guinée, Thomas Schaubroeck, Matthias Finkbeiner, Noemie Leroy-Parmentier, Cássia Ugaya, and et al. 2021. Principles for the application of life cycle sustainability assessment. *The International Journal of Life Cycle Assessment* 26: 1900–5. [CrossRef]

Xu, Jie, Shuang Guo, David Xie, and Yaxuan Yane. 2020. Blockchain: A new safeguard for agri-foods. *Artificial Intelligence in Agriculture* 4: 153–61. [CrossRef]

Zeug, Walther, Alberto Bezama, and Daniela Thrän. 2021. A framework for implementing holistic and integrated life cycle sustainability assessment of regional bioeconomy. *The International Journal of Life Cycle Assessment* 26: 1998–2023. [CrossRef]

Zhang, Abraham, Ray Y. Zhong, Muhammad Farooque, Kai Kang, and V. G. Venkatesh. 2020. Blockchain-based life cycle assessment: An implementation framework and system architecture. *Resources, Conservation and Recycling* 152: 104512. [CrossRef]