2021

Applications of blockchain technology in sustainable manufacturing and supply chain management: A systematic review

Ahmad A. A. Khanfar
Edith Cowan University

Mohammad Iranmanesh
Edith Cowan University

Morteza Ghobakhloo

Madugoda Gunaratnege Senali
Edith Cowan University

Masood Fathi

10.3390/su13147870
Khanfar, A. A. A., Iranmanesh, M., Ghobakhloo, M., Senali, M. G., & Fathi, M. (2021). Applications of blockchain technology in sustainable manufacturing and supply chain management: A systematic review. *Sustainability, 13*(14), article 7870. https://doi.org/10.3390/su13147870

sustainability

MDPI

Review

Applications of Blockchain Technology in Sustainable Manufacturing and Supply Chain Management: A Systematic Review

Ahmad A. A. Khanfar [1], Mohammad Iranmanesh [1,*], Morteza Ghobakhloo [2,3,*], Madugoda Gunaratnege Senali [4] and Masood Fathi [5,6]

1 School of Business and Law, Edith Cowan University, Joondalup, WA 6027, Australia; a.khanfar@ecu.edu.au
2 School of Economics and Business, Kaunas University of Technology, LT-44249 Kaunas, Lithuania
3 Graduate School of Business, Universiti Sains Malaysia, Penang 11800, Malaysia
4 School of Arts and Humanities, Edith Cowan University, Joondalup, WA 6027, Australia; smadugod@our.ecu.edu.au
5 School of Engineering Science, University of Skovde, P.O. Box 408, 54128 Skovde, Sweden; masood.fathi@his.se
6 Division of Industrial Engineering and Management, Uppsala University, P.O. Box 534, 75121 Uppsala, Sweden
* Correspondence: m.iranmanesh@ecu.edu.au (M.I.); morteza.ghobakhloo@ktu.lt (M.G.)

Abstract: Developing sustainable products and processes is essential for the survival of manufacturers in the current competitive market and the industry 4.0 era. The activities of manufacturers and their supply chain partners should be aligned with sustainable development goals. Manufacturers have faced many barriers and challenges in implementing sustainable practices along the entire supply chain due to globalisation, outsourcing, and offshoring. Blockchain technology has the potential to address the challenges of sustainability. This study aims to explain the applications of blockchain technology to sustainable manufacturing. We conducted a systematic literature review and explained the potential contributions of blockchain technology to the economic, environmental, and social performances of manufacturers and their supply chains. The findings of the study extend our understanding of the blockchain applications in sustainable manufacturing and sustainable supply chains. Furthermore, the study explains how blockchain can influence the sustainable performance of manufacturers by creating transparency, traceability, real-time information sharing, and security of the data capabilities.

Keywords: blockchain technology; blockchain applications; sustainability practices; sustainable performance; sustainable manufacturing; smart contract; industry 4.0; supply chain management; digital transformation; systematic literature review

Citation: Khanfar, A.A.A.; Iranmanesh, M.; Ghobakhloo, M.; Senali, M.G.; Fathi, M. Applications of Blockchain Technology in Sustainable Manufacturing and Supply Chain Management: A Systematic Review. *Sustainability* **2021**, *13*, 7870. https://doi.org/10.3390/su13147870

Academic Editor: Wen-Hsien Tsai

Received: 13 June 2021
Accepted: 13 July 2021
Published: 14 July 2021

1. Introduction

Sustainability and effective balancing of environmental, social, and business outcomes has become an essential requirement of the manufacturing sector [1]. Sustainability strategies enable manufacturers to meet growing demands with minimal impacts on the environment and society [2–4]. Considering the importance of sustainable practices, manufacturers have adopted various technologies and approaches such as big data analytics, blockchain, artificial intelligence, lean manufacturing, six sigma, and reverse logistics to enhance their sustainability performance in the industry 4.0 era [5,6]. Blockchain is one of the emerging and fast-growing technologies that can contribute to sustainable manufacturing among digital technologies.

Blockchain technology is a decentralised and distributed data structure. Data are shared on a peer-to-peer, open access network and transactions should be certified, verified, and accessed by members of the network community. Blockchain ensures the transparency and security of the transactions [7,8]. Blockchain is initially introduced in the financial industry for cryptocurrency to replace manual authentication of transactions with digital authentications [9]. As blockchain could enhance traceability, transparency, trust, data immutability, and data security, it has received attention from both academics and professionals from various industries [10,11]. Investment in blockchain solutions is growing fast and expected to reach USD 176 billion by 2025 [12]. Blockchain technology offers promising capabilities that can improve economic, social, and environmental sustainability practices of the supply chain and manufacturing industry [1,13]. Given the importance of sustainability in the manufacturing sector, there is an increasing academic interest in investigating the contributions of blockchain technology to the sustainable performance of manufacturers [14,15]. However, to our best knowledge, there is a lack of review articles that synthesise the current knowledge on the applications of blockchain technology in sustainable manufacturing and provide future research directions. Thus, this article aimed to explain the connection between blockchain technology and sustainable manufacturing. The paper used the systematic review approach to answer the following research questions:

1. What are the applications of blockchain technology in sustainable manufacturing?
2. How can blockchain attributes enhance the sustainable performance of manufacturers?

This study contributes to the literature on sustainable manufacturing by explaining the contributions of blockchain technology to the economic, social, and environmental performance of manufacturers and their supply chain based on blockchain attributes such as traceability, transparency, security, and real-time information sharing. The study may serve as the foundation for further discussion and research by both practitioners and scholars. The study also proposes directions for future studies on blockchain technology in sustainable manufacturing.

2. Background of Blockchain Technology Concept

2.1. Overview of Blockchain Technology

Blockchain technology was first conceptualised and introduced by Satoshi Nakamoto in 2008 [9]. Blockchain technology is a distributed data structure in which the data are shared on a peer-to-peer network. Blockchain consists of a chain of blocks that record transactions generated by contracting parties. Following a predefined protocol, transactions must be approved and validated by the network members who belong to a peer-to-peer network. The transaction details are recorded on a public ledger called the distributed ledger [16]. The distributed ledger is a decentralised record of transactions in which the transaction blocks are stored in all computers of the network members and can be seen by anyone in the network. When a transaction/block is generated and validated by certain members of the network, this block is added to the network and linked to previous blocks [17,18]. Verification of transactions can be performed by individuals, machines, algorithms, and organisations. Blockchain can eliminate intermediates from a network and link different parties directly, which may reduce human errors and transaction costs [19]. Storing data in share databases instead of central ones reduces the risk of losing data and increases transparency and security of information [19]. Smart contracts help to eliminate the need for intermediaries and reduce transaction costs [20]. Smart contracts enhance the privacy and security of information as all transactions should be complied with the underlying legal agreements and should be approved and verified by the members based on the transaction validation rules defined in the smart contracts [19,21].

2.2. Applications of Blockchain Technology

Blockchain is an emerging and fast-growing technology that has been adapted in various industries such as finance, real estate, health care, and energy due to its capabilities and benefits. Various industries can benefit from blockchain technology's attributes and features, such as traceability, transparency, data security, and real-time information sharing [13,17,19]. For instance, in the agri-food industry, blockchain can be integrated with other technologies such as RFID to track food supplies in real time, which may optimise processes of food operations, enhance food safety and quality, and reduce unethical practices and social harms [22]. In the financial industry, blockchain technology can be applied to decentralise and trace transactions and remove banks' financial institutions [23]. In the healthcare sector, blockchain can be used to enhance the confidentiality and accuracy of patient information. Furthermore, blockchain can reduce healthcare costs and improve the quality of services provided to patients. Using blockchain technology in healthcare can also prevent healthcare fraud and increase transparency with patients [8]. In the automobile industry, blockchain is utilised to secure and protect automated cars from being hacked and is applied to develop driving technologies. Blockchain-based systems enhance the performance of self-driving cars and contribute to fuel usage and emissions reduction [8]. Blockchain technology is one of the key technologies in developing a smart city due to its benefits, such as data security, decentralisation, real-time information sharing, and trust, which are essential for a successful smart city development [24]. Blockchain can also be utilised as a middleware solution that integrates technological advancements with Industry 4.0 smart manufacturing. This integration can facilitate information sharing, increase security, reduce costs, and increase organisational efficiency [25]. In the pharmaceutical industry, the blockchain can be utilised to improve control over the medicines supply chain, and it can facilitate detecting fake medicines [26].

2.3. Benefits of Blockchain in the Manufacturing Sector

Managing information in the supply chain is challenging as real-time and reliable data are needed to avoid poor performance, fraud, and risks [1,21]. There is a need to improve data reliability, traceability, and authenticity by using better verifiability and information sharing systems [1]. Blockchain connects supply chain stakeholders using a distributed data structure where data are shared on a peer-to-peer network. All stakeholders agree on predefined protocols, and data are communicated and validated based on the protocols [27,28]. The decentralised structure of blockchain supports transaction verification directly between stakeholders and eliminates the need for intermediaries to verify transactions [19]. Blockchain enables companies involved in the supply chain network to share, access, and verify information securely as transactions and data are protected through advanced cryptography [28]. Advanced cryptography reduces the risk of losing and altering the information and prevents any human errors in transactions [19,21]. Blockchain technology positively influences the reliability and trustworthiness of supply chain transactions, supply chain operations, time of supply chain activities, and decision-making efficiency [13,21].

Transparency is one of the attributes of blockchain and refers to the availability of information among the supply chain stakeholders [29]. Blockchain technology supports real-time information sharing among stakeholders involved in the supply chain network, which increases transparency and trustworthiness among supply chain partners and customers [1,11]. Blockchain enables customers to obtain valid and accurate information about products and processes [1,21]. Traceability is another attribute of blockchain and refers to identifying and verifying the components and chronology of events in all steps of a chain. Tracking the information in the entire chain is essential to verify compliance with specifications and trace failure events [30]. Traceability allows stakeholders to track and monitor items and shipments across all over the chain [14,15]. The traceability attribute of blockchain enhances the transparency of the supply chain activities, which in turn positively influences the level of trust among supply chain stakeholders, including suppliers and customers, reduces conflicts among them, reduces verification costs, and enable stakeholders to identify unethical practices [11,13].

3. Manufacturing Process

The supply chain operations reference (SCOR) model provides an efficient way to analyse and measure the supply chain operations and performance. The model analyses supply chain activities across four business processes: plan, source, make, deliver, and return. The SCOR model defines standard metrics and strategic objectives of supply chain processes and ensures that supply chain activities are reliable, performed as planned, and flexible and adaptive to changes which in turn lead to efficient management of the costs associated with operations such as labour, material, and transportation costs and efficient asset utilisation [31,32].

The planning process refers to planning and control activities that aim to balance the demand and supply in meeting the requirements of purchasing, production, and distribution [33]. The business rules that improve the efficiency of supply chain operations and enhance quality control activities are defined in the planning process [34]. Transparency and sharing information among the supply chain are critical in the planning process in order to facilitate the decision-making process and the accuracy of the plan for the future [35]. The sourcing process refers to identifying and selecting the sources of supply, procurement activities, and the alignment between the planned and actual orders [33]. The source process aims to build knowledge on raw materials and ensure suppliers are registered and certified, and provide high-quality products [34,35]. The making process refers to transforming raw materials into final products or services, including packaging, product staging, releasing, and production activities [33]. The making process provides guidelines on meeting production schedules with high standards and meeting the customers' requirements [34]. The delivery process refers to the activities associated with the fulfilment and management of orders [33]. The delivery process includes creating orders, order maintenance, order fulfilment, effective management of products, inventory, warehousing, and transportation [34,36]. The delivery process ensures that the customers receive the products on time [35]. Finally, the returning process refers to the activities associated with reversing products and services from customers [33]. Blockchain technology can contribute to the sustainability of manufacturers in various business processes, which are discussed in this review.

4. Systematic Review Protocol

The review was conducted based on the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guideline [37] for conducting the systematic literature review. To answer the research question of this study regarding the contributions of blockchain to the sustainability of manufacturers, the identified articles were analysed using the content-centric analysis technique [38]. The search terms, inclusion and exclusion criteria, and search results are elaborated in the following three sub-sections.

4.1. Database and Search Terms

To review the articles published on the contributions of blockchain to the sustainability of manufacturing firms, search terms related to blockchain and sustainability were used to extract articles from the Scopus database on 8 March 2021. Scopus was selected as it is the largest database of peer-reviewed journals [39]. The search within the title, abstract, and keywords of articles was conducted using ("Sustainab*" OR "environ*" OR Green OR "eco*" OR "Social" OR "Societal" OR "CSR") AND ("Blockchain" OR "Smart Contract" OR "distributed ledger") search terms.

4.2. Article Inclusion and Exclusion Criteria

To screen the articles and find the relevant works, four inclusion and exclusion criteria were defined as follows: (1) articles should be in English, (2) articles should be published in journals, (3) the application of blockchain technology in sustainable manufacturing should be discussed in the articles, and (4) full text of the identified articles should be accessible for further analysis.

4.3. Search Results

The result of the search within the title, abstract, and keywords of documents indexed by the Scopus database was 883 works (Figure 1). Following the first and second inclusion criteria, the search was limited to journal, article, and English, which resulted in 295 articles. The titles and abstracts of 295 identified articles were reviewed by two authors using the third inclusion criteria of the study. The disagreements between these two authors on excluding or including some articles were resolved by consensus after discussion among all authors. The initial screen was performed based on titles and abstracts and resulted in 41 articles. In the subsequent screen, five articles were excluded due to full-text unavailability, and 21 articles were excluded as they did not meet the inclusion criteria based on the full-text screen. Finally, six articles were added by checking the references of included articles and 21 articles related to the contributions of blockchain to the sustainability of manufacturers were found (Appendix A). The authors reviewed the articles, and the applications of blockchain to sustainable manufacturing described in the articles were identified and summarised in a table. Later, all the authors discussed and the applications were categorised based on the framework for sustainable performance assessment of supply chain management practices proposed by Chardine-Baumann and Botta-Genoulaz [40].

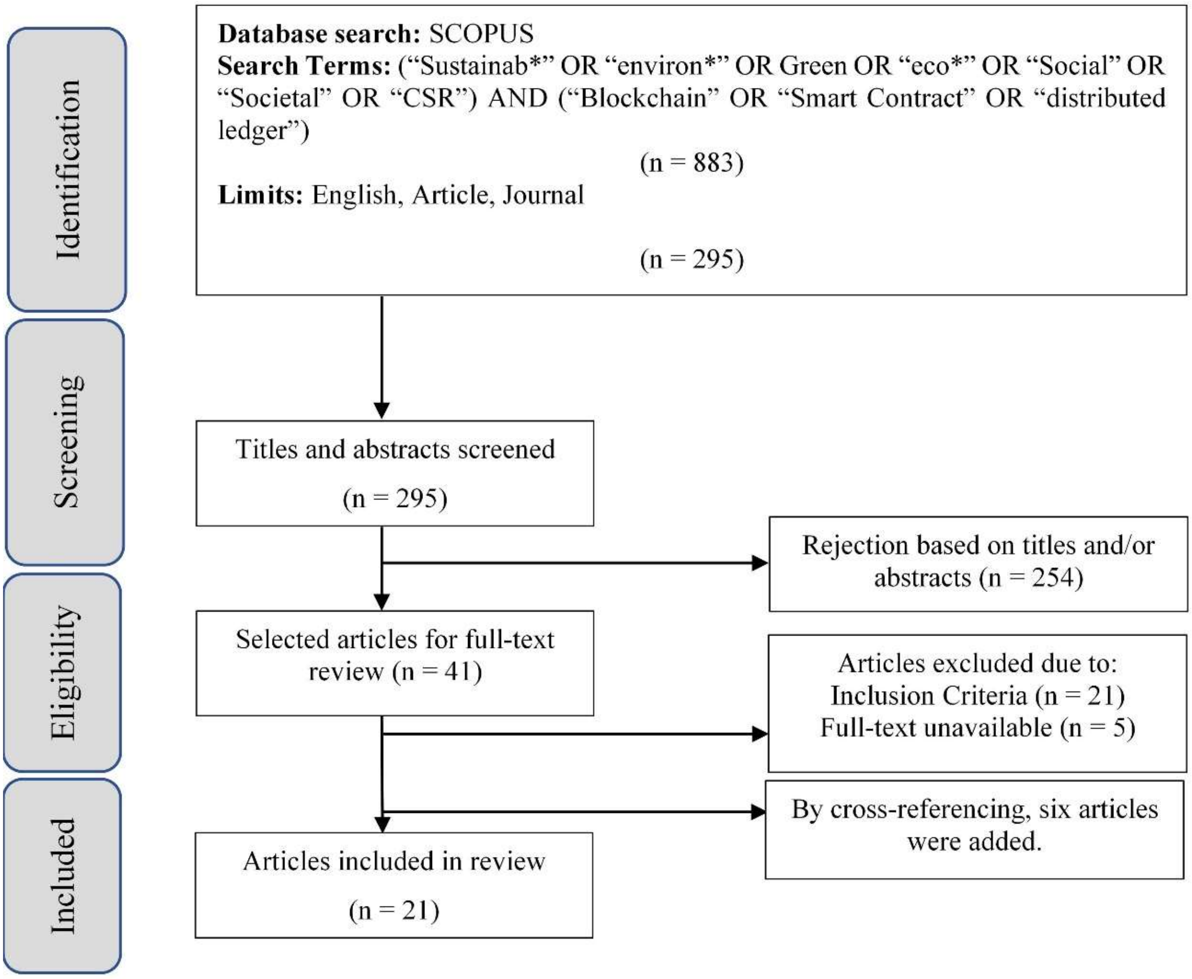

Figure 1. Flow diagram of the article search and selection process.

5. Applications of Blockchain in Sustainable Manufacturing

Manufacturers are facing various challenges and seeking to overcome these challenges to achieve growth and development. Sustainability development empowers manufacturers to respond to various challenges effectively and became a critical factor for manufacturers to achieve their objectives of achieving economic and social benefits while maintaining practices that minimise environmental impacts [41,42]. Sustainable development is defined as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" with ensuring the continuity of economic, social, and environmental aspects [42]. The U.S. Department of Commerce defined manufacturing sustainability as "the creation of manufactured products that use processes that minimise negative environmental impacts, conserve energy and natural resources, are safe for employees, communities and consumers and are economically sound" [43].

In the conventional manufacturing supply chain, the information is managed using a centralised approach and stored in a single location. Centralisation increases the risks of losing data, and the whole system is vulnerable to error, hacking, corruption, or attack [1], and consequently may reduce trust between supply chain parties. Furthermore, the centralised manufacturing supply chain does not provide the required level of reliability and transparency in supply chain processes, products, and activities [44]. Thus, it is required to improve the transparency, security of information, reliability, and traceability of the current supply chain to enhance trust and sustain the supply chain [1]. Blockchain supports sustainable practices in the manufacturing sector by building a reliable, transparent, traceable, and secured supply chain [19]. The contributions of blockchain technology to three pillars of sustainability, namely economic, environmental, and social, are elaborated in the following sections.

5.1. Economic Performance

Manufacturers face various challenges such as high labour cost, high business environment complexity, and rapid customer needs and wants changes. To deal with these challenges and achieve economic sustainability, manufacturers should manage operations and supply chains effectively and efficiently [42]. According to Chardine-Baumann and Botta-Genoulaz [40], the economic performance of the manufacturing supply chain should be assessed in five fields, namely reliability, responsiveness, flexibility, financial performance and quality. The contributions of blockchain technology to these five fields of economic performance are elaborated in the following sub-sections. A summary of the applications of blockchain technology is provided in Table 1.

5.1.1. Reliability

Reliability refers to the reliability of customer service, reliability of suppliers' service, reliability of forecasts, and reliability of stocks [40] which depend on the accuracy of provided information [45] and efficiency of the production process [2]. Obtaining and accessing accurate and timely information may enhance inventory and warehouse management efficiency, reduce inventory inaccuracy, enhance predictive analysis accuracy, and reduce production mistakes [2].

Transparency and traceability are two attributes of blockchain technology that enhance the accuracy of information. Information and any modifications are shared and validated in the distributed ledger among different stakeholders in real time, protecting data from any wrong entries on the network. Sharing and validating information by different stakeholders make information processing in the supply chain more accurate and minimise any potential errors or mistakes [1,15,46]. Blockchain can speed up the automation of manufacturing and increase the efficiency of operations by enhancing the accuracy and velocity of the information. It increases the efficiency of activities related to the product life cycle, such as designing, planning, inventory, and recycling [15,46]. Blockchain can enhance the accuracy of predictions by providing quality data for trend prediction analysis [15]. The accuracy of prediction is greatly influenced by the quality of the data (e.g., timely and accurate).

5.1.2. Responsiveness

Responsiveness describes manufacturers' response agility and flexibility in response to growing pressures on firms in terms of time, cost, and organisational disruptions [47]. Manufacturers should respond efficiently to the changes and new requirements and respond to products/services development, raw materials purchasing, production, sales, delivery, return, and supply chain [40].

The supply chain is a network that includes agents and stakeholders. Blockchain connects all stakeholders directly without the need for a centralised entity in which it reduces network tiers [1]. Blockchain enables stakeholders to communicate directly, and this may result in reducing transaction costs and time [1,8] and the amounts of business waste in the supply chain [1,15]. The decentralisation and information and resources sharing capabilities of blockchain facilitate distributed operations in which product and design information and machine parameters are shared and thus optimise manufacturing processes and minimise production times. Moreover, the blockchain's real-time information sharing capability helps manufacturers optimise their operations and minimise production time, response time to customers, and maintenance time [15].

5.1.3. Flexibility

Manufacturers are required to meet new changes and to be agile and flexible in responding to the changes. As such, manufacturers should adopt approaches that enhance flexibility such as flexible organisational structure, flexible management and leadership approaches, or innovative technologies [48] in order to respond effectively to market changes, customer demand changes, product individualisation demands, and product and customer diversification [42]. Blockchain, as an innovative technology, is able to enhance the flexibility of manufacturers.

Using smart contracts in blockchain technology enables supply chain partners to develop a consensus on a set of terms and conditions. The agreements among supply chain partners can facilitate the resource and machine sharing and alliance among partners, innovative processes development, operation decentralisation, agile decision-making, and partnership optimisation, which in turn enhance the flexibility of manufacturers in improving the production process, meeting customer requirements, producing customised products, and responding to the market changes [15]. Blockchain can also enhance the agility of the manufacturers in responding to the changes by minimising the need for intermediaries [13].

5.1.4. Financial Performance

Financial performance refers to the measures of manufacturers' financial efficiencies such as profitability, liquidity, and investment potential [49]. The financial performance of manufacturers is affected significantly by costs associated with the production of goods and/or services before, during, and after production processes such as design and supply chain costs [40], material, energy, labour, equipment costs [49,50], and delivery and return costs [40]. Manufacturers should improve their financial performance by reducing costs associated with product development, use resources such as energy, inventory, raw materials, waste treatment, and manufacturing costs [51].

Blockchain technology ensures the safety and authenticity of data, which reduces the costs associated with the risks of alteration. Blockchain technology also enhances the transparency of information and transactions, which increases the transparency and trust amongst stakeholders. Lack of transparency and trust leads to higher risks and requires stakeholders to increase their efforts to mitigate the risks, which increases transaction costs. Thus, blockchain technology ensures transparency of data which in turn enhances the trust between stakeholders and consequently reduces transaction costs and creates financial benefits for businesses [1,52]. Moreover, the ability of blockchain technology in sharing and validating information in real time among supply chain stakeholders reduces the cost of information monitoring and verification [13,52]. Blockchain technology also enables manufacturers to monitor the markets and competitors' prices and performance of management, which can enhance their financial performance [13].

5.1.5. Quality

Quality refers to the product quality, quality performance of suppliers, and production quality [40]. Quality reduces the rate of customer complaints [48]. Blockchain can significantly improve quality management and assurance practices and enhance product design quality by enhancing the availability of the data and enabling stakeholders to share information [15]. The ability to trace information along the supply chain enables stakeholders to access information related to raw materials, products, suppliers, retailers, manufacturing, and supply chain activities. Thus, blockchain technology enables customers to verify the quality of products and ensures that products comply with standards, are legally sourced, and manufactured under quality assurance standards [13,46]. Furthermore, blockchain can enhance the ability of other technologies and techniques such as big data analytics, artificial intelligence, and IoT in-process monitoring, fault diagnosis, trend prediction, and decision-making by enhancing the quality, transparency, traceability, and security of the data [24].

Table 1. Contributions of blockchain to economic performance of manufacturers.

Fields	Subfields	Blockchain Contributions
Reliability	• Customer service • Suppliers' service • Reliability of stocks • Reliability of forecasts	• Enhancing the accuracy of information • Minimising errors and mistakes • Facilitating automation of manufacturing • Enhancing the efficiency of manufacturing processes • Enhancing the efficiency of supply chain activities • Improving the accuracy of predictions
Responsiveness	• Design responsiveness • Purchase responsiveness • Source responsiveness • Production responsiveness • Delivery responsiveness • Sell responsiveness • Return responsiveness • Supply chain responsiveness	• Eliminating intermediaries and connecting stakeholders directly • Facilitating communication and collaboration among stakeholders • Facilitating information and resource sharing among stakeholders • Reducing transaction costs and time • Optimising manufacturing processes • Optimising operations • Minimising production time • Minimising response time to customers • Minimising maintenance time
Flexibility	• Suppliers' flexibility • Supply flexibility • Production flexibility • Delivery flexibility	• Eliminating intermediaries and connecting stakeholders directly • Facilitating communication and collaboration among stakeholders • Facilitating information and resource sharing among stakeholders • Facilitating innovative process development • Facilitating operation decentralisation • Facilitating agile decision making • Optimising partnership • Enhancing flexibility in the production process • Enhancing flexibility in producing customised products • Enhancing agility in responding to the changes

Table 1. *Cont.*

Fields	Subfields	Blockchain Contributions
Financial Performance	• Design cost • Purchase cost • Source cost • Production cost • Delivery cost • Return cost • Supply chain cost	• Reducing risks • Reducing costs associate with risks • Enhancing trust among stakeholders • Reducing transaction costs • Reducing costs of information monitoring and verification
Quality	• Product/service quality • Quality performance of suppliers • Production quality	• Facilitating information sharing among stakeholders • Facilitating access to information related to raw materials, products, suppliers, retailers, manufacturing, and supply chain activities • Facilitating process monitoring • Facilitating fault diagnosis • Enabling customers to verify the quality of products • Assuring products do comply with quality assurance standards • Assuring products do comply with laws and legally sourced • Improving quality controls and monitoring

5.2. Environmental Performance

Manufacturers are required to optimise their operations and processes and reduce their negative impacts on the environment. Manufacturers implement sustainable practices to improve energy consumption, increase resource efficiency, reduce wastes, and produce recyclable products [53]. Following Chardine-Baumann and Botta-Genoulaz [40], we categorised the environmental performance of manufacturing firms to environmental management, use of resources, pollution, dangerous, and natural environment. The contributions of blockchain technology to these five fields of environmental performance are elaborated in the following sub-sections. The summary of the blockchain applications is provided in Table 2.

5.2.1. Environmental Management

Environmental management is related to the management and control of the production process and product life cycle, starting from development to delivery and disposal of the product. Environmental management practices contribute significantly to environmental protection and impact positively on businesses and society. Manufacturers should implement proper environmental management practices and audits such as applying environmental management and controlling systems (e.g., ISO 14001), assigning budgets to reduce the impact of manufacturing on the environment, measuring environmental impacts of activities, and educating and communicating the causes of environmental accidents with employees [48,54].

Blockchain technology can play a significant role in developing environmental management practices [1,55]. Traceability, accuracy, and reliability of data and access to real-time information facilitate the process of reproducing and recalling products. This can result in saving resources and reducing emissions. Transparency and traceability created by blockchain technology empower customers to identify whether the products produced by manufacturers are environmentally friendly or not, which in turn enforce manufacturers to practice environmentally friendly manners and reduce emissions. The customers can track the manufacturing planning, sourcing, making, delivery, and returning processes and identify and identify the potential environmental unfriendly practices [1].

5.2.2. Use of Resources

Use of resources refers to the use of materials, water, energy, and products in an efficient way [56]. Sustainability practices ensure an optimised usage of materials before, during, and after manufacturing and cause a reduction in the production of emissions associated with the manufacturing process [50,53]. Sustainability practices minimise the impact of resources on the environment, and such practices include using renewable energy in production, using resources such as water and energy in an efficient way, reducing the produced waste [57], and recycling and re-using resources [41,48].

Blockchain technology enables manufacturers to optimise the use of energy and resources by creating decentralisation capabilities and enhancing the traceability and transparency of resource and energy-related information [1,8]. Furthermore, traceability and transparency motivate manufacturers to use renewable energy. Blockchain technology can be applied in recycling by tracing recyclables and motivating people to contribute to depositing recyclable items [1]. Blockchain can also be adopted to improve the sustainability of the clean energy industry. It provides decentralised solutions for promoting the use of clean/renewal energy [17].

5.2.3. Pollution

The pollution dimension of environmental performance refers to reducing harmful substances, toxic materials, and emissions released to the environment caused by manufacturing processes [41,49]. Pollution refers to the influence of wastages on the environment, such as increasing acidification levels of water and soil [50]. Manufacturers should control emissions and reduce the impact of wastages on the environment by identifying and controlling emissions and pollution created in the manufacturing process [57].

Blockchain technology enables manufacturers to reduce the waste and pollution in the entire manufacturing supply chain by facilitating the usage of renewal sources of energy and reducing fuel usage [8]. Manufacturers can optimise resource consumption, reduce gas emissions, and trace and measure the carbon footprint of each product by sharing accurate and authentic information and enhancing traceability capability through blockchain adoption [1,8,55]. Traceability and transparency attributes of blockchain also fulfil customer needs of having transparent information about carbon emissions [1,8]. In addition, the traceability of data related to energy and resource usage helps manufacturers optimise their production process and reduce energy and production wastes [1,8].

5.2.4. Dangerousness

The dangerousness dimension of environmental performance refers to the dangerous impact of manufacturing materials on the environment. Dangerousness can be measured by monitoring the raw materials used in the production, the products or output of the production process, and the production of dangerous wastes [40]. Measuring and tracking the amounts of dangerous inputs and outputs in the manufacturing supply chain are crucial in managing and reducing dangerousness [48].

The traceability, authentic verification, and security of information capabilities created by using blockchain help supply chain stakeholders to trace and remove the dangerous inputs and outputs in the entire manufacturing supply chain, including planning, sourcing, making, delivering, and returning. Tracing the manufacturing supply chain process assures the customers that they purchase and consume safe, legitimate, undamaged, and unaltered products [58].

5.2.5. Natural Environment

The natural environment dimension of environmental performance refers to the impact of manufacturing processes and industrialisation on the ecosystem and environment. The natural environment dimension aims to measure and reduce the impacts of manufacturing practices on ecosystem services, all forms and combinations of life, land use, urban and rural development [40,48]. The decentralisation and real-time information sharing about supply chain activities in blockchain technology helps organisations trace, control, monitor, and measure the impacts of their activities on ecosystem diversity and sustainability of natural resources, which enable manufacturers to make better decisions and minimise their harmful influences on the natural environment [55,59].

Table 2. Contributions of blockchain to environmental performance of manufacturers.

Fields	Subfields	Blockchain Contributions
Environmental Management	• Environmental certification • Environmental compliance • Worker implications • Environmental budget	• Reducing reproducing and recalling processes • Saving resources • Decreasing the consumption of resources • Tracking the sources of raw material • Reducing emission
Use of Resources	• Renewable energy • Recycled water • Inputs stemming from the recycling • Recyclable outputs • Recyclable wastes	• Optimising the use of energy • Optimising the use of resources • Promoting the use of renewable energy • Facilitating reverse logistics • Motivating people to contribute in depositing recyclable items
Pollution	• Air pollution • water pollution • land pollution • Other pollution	• Facilitating the usage of renewal sources of energy • Reducing fossil fuel usage • Reducing resource consumption • Reducing the energy usage in production • Reducing gas emissions • Tracing and measuring the carbon footprint product • Providing transparent carbon footprint information • Reducing production waste • Reducing energy waste
Dangerousness	• Dangerous inputs • dangerous outputs • dangerous wastes	• Monitoring the raw material used in the production • Tracing and removing dangerous inputs (raw materials) • Tracing and removing dangerous outputs (products) • Ensuring product safety • Monitoring the production of dangerous wastes
Natural Environment	• Eco-systemic services • respect of biodiversity • land use	• Making better decisions on using natural resources. • Making better decisions related to waste management • Improving resource management • Tracing and measuring the impacts of manufacturers' activities on ecosystem diversity • Reducing harmful influences of manufacturers' activities on the sustainability of natural resources

5.3. Social Performance

Social performance is another pillar of sustainability that plays a critical role in creating and maintaining relationships with stakeholders [60] and creating a favourable image and reputation [61]. Social issues can impact the financial performance and reputation of manufacturers [61]. Manufacturers face various social challenges and should develop a sustainable business model and adopt proper activities and technologies to overcome these challenges. Following Chardine-Baumann and Botta-Genoulaz [40], we categorised the social performance of manufacturing firms into five fields: work conditions, human rights, societal commitment, consumers issues, and business practices. Blockchain technology can contribute significantly to sustainable manufacturing and help manufacturers face social challenges related to manufacturing supply chain processes [15,62]. The contributions of blockchain technology to the five fields of social performance are argued in the following sub-sections. The summary of the blockchain applications is provided in Table 3.

5.3.1. Work Conditions

Work conditions refer to the employees' health and safety issues associated with the workplace. Work conditions include the practices related to safety, health, productivity, and development of employees [50]. Manufacturers should adopt practices that reduce health and safety risks and assure workplace safety [60]. Furthermore, firms should pay attention to social communications among employees at the workplace, resulting in better working conditions, higher productivity, better health and security, and higher working environment quality [48]. Work condition-related practices involve providing training to develop employees' knowledge and skills on various aspects of their jobs, potential workplace challenges, employability skills, and health and safety measures at the workplace. Such developments increase employees' awareness and knowledge of sustainability practices and may facilitate efficient implementation of sustainability practices at the workplace [41,60].

Blockchain technology empowers stakeholders to track the work conditions of sellers and suppliers and identify whether they respect human resource development, and implement health and safety practices at the workplace. Blockchain provides a secure and unchangeable platform for recording information related to working hours, wages, and overtime limits which can be accessed by stakeholders such as customers, retailers, and governments in order to check whether a manufacturer and its chain partners apply fairness and justice principles in the workplace. Furthermore, the health and safety information, such as whether the supplier obtained health and safety required certifications and approvals (e.g., fire and building safety), can be safely recorded and tracked through blockchain [18]. Traceability and the ability to share and store information safely make it possible for buyers and supply chain stakeholders to track the sources of materials all over the chain and make sure that the materials were purchased from ethical and certified sources [18,62].

5.3.2. Human Rights

The human rights dimension of social performance refers to any possible violations of human rights such as child labour [61], discrimination, forced labour, extortion, or bribery [63]. Manufacturers should not only respect human rights in their internal activities but also ensure that the activities of their supply chain partners are consistent with human rights. Blockchain technology provides the required infrastructure for monitoring activities of firms which in turn reduce workplace exploitation [18,62]. The transparency, visibility, and authenticity of data and the instant traceability capability facilitate tracking of supply chain activities and identifying unethical practices from corrupted individuals or organisations [1,62]. Blockchain enables manufacturers to monitor the practices of their suppliers and ensure that human rights and fairness are not violated in their activities and consequently prevent any potential unethical practices such as social harm, abuse [8,62], child labour, or corruption [62,64].

5.3.3. Societal Commitment

Societal commitment refers to the practices aiming to provide benefits for the society and community. Benefits can be in the form of involvement in local communities, job creation, healthcare and societal investment, education, culture, and technological development [41,48,63]. To meet social commitments, manufacturers should develop rules, policies, and strategies to positively impact society and communities.

Blockchain technology enhances the authenticity and reliability of information and prevents fraudulent transactions. Such information contributes to the welfare of societies by creating new opportunities, improving business models, attracting investments into various aspects of social welfare and society, improving social services (e.g., healthcare and education), and reducing service costs [8,62]. Furthermore, blockchain can create trust between donors, non-profit organisations, and governments, which in turn enhance the success of fundraising activities. The non-profit organisation and government also can control the flow of donations and financial aids in a more effective manner. Storing accurate information and real-time information sharing may reduce the time of receiving donations and delivering service to beneficiaries. Blockchain attributes also enhance trust in emergency times and promote solidarity among people [64,65].

5.3.4. Customer Issues

Customer issues include the ability of manufacturers to fulfil the needs and requirements of various customer groups [63]. Manufacturers should redesign their strategies and practices and reconfigure their manufacturing processes in order to develop personalised products and services. Personalised products may enhance customer satisfaction [48] and consequently increase profits and support the position of manufacturers in the market [3].

The smart contracts, decentralisation, and information sharing attributes of blockchain technology facilitate direct relations between customers, manufacturers, suppliers, and retailers [15,46]. Customers can directly communicate with manufacturers to request customised products. On the other hand, retailers, suppliers, and manufacturers can communicate directly and share their resources and capabilities to fulfil customers' needs more effectively and efficiently. The real-time and secure information sharing and transparency attributes of blockchain facilitate collaboration and resource sharing among supply chain partners, which in turn optimise manufacturing planning, sourcing, making, delivery, and returning. Blockchain improves manufacturing productivity and quality, facilitates products personalisation, and extends the innovation practices of manufacturers [15,46].

5.3.5. Business Practices

Business practices refer to the firms' practices aiming to fight against corruption and promote fair trading and social responsibility [40]. Manufacturers should understand foreign cultures to operate in line with fair trading principles regarding markets and competitions and to fight against corruption [48]. Dealing with corruption and fair-trading issues improves the social sustainability performance of manufacturers [40,48]. Transparency, traceability, and decentralisation attributes of blockchain enforce manufacturers to give more attention to corruption and fair-trading concepts. As customers and governments can track the firms' and their partners' activities, a potential shortfall in social responsibilities may harm the brand and reputation of a manufacturer for a long time. Accordingly, blockchain technology can promote the fight against corruption and unfair trading practices [58,66].

Table 3. Contributions of blockchain to social performance of manufacturers.

Fields	Subfields	Blockchain Contributions
Work Conditions	• Work conditions • Health and security • Human resource development • Respect to social dialogues	• Promoting human resource development • Extending health and safety practices • Reduction of safety incidents • Tracking health and safety certifications • Improving working conditions • Tracking working hours, wages, and overtime limits
Human Rights	• Child and forced labour • Freedom of association • Discrimination	• Monitoring violations of human rights • Preventing unethical sourcing such as child or forced labour • Preventing social harm and abuse • Reducing workplace exploitation
Societal Commitment	• Involvement in the local community • Education, culture and technological development • Job creation • Healthcare and societal investment	• Creating new opportunities • Improving business models • Attracting investments into social welfare • Improving social services • Reducing service costs • Boosting donations • Improving humanitarian service efficiency
Customer Issues	• Product and service personalisation • Meeting customer needs	• Facilitating product personalisation • Extending innovative practices • Optimising production and delivery processes • Facilitating collaboration among stakeholders • Enabling direct relations between stakeholders
Business Practices	• Fight against corruption • Promote fair trading	• Tracking firm activities • Reducing corruptions • Promoting fair trading activities

6. Conclusions and Future Research

The primary purpose of this systematic review was to give a structure to the literature on the applications of blockchain in sustainable manufacturing. The study aims to answer two research questions: (1) "what are the applications of blockchain technology in sustainable manufacturing?" and (2) "how can blockchain attributes enhance the sustainable performance of manufacturers?" To answer the first research question, the 21 identified articles were reviewed, and the applications of blockchain technology in sustainable manufacturing were identified. The model of sustainable performance developed by Chardine-Baumann and Botta-Genoulaz [40] was used to categorise the contributions of blockchain to the sustainable performance of the manufacturing supply chain. This model categorised economic performance according to reliability, responsiveness, flexibility, financial performance, and quality; environmental performance to environmental management, use of resources, pollution, dangerousness, and natural environment; and social performance to work conditions, human rights, societal commitment, customers issues, and business practices. The applications of blockchain technology in sustainable manufacturing are summarised in Tables 1–3. To answer the second research question, attributes of blockchain technology and the SCOR model were explained to create a foundation for explaining how blockchain may facilitate sustainable manufacturing. Later, the ways that blockchain contributes to the sustainable performance of manufacturers were explained based on the features and attributes of blockchain technology such as smart contracts, traceability, transparency, security, and real-time information sharing.

The study proposes a model on the applications of blockchain technologies in sustainable manufacturing (Figure 2). The model provides a reference for the contributions of blockchain technology to sustainability. This model illustrates that blockchain contributes to economic, environmental performance by creating transparency, traceability, real-time information sharing, and information security capabilities. The applications of blockchain technology in sustainable manufacturing are illustrated on the right side of the model. The details of applications are provided in Section 5 and Tables 1–3.

In terms of practical implications, the greater awareness of manufacturing managers about the contributions of blockchain technology to sustainable performance may motivate managers to support the adoption of blockchain. This study enables manufacturing managers to understand the benefits of investing in blockchain technology and how this emerging technology can address the challenges of implementing sustainable practices, which the manufacturers have struggled with for many years. This paper can also be used for educational purposes, and it provides structured and updated information on the potential contributions of blockchain technology to suitable manufacturing.

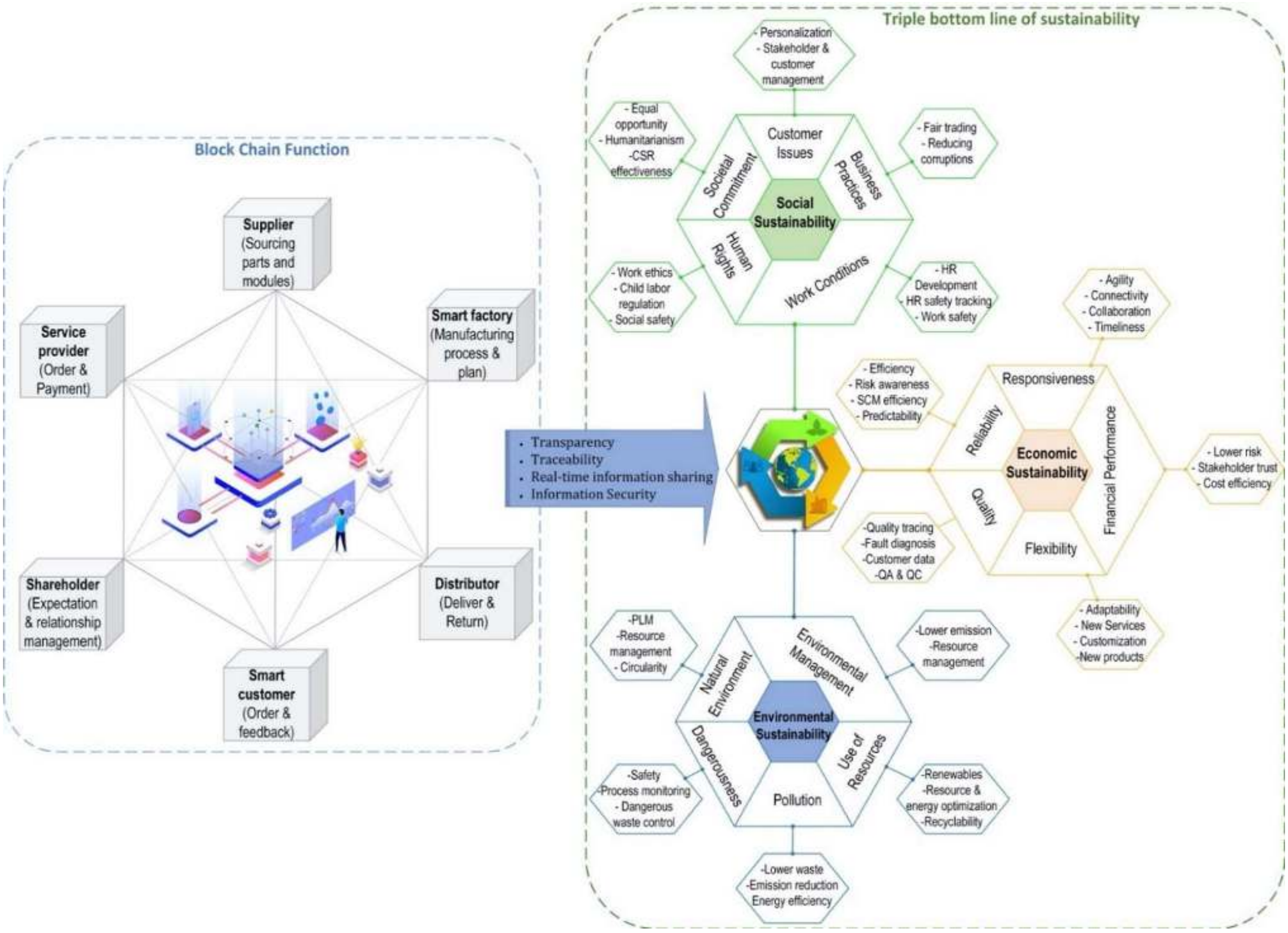

Figure 2. Contributions of blockchain to sustainable performance of manufacturers.

By synthesising the literature on applications of blockchain to sustainable manufacturing, this article makes contributions to the literature in three aspects. First, the study provides an overview of the current scholarly knowledge on the application of blockchain technology in sustainable manufacturing. Second, the paper categorised the contributions of blockchain technology to the sustainable performance of the manufacturing supply chain based on the model of Chardine-Baumann and Botta-Genoulaz [40]. Third, the gaps in the literature were identified, and future research directions were proposed. Specifically, the following future studies are needed:

1. The identified contributions of blockchain to sustainability are interrelated. Future studies are needed to use mind mapping or interpretive structural modelling to map the interrelationships among sustainable applications of blockchain technology.
2. The focus of most of the reviewed studies was not sustainability, and they mentioned the contributions of blockchain technology to sustainable manufacturing as a part of the article. It is essential to promote research on the implications of blockchain technology on sustainable performance.
3. In comparison to economic and environmental dimensions of sustainability, the social dimension has appeared in less studies in the blockchain literature. Future studies are recommended to explore the contributions of blockchain technology to the social performance of manufacturing firms.
4. There is a lack of empirical study on the real influence of blockchain technology adoption on the sustainable performance of firms. Future studies are required to test the association between blockchain adoption and sustainable performance empirically.
5. The challenges and determinants of adopting blockchain technology for sustainability purposes have received less attention in the literature, and future studies are needed to address the gap.
6. The applications of blockchain technology to sustainable performance may vary in different sectors. Future studies are recommended to investigate the potential contributions of blockchain technologies to the sustainable performance of firms in different sectors.

Although the study answered the two research questions of the study, there are some limitations that should be considered. Firstly, the reviewed documents were limited to the articles published in Scopus indexed journals. Although Scopus is the largest database, future studies can also include Web of Science, EBSCO, and ProQuest databases. Secondly, conference papers and book chapters were excluded in this study but can be included in future reviews. Finally, the inclusion and exclusion of articles were based on subjective judgments. To reduce the errors, two authors independently screened the articles and the disagreements were addressed by consensus among all authors.

Author Contributions: All authors have contributed equally. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Acknowledgments: There are no specific acknowledgments.

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

Appendix A

Table A1. List of reviewed articles.

Source	Year	Description
Kshetri et al. [14]	2021	The study described how blockchain could help various stakeholders address many challenges in promoting sustainable supply chains in developing countries.
Park and Li [62]	2021	The study elaborated on the implications of blockchain technology in sustainable performance in the areas of environmental protection, social equity, and governance efficiency.
Katsikouli et al. [66]	2021	The study discussed the use of blockchain technology and distributed ledgers to manage supply chains in the food sector. The role of blockchain technology in addressing the challenges of typical food management systems was elaborated.
Upadhyay et al. [8]	2021	The study discussed the contributions of blockchain technology to the circular economy through the lens of sustainability and social responsibility.
Saurabh and Dey [22]	2021	The benefits of blockchain technology in agri-food supply chains that promote the adoption of blockchain in this sector were discussed.
Badhotiya et al. [26]	2021	The study investigated the benefits and challenges of integrating blockchain into pharmaceutical supply chains.
Agrawal et al. [46]	2021	The study investigated a blockchain-based traceability framework for traceability in multi-tier textiles and discussed the opportunities blockchain technology creates for a sustainable supply chain.
Ali et al. [27]	2021	The contributions of blockchain technology to halal sustainable production were discussed.
Ebinger and Omondi [29]	2020	The article gave an overview of the current applications of digital technologies, including blockchain technology, artificial intelligence, and cloud computing, in sustainable supply chain management.
Esmaeilian et al. [19]	2020	The study unfolded the capabilities that blockchain offers for increasing sustainability under four main areas: (1) design of incentive mechanisms and tokenisation to promote consumers' green behaviour; (2) enhance visibility across the entire product lifecycle; (3) increase systems efficiency while decreasing development and operational costs; and (4) foster sustainability monitoring and reporting performance across supply chain networks.
Leng et al. [15]	2020	The study investigated how blockchain can overcome potential barriers to achieving sustainability from two perspectives: the manufacturing system perspective and the product lifecycle management perspective.
Manupati et al. [55]	2020	The study proposed a blockchain approach for monitoring supply chain performance and optimising both emission levels and operational costs in a synchronised fashion, producing a better outcome for the supply chains.
Rejeb and Rejeb [64]	2020	The study discussed the economic, social, and environmental value of blockchain for all stakeholders involved in supply chains.
Schulz et al. [65]	2020	The study provided an exploratory assessment of how blockchain technology may support, hinder and/or re-shape sustainability transformations in selected areas of sustainable development.
Venkatesh et al. [18]	2020	The study developed a system architecture that integrates the use of blockchain, internet-of-things (IoT) and big data analytics to allow sellers to monitor their supply chain social sustainability efficiently and effectively.
Vujičić et al. [59]	2020	The paper discussed the possible applications of blockchain technology for environmental sustainability in the shipping industry.
Roeck et al. [52]	2020	The study elaborated on the implications of blockchain technology to the transaction costs of supply chains.

Table A1. *Cont.*

Source	Year	Description
Alles and Gray [58]	2020	The study modelled the business process within which blockchain applications operate in order to extract an endogenous demand for auditing in that environment.
Saberi et al. [1]	2019	The paper critically examined blockchain technology and explained the potential application of blockchain to sustainable supply chain management.
Ko et al. [13]	2018	The study explained how firms could employ distributed ledger technology by adopting blockchain technology to achieve real-time transparency and cost savings. The blockchain's mechanism for enabling real-time transparency and cost savings in the manufacturing industry was elaborated.
Fu et al. [17]	2018	The study proposed a blockchain supported environmentally sustainable solution for the fashion apparel manufacturing industry.

References

1. Saberi, S.; Kouhizadeh, M.; Sarkis, J.; Shen, L. Blockchain technology and its relationships to sustainable supply chain management. *Int. J. Prod. Res.* **2019**, *57*, 2117–2135. [CrossRef]
2. Braccini, A.; Margherita, E. Exploring Organizational Sustainability of Industry 4.0 under the Triple Bottom Line: The Case of a Manufacturing Company. *Sustainability* **2018**, *11*, 36. [CrossRef]
3. Ghobakhloo, M. Industry 4.0, digitization, and opportunities for sustainability. *J. Clean. Prod.* **2020**, *252*, 119869. [CrossRef]
4. Vrchota, J.; Pech, M.; Rolínek, L.; Bednář, J. Sustainability Outcomes of Green Processes in Relation to Industry 4.0 in Manufacturing: Systematic Review. *Sustainability* **2020**, *12*, 5968. [CrossRef]
5. Shaharudin, M.R.; Govindan, K.; Zailani, S.; Tan, K.C.; Iranmanesh, M. Product return management: Linking product returns, closed-loop supply chain activities and the effectiveness of the reverse supply chains. *J. Clean. Prod.* **2017**, *149*, 1144–1156. [CrossRef]
6. Yadav, G.; Luthra, S.; Huisingh, D.; Mangla, S.K.; Narkhede, B.E.; Liu, Y. Development of a lean manufacturing framework to enhance its adoption within manufacturing companies in developing economies. *J. Clean. Prod.* **2020**, *245*, 118726. [CrossRef]
7. Shin, E.-J.; Kang, H.-G.; Bae, K. A Study on the Sustainable Development of NPOs with Blockchain Technology. *Sustainability* **2020**, *12*, 6158. [CrossRef]
8. Upadhyay, A.; Mukhuty, S.; Kumar, V.; Kazancoglu, Y. Blockchain technology and the circular economy: Implications for sustainability and social responsibility. *J. Clean. Prod.* **2021**, *293*, 126130. [CrossRef]
9. Nakamoto, S. Bitcoin: A Peer to Peer Electronic Cash System. 2008. Available online: https://www.ussc.gov/sites/default/files/pdf/training/annual-national-training-seminar/2018/Emerging_Tech_Bitcoin_Crypto.pdf (accessed on 25 May 2021).
10. Zheng, W.; Zheng, Z.; Dai, H.-N.; Chen, X.; Zheng, P. XBlock-EOS: Extracting and exploring blockchain data from EOSIO. *Inf. Process. Manag.* **2021**, *58*, 102477. [CrossRef]
11. Francisco, K.; Swanson, D. The Supply Chain Has No Clothes: Technology Adoption of Blockchain for Supply Chain Transparency. *Logistics* **2018**, *2*, 2. [CrossRef]
12. KPMG LLP. *Blockchain and the Future of Finance: A Potential New World for CFOs—and How to Prepare*; KPMG: Amstelveen, The Netherlnads, 2018.
13. Ko, T.; Lee, J.; Ryu, D. Blockchain Technology and Manufacturing Industry: Real-Time Transparency and Cost Savings. *Sustainability* **2018**, *10*, 4274. [CrossRef]
14. Kshetri, N. Blockchain and sustainable supply chain management in developing countries. *Int. J. Inf. Manag.* **2021**, *60*, 102376. [CrossRef]
15. Leng, J.; Ruan, G.; Jiang, P.; Xu, K.; Liu, Q.; Zhou, X.; Liu, C. Blockchain-empowered sustainable manufacturing and product lifecycle management in industry 4.0: A survey. *Renew. Sustain. Energy Rev.* **2020**, *132*, 110112. [CrossRef]
16. Giungato, P.; Rana, R.; Tarabella, A.; Tricase, C. Current Trends in Sustainability of Bitcoins and Related Blockchain Technology. *Sustainability* **2017**, *9*, 2214. [CrossRef]
17. Fu, B.; Shu, Z.; Liu, X. Blockchain Enhanced Emission Trading Framework in Fashion Apparel Manufacturing Industry. *Sustainability* **2018**, *10*, 1105. [CrossRef]
18. Venkatesh, V.G.; Kang, K.; Wang, B.; Zhong, R.Y.; Zhang, A. System architecture for blockchain based transparency of supply chain social sustainability. *Robot. Comput. Integr. Manuf.* **2020**, *63*, 101896. [CrossRef]
19. Esmaeilian, B.; Sarkis, J.; Lewis, K.; Behdad, S. Blockchain for the future of sustainable supply chain management in Industry 4.0. *Resour. Conserv. Recycl.* **2020**, *163*, 105064. [CrossRef]
20. Leng, J.; Ye, S.; Zhou, M.; Zhao, J.L.; Liu, Q.; Guo, W.; Cao, W.; Fu, L. Blockchain-Secured Smart Manufacturing in Industry 4.0: A Survey. *IEEE Trans. Syst. Man Cybern. Syst.* **2021**, *51*, 237–252. [CrossRef]
21. Sundarakani, B.; Ajaykumar, A.; Gunasekaran, A. Big data driven supply chain design and applications for blockchain: An action research using case study approach. *Omega* **2021**, 102452. [CrossRef]

22. Saurabh, S.; Dey, K. Blockchain technology adoption, architecture, and sustainable agri-food supply chains. *J. Clean. Prod.* **2021**, *284*, 124731. [CrossRef]
23. Abeyratne, S.A.; Monfared, R.P. Blockchain Ready Manufacturing Supply Chain Using Distributed Ledger. *Int. J. Res. Eng. Technol.* **2016**, *5*, 1–10.
24. Sun, M.; Zhang, J. Research on the application of block chain big data platform in the construction of new smart city for low carbon emission and green environment. *Comput. Commun.* **2020**, *149*, 332–342. [CrossRef]
25. Mohamed, N.; Al-Jaroodi, J. Applying Blockchain in Industry 4.0 Applications. In Proceedings of the 2019 IEEE 9th Annual Computing and Communication Workshop and Conference (CCWC), Las Vegas, NV, USA, 7–9 January 2019; IEEE: Piscataway, NJ, USA, 2019; pp. 852–858.
26. Badhotiya, G.K.; Sharma, V.P.; Prakash, S.; Kalluri, V.; Singh, R. Investigation and assessment of blockchain technology adoption in the pharmaceutical supply chain. *Mater. Today Proc.* **2021**. [CrossRef]
27. Ali, M.H.; Chung, L.; Kumar, A.; Zailani, S.; Tan, K.H. A sustainable Blockchain framework for the halal food supply chain: Lessons from Malaysia. *Technol. Forecast. Soc. Chang.* **2021**, *170*, 120870. [CrossRef]
28. Chen, Y.; Bellavitis, C. Blockchain disruption and decentralized finance: The rise of decentralized business models. *J. Bus. Ventur. Insights* **2020**, *13*, e00151. [CrossRef]
29. Ebinger, F.; Omondi, B. Leveraging Digital Approaches for Transparency in Sustainable Supply Chains: A Conceptual Paper. *Sustainability* **2020**, *12*, 6129. [CrossRef]
30. Skilton, P.F.; Robinson, J.L. Traceability and normal accident theory: How does supply network complexity influence the traceability of adverse events? *J. Supply Chain Manag.* **2009**, *45*, 40–53. [CrossRef]
31. Dissanayake, C.K.; Cross, J.A. Systematic mechanism for identifying the relative impact of supply chain performance areas on the overall supply chain performance using SCOR model and SEM. *Int. J. Prod. Econ.* **2018**, *201*, 102–115. [CrossRef]
32. Ayyildiz, E.; Taskin Gumus, A. Interval-valued Pythagorean fuzzy AHP method-based supply chain performance evaluation by a new extension of SCOR model: SCOR 4.0. *Complex. Intell. Syst.* **2021**, *7*, 559–576. [CrossRef]
33. Chehbi-Gamoura, S.; Derrouiche, R.; Damand, D.; Barth, M. Insights from big Data Analytics in supply chain management: An all-inclusive literature review using the SCOR model. *Prod. Plan. Control.* **2020**, *31*, 355–382. [CrossRef]
34. Sundarakani, B.; Abdul Razzak, H.; Manikandan, S. Creating a competitive advantage in the global flight catering supply chain: A case study using SCOR model. *Int. J. Logist. Res. Appl.* **2018**, *21*, 481–501. [CrossRef]
35. Krishnan, R.; Yen, P.; Agarwal, R.; Arshinder, K.; Bajada, C. Collaborative innovation and sustainability in the food supply chain-evidence from farmer producer organisations. *Resour. Conserv. Recycl.* **2021**, *168*, 105253. [CrossRef]
36. Georgise, F.B.; Wuest, T.; Thoben, K.-D. SCOR model application in developing countries: Challenges & requirements. *Prod. Plan. Control.* **2017**, *28*, 17–32. [CrossRef]
37. PRISMA Systematic Reviews and Meta-Analyses. Available online: http://www.prisma-statement.org (accessed on 25 May 2021).
38. Tranfield, D.; Denyer, D.; Smart, P. Towards a methodology for developing evidence-informed management knowledge by means of systematic review. *Br. J. Manag.* **2003**, *14*, 207–222. [CrossRef]
39. Kwary, D.A. A corpus and a concordancer of academic journal articles. *Data Br.* **2018**, *16*, 94–100. [CrossRef]
40. Chardine-Baumann, E.; Botta-Genoulaz, V. A framework for sustainable performance assessment of supply chain management practices. *Comput. Ind. Eng.* **2014**, *76*, 138–147. [CrossRef]
41. Govindan, K.; Jha, P.C.; Garg, K. Product recovery optimization in closed-loop supply chain to improve sustainability in manufacturing. *Int. J. Prod. Res.* **2016**, *54*, 1463–1486. [CrossRef]
42. Pham, D.T.; Thomas, A.J. Fit manufacturing: A framework for sustainability. *J. Manuf. Technol. Manag.* **2011**, *23*, 103–123. [CrossRef]
43. Huang, A.; Badurdeen, F. Sustainable Manufacturing Performance Evaluation: Integrating Product and Process Metrics for Systems Level Assessment. *Procedia Manuf.* **2017**, *8*, 563–570. [CrossRef]
44. Longo, F.; Nicoletti, L.; Padovano, A.; D'Atri, G.; Forte, M. Blockchain-enabled supply chain: An experimental study. *Comput. Ind. Eng.* **2019**, *136*, 57–69. [CrossRef]
45. Saad, M.H.; Nazzal, M.A.; Darras, B.M. A general framework for sustainability assessment of manufacturing processes. *Ecol. Indic.* **2019**, *97*, 211–224. [CrossRef]
46. Agrawal, T.K.; Kumar, V.; Pal, R.; Wang, L.; Chen, Y. Blockchain-based framework for supply chain traceability: A case example of textile and clothing industry. *Comput. Ind. Eng.* **2021**, *154*, 107130. [CrossRef]
47. Hicks, B.J.; Matthews, J. The barriers to realising sustainable process improvement: A root cause analysis of paradigms for manufacturing systems improvement. *Int. J. Comput. Integr. Manuf.* **2010**, *23*, 585–602. [CrossRef]
48. Garbie, I.H. An analytical technique to model and assess sustainable development index in manufacturing enterprises. *Int. J. Prod. Res.* **2014**, *52*, 4876–4915. [CrossRef]
49. Tan, H.X.; Yeo, Z.; Ng, R.; Tjandra, T.B.; Song, B. A Sustainability Indicator Framework for Singapore Small and Medium-Sized Manufacturing Enterprises. *Procedia CIRP* **2015**, *29*, 132–137. [CrossRef]
50. Chen, D.; Heyer, S.; Ibbotson, S.; Salonitis, K.; Steingrímsson, J.G.; Thiede, S. Direct digital manufacturing: Definition, evolution, and sustainability implications. *J. Clean. Prod.* **2015**, *107*, 615–625. [CrossRef]

51. Kamble, S.; Gunasekaran, A.; Dhone, N.C. Industry 4.0 and lean manufacturing practices for sustainable organisational performance in Indian manufacturing companies. *Int. J. Prod. Res.* **2020**, *58*, 1319–1337. [CrossRef]
52. Roeck, D.; Sternberg, H.; Hofmann, E. Distributed ledger technology in supply chains: A transaction cost perspective. *Int. J. Prod. Res.* **2020**, *58*, 2124–2141. [CrossRef]
53. Eslami, Y.; Dassisti, M.; Lezoche, M.; Panetto, H. A survey on sustainability in manufacturing organisations: Dimensions and future insights. *Int. J. Prod. Res.* **2019**, *57*, 5194–5214. [CrossRef]
54. Ikram, M.; Zhou, P.; Shah, S.A.A.; Liu, G.Q. Do environmental management systems help improve corporate sustainable development? Evidence from manufacturing companies in Pakistan. *J. Clean. Prod.* **2019**, *226*, 628–641. [CrossRef]
55. Manupati, V.K.; Schoenherr, T.; Ramkumar, M.; Wagner, S.M.; Pabba, S.K.; Inder Raj Singh, R. A blockchain-based approach for a multi-echelon sustainable supply chain. *Int. J. Prod. Res.* **2020**, *58*, 2222–2241. [CrossRef]
56. Carvalho, N.; Chaim, O.; Cazarini, E.; Gerolamo, M. Manufacturing in the fourth industrial revolution: A positive prospect in Sustainable Manufacturing. *Procedia Manuf.* **2018**, *21*, 671–678. [CrossRef]
57. Mani, M.; Madan, J.; Lee, J.H.; Lyons, K.W.; Gupta, S.K. Sustainability characterisation for manufacturing processes. *Int. J. Prod. Res.* **2014**, *52*, 5895–5912. [CrossRef]
58. Alles, M.; Gray, G.L. "The first mile problem": Deriving an endogenous demand for auditing in blockchain-based business processes. *Int. J. Account. Inf. Syst.* **2020**, *38*, 100465. [CrossRef]
59. Vujičić, S.; Hasanspahić, N.; Car, M.; Čampara, L. Distributed Ledger Technology as a Tool for Environmental Sustainability in the Shipping Industry. *J. Mar. Sci. Eng.* **2020**, *8*, 366. [CrossRef]
60. Baumgartner, R.J.; Ebner, D. Corporate sustainability strategies: Sustainability profiles and maturity levels. *Sustain. Dev.* **2010**, *18*, 76–89. [CrossRef]
61. Varsei, M.; Soosay, C.; Fahimnia, B.; Sarkis, J. Framing sustainability performance of supply chains with multidimensional indicators. *Supply Chain Manag. Int. J.* **2014**, *19*, 242–257. [CrossRef]
62. Park, A.; Li, H. The Effect of Blockchain Technology on Supply Chain Sustainability Performances. *Sustainability* **2021**, *13*, 1726. [CrossRef]
63. Sutherland, J.W.; Richter, J.S.; Hutchins, M.J.; Dornfeld, D.; Dzombak, R.; Mangold, J.; Robinson, S.; Hauschild, M.Z.; Bonou, A.; Schönsleben, P.; et al. The role of manufacturing in affecting the social dimension of sustainability. *CIRP Ann.* **2016**, *65*, 689–712. [CrossRef]
64. Rejeb, A.; Rejeb, K. Blockchain and supply chain sustainability. *Logforum* **2020**, *16*, 363–372. [CrossRef]
65. Schulz, K.A.; Gstrein, O.J.; Zwitter, A.J. Exploring the governance and implementation of sustainable development initiatives through blockchain technology. *Futures* **2020**, *122*, 102611. [CrossRef]
66. Katsikouli, P.; Wilde, A.S.; Dragoni, N.; Høgh-Jensen, H. On the benefits and challenges of blockchains for managing food supply chains. *J. Sci. Food Agric.* **2021**, *101*, 2175–2181. [CrossRef] [PubMed]