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Blockchain Technology for Green Manufacturing: A Systematic Literature Review on Applications, Drivers, Enablers and Challenges

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Abstract Blockchain technology(BCT) is a promising technology for Industry 4.0 and enhancing sustainability, traceability, and resilience for Green manufacturing(GM) in the value chain. This literature study aims to evaluate the existing and current literature for contributing to the research focusing on BCT to GM industries with discussing insight on the drivers, enablers, and challenges of BCT. This review is not limited to highlighting the contributions and application of blockchain to eco-friendly manufacturing, it will consider the role of emerging technology applicable to GM in Industry 4.0. In conducting this review, the number of 113 qualitative articles were selected to be analyzed deeply using bibliometric and content analysis, based on their contents, year of publication, keywords, the methodology used, and recommendations of the authors. The results accentuated the connection between BCT and their associated technology including Artificial Intelligence(AI) and the Internet of Things(IoT) for enhancing GM with accounting for the drivers, enablers, and challenges of implementing the BCT to GM.
The conclusion of our literature review reveals that BCT is a promising technology in the context of our review since it offers two main capabilities: transaction transparency and robustness, which are mandatory for GM implementation. In addition, we concluded that the majority of existing research works focus only on one or two aspects of GM and are destined to specific industries or use cases that limited their applicability. Unfortunately, there are gaps related to standardization, the 4.0 industry implications, and the adoption of BCT identified during the analysis of this review.

Keywords Blockchain, Blockchain technology, Green Manufacturing, Industry 4.0

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1. Introduction and background

1.1. Blockchain technology

The world is changing, and technology is among the key drivers that change how people perform their daily activities based on production, consumption, lifecycle management, and supply chain management; this affects the environmental ecosystem.One of the most trending technologies of the 21^{st} century is "blockchain", and the history of blockchain started 14 years ago in 2009 When Satoshi Nakamoto implemented the first digital currency known as bitcoin was created using the mathematical foundation to formulate the cryptography algorithm [1, 2]. Blockchain play effective impacts on social, economic and environment; and has many applications in financial transaction[3], smart waste management[4], sustainable supply chain[5], e-health sector[6], gaming industry[7], environmental sustainability[8],transportation[9], smart factories[10] and, other more different applications. The

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history of blockchain generation is described in Table 1 from generation one to the current generation while considering the future generation[11].

Model	Initiation	Feature	Blockchain Generation
Bitcoin network	2009	Bitcoin	1.0
Ethereum	2015	Ethereum	2.0
Hyperledger	2018	Hyperledger	3.0
Decentralized AI	2020	Deepbrain chain	4.0
Public ledger	2022	Hashgraph	5.0

Table 1. BCT generation[11].

Blockchain technology(BCT), as an open distributed ledger, can effectively record the transactions between two parties in a verifiable and permanent way[12]. Blockchain has at least two core features, namely decentralization and data tamper-proofing[13]. The chain is composed of multiple blocks connected according to time order, and if the information stored in the chain needs to be modified, more than half of the servers must agree. All servers store the chain information, making it difficult to tamper with the decentralized data[14]. Several types of blockchain protocols include Bitcoin, Hyperledger fabrics, Ethereum, International Business Machines(IBM)blockchain, IoTA, Palkadot, and Cosmos[15]. The blockchain has the network structure levels from the peer-to-peer network level to the data layer and to the upper architecture development layer known to apply to the consensus layer, application layer, and smart contract application layer[16]. The "flattened" topology of the peer-to-peer network structure is a crucial manifestation and foundation of the decentralized feature of blockchain. There is no centralized server in the peer-to-peer network structure, and each node is both an information user and a provider. Each node maintains connections to neighboring nodes and participates in transaction propagation and validation as well as data block synchronization throughout the network. The data layer is the distributed ledger, in which transaction data generated through users' digital signatures or smart contract scripts are packed into sequential blocks and connected through a chain-like structure[17, 18]. The core of the consensus layer is the consensus algorithm, which is used to solve the consistency problem of transaction content among nodes in a distributed network. Commonly used algorithms include Proof of Work (PoW), Proof of Stake (PoS), Practical Byzantine Fault Tolerance (PBFT), Delegated Proof of Stake (DPoS), Ripple, and Tendermint[19]. The application layer is the connecting part between the blockchain system and the business application system, and it deploys distributed applications (DApps)[20, 21].

The BCT has trending characteristics that include traceability, reliability, resilience, decentralization, security and privacy, smart contracts, sustainability, interoperability, scalability, regulatory compliance, and tokenization. These characteristics are not limited to these and as technology grows, and other factors that can be considered[22]. The BCT has limitations of being adopted based on their implementation, energy consumption in mining the operations, the resources needed for equipment, and the issue of storage[23]. Table 2 highlights the particular attributes of blockchain based on their context of definition and functions.

Attributes	Functions	Reference
Traceability	The use of BCT to track the GM processes	[24]
Interoperability	Integration of BCT systems in the GM industries	[25]
Security and Privacy	Balance of transparency and decentralization	[26]
Decentralization	Decision-making with no involvement of central authority	[27]
Smart contract	Written code self-executed	[28]
Compliance	Environment management systems	[29]

Table 2. The particular attributes of BCT to the GM industry.

1.2. Green manufacturing for sustainability

The environmental outcomes from Green Manufacturing(GM) are generated from different perspectives of production, supply chain, and consumption. Climate disruption has had a significant impact due to the advance of environmental degradation. The possible perspectives may include: global warming; acidification; eutrophication; ozone depletion; photochemical smog formation; primary energy demand; eco-system toxicity; human health toxicity; water use; waste generation; and resource depletion[30]; and this has negative consequences on social, economic and environmental aspects[31]. The GM industry defined as sustainable manufacturing in industries based on eco-friendly manufacturing, results in minimizing the environmental issues that have negative impacts to the ecosystem as well to the human being[32]. The efficiency of energy and resources, sustainability of the environment, and the sustainable solution for preventing pollution are the key components of GM[33]. Many conducted studies were focused on the sustainability of the supply chain, and production operations while considering the lifecycle management of products on reducing the environmental effects. There are elements and features of GM listed in Table 3 with considering the BCT applications to manufacturing industries.

For sustainable GM, a lot of studies have focused on managing the environmental impacts using the blockchain while considering the process of lifecycle management, supply chain management, and product operations. For conducting this review, we will focus only on the environmental performance of GM industries and the methodology used highlighting the five main research questions:

1. What is the existing literature on BCT for GM industries?
2. What are the research gaps in the application of BCT to GM industries?
3. What are the challenges and risks associated with implementing BCT for GM and how to overcome them?
4. Is it possible for BCT to be integrated with other emerging technologies to boost the GM industries?
5. Are we ready to adopt BCT for GM industries?

The structure of this review paper is as follows: Section 2, describes the methodology used for literature review analysis, section 3 describes the contents analysis for the bibliometric of the literature and results discussions then section 4 concludes by highlighting the limitations of the literature and future recommendations to other authors.

Factors	Strategies	Characteristics	references
Waste recycling	Environmental management	Minimizing and reduce the wastes	[34]
Eco-friendly technologies	Green applications	IoT, big data and AI	[35]
Resources	Resources use	Efficiency and the optimization	[36]
Innovation	Sustainable manufacturing	Supporting the UN SDGs	[37, 38]
Certification	Environmental management	Compliance to ISO 14001	[24]
Sustainability	Sustainable manufacturing	Ecofriendly products	[39, 40]
Packaging	Green operations	Green processes	[41]
Local sourcing	Green operations	BCT to enhance the GM	[42]
Life cycle assessment	Environmental management	Support GM	[43]
Risk management	Environmental management	Risk assessment	[44]

Table 3. GM factors, strategies and characteristics.

2. Methodology

This study includes the content analysis and the bibliometric review analysis considering the quality of literature on BCT applications and GM characteristics. A VOS viewer application was used for bibliometric analysis, and it is a flexible tool to explore the correlation between keywords based on co-occurrence. In our study, the keywords

were mainly focused on the application of BCT to GM and the results of the analysis are expected to provide much explanation about the contribution of BCT to GM and will explore the drivers, enablers, and challenges of BCT.

This study was conducted using a systematic literature review:

(i) Searching the related literature through Scopus, WoS, Google Scholar, and ScienceDirect to summarize it.
(ii) Classifying the selected literature by considering their application.
(iii) Screening the literature to identify literature focused on the selected keywords of the blockchain and GM for exploring further study in this area.
(iv) Analyzing and refining the screened literature dataset for text analysis, visualizing and constructing the bibliometric networks.

The articles were reviewed by acknowledging the title, abstract, keywords, most cited paper, and the most updated study with highly indexed updates for emphasizing that BCT has been used to address various types of environmental problems in multiple stages of the lifecycle management, production operations and, supply chain management. It is demonstrated that BCT can effectively applied in providing the sustainability of managing the environmental issues[42]. The article selected was scrutinized for bibliometric analysis by considering the stated keywords in Table 4 such as blockchain, blockchain technology, green, manufacturing, green manufacturing, industry, and industry 4.0 as the main keywords for title, abstracts, and keywords search from the four research platforms of Scopus, WoS, Google Scholar (GS), and ScienceDirect(SD). A total of 147 articles were reviewed deeply and 113 articles were selected to be analyzed based on their qualitative literature that provides more recent information on the BCT and GM industry as demonstrated by (Fig.1) of this study.

Focus	Terms	Repository
Technology	Blockchain, Blockchains and Blockchain technology	Scopus, WoS, GS and SD
Environment	Green	Scopus, WoS, GS and SD
Application	Manufacturing, Industry and Industry 4.0	Scopus, WoS, GS and SD

Table 4. Search Criteria for keywords.

2.1. Applications of Blockchain in Green Manufacturing for Sustainability of Industry 4.0 and Industry 5.0

Green manufacturing industries facing various challenges and seeking to overcome these challenges to achieve growth and development of industry 4.0 and 5.0. Sustainability development empowers GM to respond to various challenges effectively and became a critical factor for industries to achieve their target of achieving industry benefits while putting in place practices that minimize environmental issues[42].

The contributions of blockchain technology to support meeting the needs, namely economic and social are elaborated as follows:

a. Economic implications

GM faces various challenges such as high labor costs, high business environment complexity, and rapid customer needs and wants changes. To manage these challenges and achieve economic sustainability, industries should manage operations and supply chains effectively and efficiently. According to [45], the economic implications of the GM supply chain should be assessed on namely reliability, responsiveness, flexibility, financial performance, and quality[42].

b. Organizational and social implications

Organization and social performance of GM in industry 4.0 and 5.0 is another pillar that plays a role in creating and maintaining relationships with stakeholders[46] and creating a clear picture and recognition. Organizational and social issues affect the production of GM, where industries face various challenges and they have to build a framework model and accept emerging technologies such as IoT, AI, and, others to overcome these challenges.

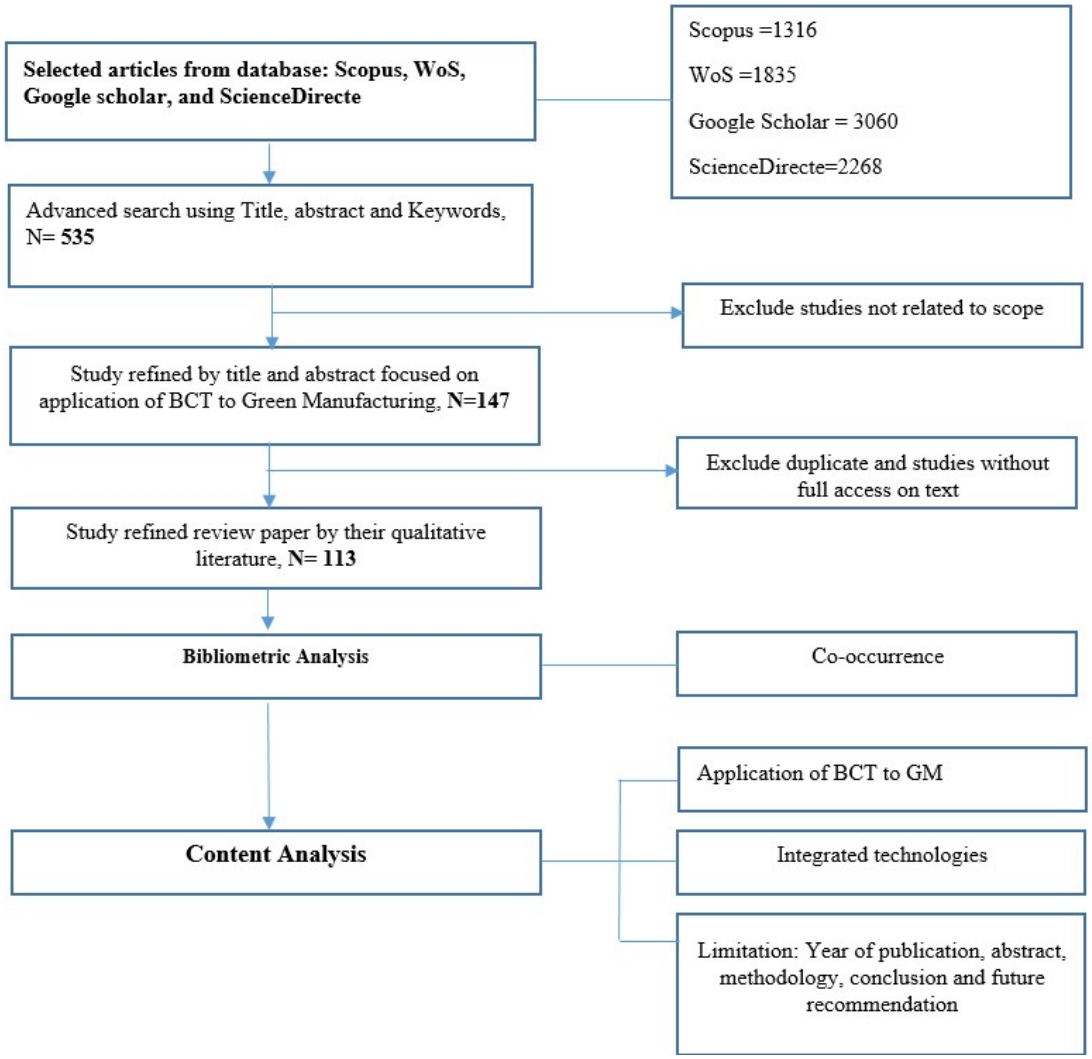

Figure 1. Systematic literature review and analysis process.

The organizational and social implications may be due to human rights, societal commitment, consumer behaviors, business practices, and the work environment. BCT can contribute significantly to sustainable GM and help industries to overcome the organization and social challenges for the industries[42, 47, 48].

3. Analysis and discussion

3.1. Bibliometric analysis

Using bibliometric and content analysis, this study comprehensively reviews the previously existing and current state of research on BCT in the field of manufacturing. The BCT applications in GM will be summarized and discussed based on their classification and processes as shown in Table 5. Even if the blockchain technology started in preceding years, we observed that the BCT can be applied in GM[49], and the GM is not a new topic in research but the application of emerging technology including the blockchain to GM is rapidly increasing and attracted more researchers and the community[50], this will be indicated by the number of research articles that

were selected to be used for conducting this review in (Fig.2).

The articles were selected through an advanced search on Scopus, WoS, Google Scholar, and ScienceDirect using title, abstract, and keywords as shown in Table 4 while considering the applications related to GM such as manufacturing industry 4.0, supply chain, environmental management, agri-food and, other many applications that were not presented on the graphs made by using python. The criteria for the selected articles, we considered the most updated published literature as indicated, and recently, emerging technologies like the IoT and AI have been increasing the research due to their applicability in many domains and their ability to be combined with other technologies like the blockchain; thus highlight that the combination of BCT and their associated technology of IoT and AI is the key tool for having the sustainable GM.

The selected articles on BCT and their integration with other emerging technologies in the advanced search presented in (Fig.2) highlight the contribution of emerging technology as well as the growing research in the area of GM using the IoT and AI. Even if there are other emerging technologies not listed such as big data, quantum technology, robotics, green hydrogen, renewable energy, green computing, and smart automation in the review cause, our research focused on the most trending technology for having a deep understanding of BCT to GM. However, this review considered the literature not related to the scope of environmental performance implications and the direction of this review but there are removed to remain with the most qualitative literature for bibliometric analysis focus on GM in the industries with considering the GM strategies and environmental factors.

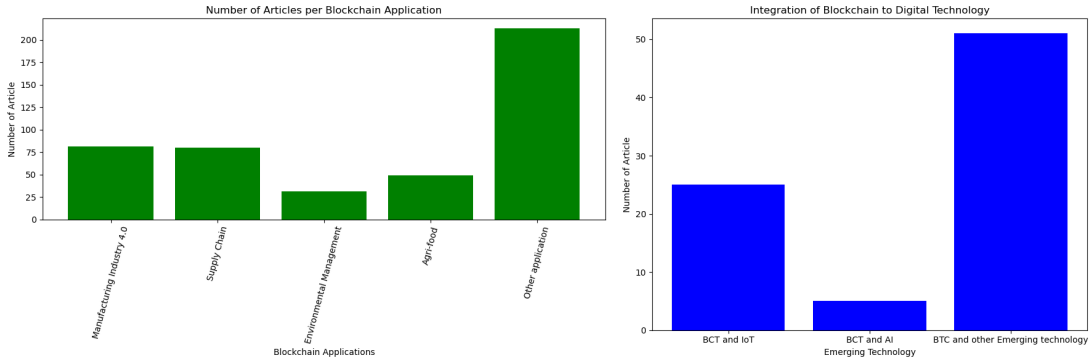

Figure 2. The selected articles centered on the BCT application to GM and the selected articles on the integration of BCT and their associated technology.

In terms of co-occurrence analysis of keywords (Fig.3 and Fig.4) highlight the co-occurrence analysis based on author keywords; the blockchain is firstly applied in supply chain management and is integrated with the IoT and blockchain application with the high frequency of co-occurrence based on their strongest correlation. The existence of circular economy, waste, climate change, carbon emission, and renewable energy act as the main key pillars for blockchain application. The transaction, security, interoperability, cryptocurrency, healthcare, smart contract, smart city, and privacy are the drivers of blockchain technology as indicated by the connection of the blockchain application. The bibliometric analysis based on the co-occurrence of the selected keywords of the whole literature by author-keywords highlights that supply chain management was the keyword that had the most connection with other keywords related to GM and BCT including food supply chain, food traceability, BCT adoption, and supply chain management.

In this study, the publications used were the most updated papers as indicated by (Fig.4) highlighting a network based on keywords co-occurrence in dark-green color considering the average publication year; an average was calculated based on the qualitative 113 literature from bibliometric analysis focused on environmental performance with considering the processes of GM operations. The bibliometric analysis performed considering the attributes of BCT directly points to sustainability, smart contract, smart manufacturing, environmental sustainability, green

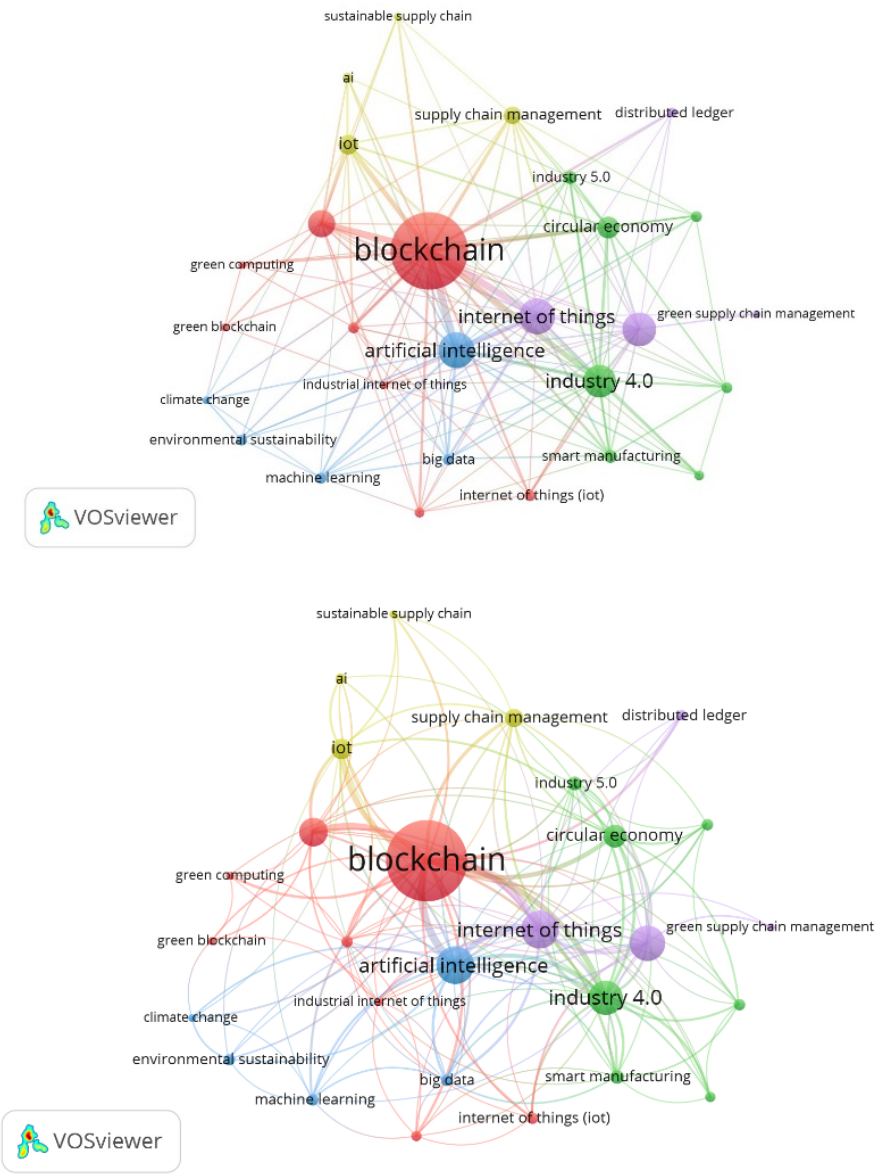

Figure 3. Author analysis network diagram using the bibliometric analysis based on co-occurrence of keywords by selected author-keywords.

supply chain, circular economy, industry 4.0, industry 5.0, manufacturing, big data, environmental sustainability, climate change, and, green computing. This presents the impact of blockchain in the GM industries while considering their characteristics and was explained in detail for further understanding.

The conducted data analysis, results prove that the BCT contributes to environmental aspects based on supply chain management[51], waste management[52], product lifecycle[53], resources enhancement[54], carbon trading[55], carbon emission reduction[56], eco-friendly technology [57], environmental compliance, innovation and, research. In addition, this review contributes to the SDGs [38]as indicated in Table 6. This study discusses

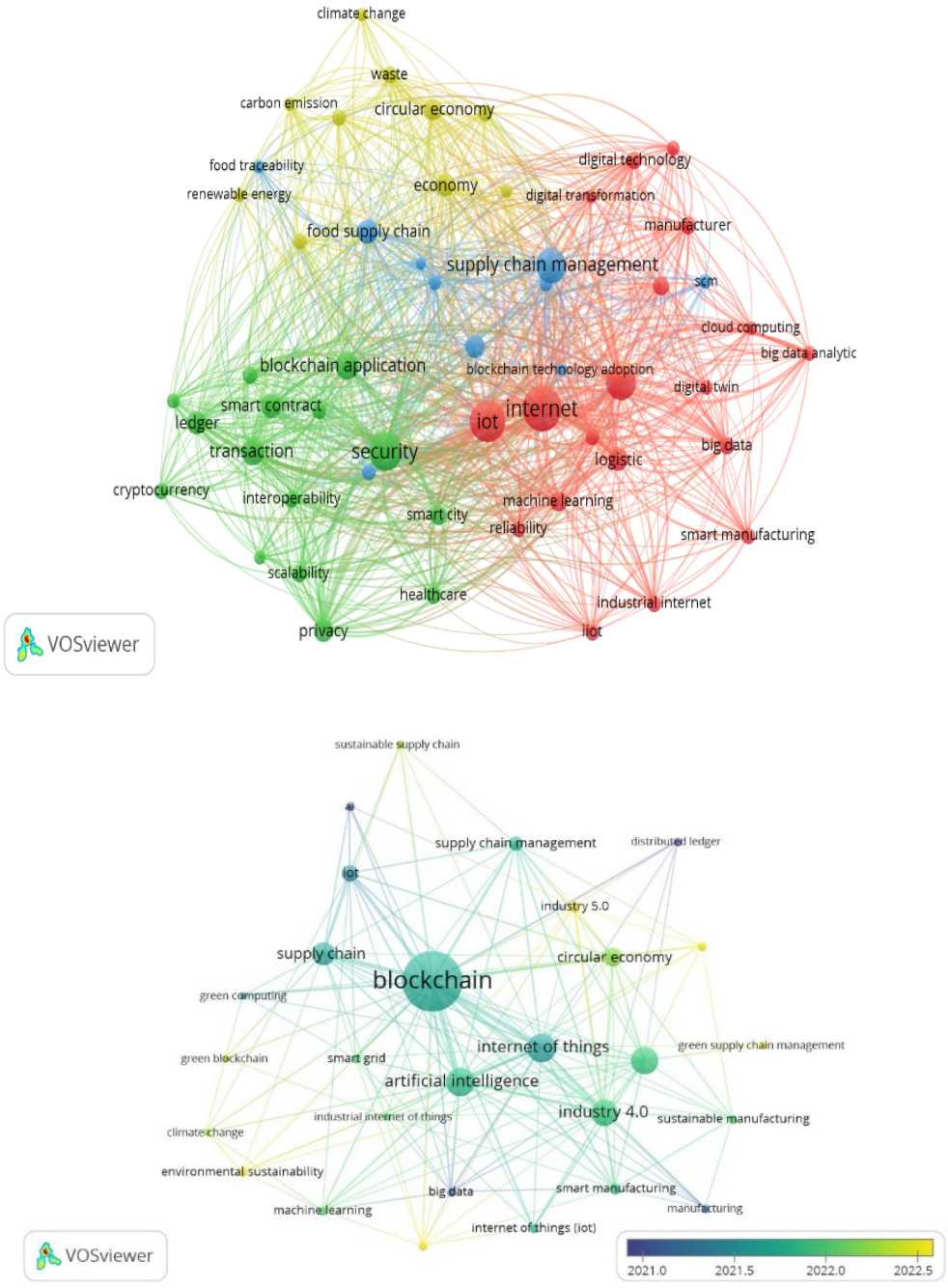

Figure 4. Author analysis network and keywords analysis network diagram based on the average year.

the potentiality of the application of BCT to GM from the perspective of environmental performance and serves as fundamental information for the relationship between BCT and GM in Industry 4.0. However, there are significant goals and methods discovered as it's elaborated below.

3.2. The application of BCT to GM industry processes based on environmental performance

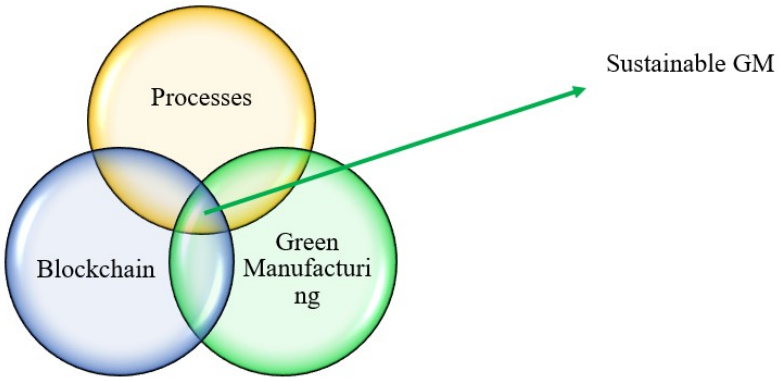

Figure 5. Overlap of BCT to the GM processes.

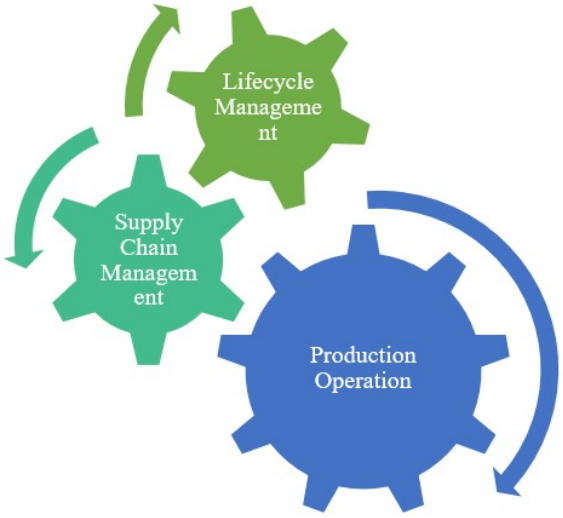

Figure 6. Process interaction of the GM industries.

Fig.5 indicates that the BCT plays a significant contribution to the GM through the operational processes of the manufacturing industry; where the production operation, supply chain management, and lifecycle management are the key drivers for the sustainable GM. Emerging technologies such as blockchain, IoT, and AI are applied to implement the GM industry, which leads to solving the existing environmental challenges in the GM industry area. Fig.6 describes a process interaction from inputs to outputs considering the relationship between the 3 key aspects of GM while Fig.7 indicates the framework of BCT in integration with the IoT and AI that are the enablers to sustainable GM with considering their applicability to the industries. The framework in Fig.7 represents the role of digital technology of AI and IoT in the GM industry as described by their co-occurrence in the bibliometric performed with a great interest in the supply chain and green industries. One of the objectives of the study was to measure the contribution of BCT to the GM industry by considering the drivers, enablers, and challenges for each node in the bibliometric analysis focusing on manufacturing industries and considering the applicability of their associated enabling technologies.

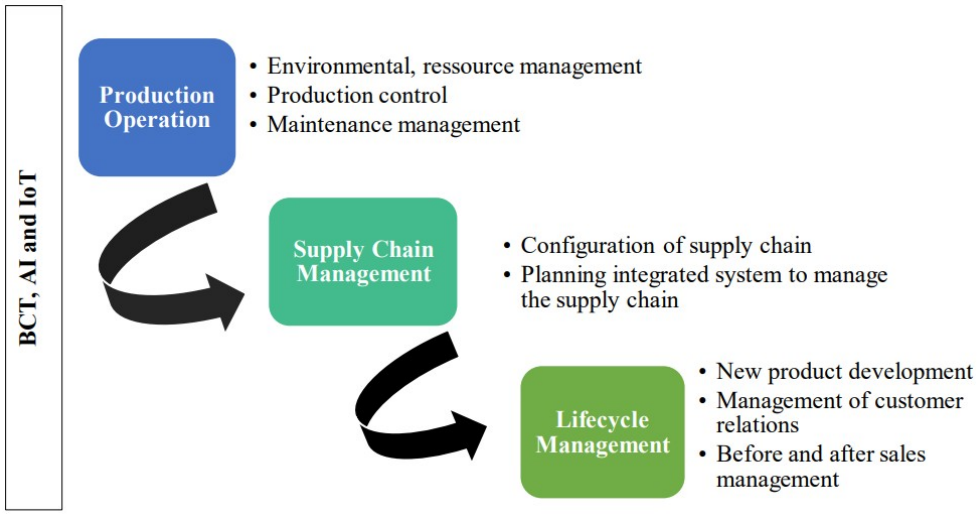

Figure 7. Framework of GM industry based on BCT and their integrated emerging technology.

Area of focus	Scope	BCT contribution
Supply chain	The use of BCT to track the GM processes	Monitoring of supply chain
Environment	Environmental management	Sustainability and circular economy
Product lifecycle	Lifecycle management	Product and green operations
Resources	Energy , water and gas	Ressources efficiency
Carbon emission	CO_2 emission	Carbon trading
Ecofriendly technology	AI, IoT and Big data	Green applications
Certification	ISO 14001	Compliance audibility
Innovation and research	SDGs	Industry innovation

Table 5. Contribution of BCT to GM industries.

The contribution of the BCT to the GM is explained in detail as indicated in Table 5:

1.Supply chain: Blockchain is used for supply chain management by providing an invariability of records and ensuring transparency by verifying the source of products for supporting GM and environmentally friendly products[58].

2.Environment: Blockchain facilitates the sustainability of managing the negative environmental impacts from the manufacturing industries to have sustainable solutions that support the GM operations[57].

3.Product lifecycle:Blockchain plays a significant role in contributing to the circular economy on the traceability of products sustainably for circular economy promotion and ensuring compliance to the environmental management systems[59].

4.Resources:Blockchain contributes to the optimization of resources such as water, energy, gas, and others for the efficient use targeting to facilitate the manufacturers to have sustainable GM based on the efficiency of production operations and reducing the environmental impacts[60, 61].

5.Carbon emission: The BCT significantly contributes to the GM through carbon trading by minimizing the carbon emitted into the environment from the manufacturing industries and favoring the net zero target and

creation of Eco-park industries for enhancing the industries based on GM processes[55, 62].

6.Eco-friendly technologies:The integration of blockchain with emerging technologies such as AI and IoT provides a systematic way of supporting transparency, traceability, minimization of carbon emission, and data security for sustainable practices to support the GM industry while contributing to the environmental performance[63, 26, 28].

7.Quality assurance and certification:The blockchain enhances the GM through audibility like smart contracts that can be executed automatically to ensure the manufactured products are produced with considering the environmental performance to meet the requirements of environmental standards and required regulations[24, 5].

8.Innovation and research:The BCT contributes to innovations and the advances of research in the field of sustainable GM. Moreover, a lot of studies are targeting to create solutions and resolve environmental problems[64].

The contribution of BCT to GM industries discussed highlights the impacts of emerging technologies on the GM and, is an added value to this research. The study focused on the environmental performance of manufacturing industries by performing a systematic review and analysis considering the BCT application to GM. This study contributes to the United Nations Sustainable Development Goals (UN SDGs) agenda 2030 focusing on the 9^{th} goal of industry, innovation, and infrastructure, the 11^{th} goal of sustainable cities and communities, the 12^{th} goal of responsible consumption and production, and the 13^{th} goal of climate actions for their valuable contributions on mitigating the environmental issues as indicated in Table 6.

SDGs	Description	Contribution of BCT	references
SDG 9	Industry,innovation and infrastructure	Industry 4.0 and 5.0	[65]
SDG 11	Sustainable cities and communities	Eco-industrial park	[66]
SDG 12	Responsible consumption	Green operations and processes	[67]
SDG 13	Climate action	Circular economy	[68]

Table 6. Contribution of BCT to GM industry based on UN SDGs agenda.

3.3. Blockchain technology implementation challenges to Green manufacturing

3.3.1.Technical Challenges: The Technical challenges to be addressed insight include the systems integrations, modeling, scalability, security and privacy, and energy consumption[5]. The blockchain enables the secure transaction and data processing of information, however in the implementation of blockchain to GM of this review, we discovered the technical issues as indicated in Fig.8. The integration of BCT with other digital technology is a serious challenge to be solved, the modeling of blockchain have presented critical issues on the prediction of blockchain behavior on their mechanism of consensus (PoW, PoS and other alternative consensus algorithm)[69]. The scalability issues arise due to the latency of networks that may affect critically the throughput of an overall performance of blockchain.

The security and privacy, in the use of blockchain will remain a great issue to be solved by the researcher, particularly on the scenarios of integrating the BCT to the emerging technologies. In[70] highlight many types of attacks regarding the security and privacy of BCT, It was critically observed on the public blockchain and this critically affects the use of BCT in technical terms. The energy consumption of using the BCT to the GM is another technical challenge based on the consensus mechanism of high energy consumption due to mining activities of the blockchain, and this is very different from the GM goals and strategies, and there is an urgent intervention needed of finding other alternative solutions for minimizing the energy consumed by adopting BCT in the GM for sustainability purpose.

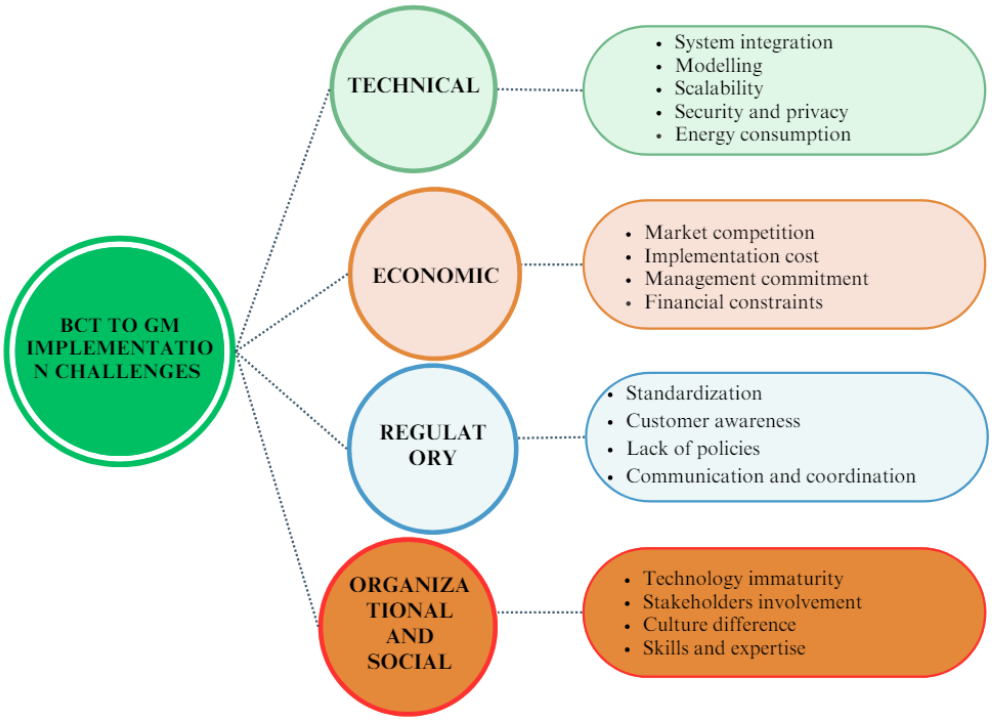

Figure 8. BCT implementation challenges to GM.

3.3.2.Economic Challenges: The implementation of BCT to GM highlights the economic challenges that may affect the sustainability of GM and the adoption of BCT in Industry 4.0. One of the characteristics of challenges are the required investment in the implementation of blockchain in the industries, the market competitions, the commitment of top management to understanding the role of BCT to boost the manufacturing industries, and the financial constraints for setting up the blockchain infrastructures and required supports[42].

3.3.3. Regulatory Challenges: In the implementation of BCT to GM, the challenges centered on the absence of standards such as the compliance to the ISO 14001(Environmental Management Systems)[71] provide the regulatory issues based on legal compliances that may vary by jurisdictions and create complex use of BCT[72] and this may arise and create the lack of customer awareness, the lack of new developed standards in the area of BCT that fit the use of blockchain in the manufacturing industries, the absence of communication and coordination to the parts of government to the stakeholders and industry owners. The works are in progress in the standardization sector through the collaborations of the International Organization for Standardization(ISO) and other standards associations such as the Institute of Electrical, and Electronics Engineers(IEEE), the International Electro-Technical Commission (IEC), and the International Telecommunication Union(ITU) for developing the standards based on the interoperability, integration and, architecture of blockchain. whoever, government institutions try to put more effort into drafting the rules and regulations in the use of blockchain[73].

3.3.4. Organizational and Social Challenges: The implementation of BCT to the GM as an industry organization may require the involvement of technology maturity, stakeholder involvement, skills, and expertise of the personnel in the manufacturing industries. The GM faces many social and organizational management challenges, which remains a critical issue for researchers to solve. The trust of BCT to engage the stakeholders of GM and adopt the blockchain is a serious issue to be discussed and the local community engagement with the resistance to change based on their ethics about technology such as data privacy and security of information needs to be solved by the

researchers for contributing to the adoption of BCT in the manufacturing industries through assuring the sustainable GM in the era of manufacturing industries[5].

4. Conclusion

This study review was focused on investigating the environmental performance of GM industries using the systematic review and analysis considering the BCT application to GM. The findings explore the potentiality of BCT, research opportunities, and future directions based on current gaps, challenges, and limitations by presenting diverse critical items from the position of GM. This research contributes to the existing literature on sustainable manufacturing focusing on the role of BCT for environmental performance on production operations, supply chain management, and lifecycle management considering parameters that have impacts on the GM industry and contribute to smart industry. In addition, this review attracts researchers, engineers, governments, the manufacturing industry, business owners, and policymakers, and serves as a fundamental contribution for future research studies. There is a limitation to this study review for considering only the 113 published articles focusing on environmental performance in manufacturing industry. Moreover, technology is moving very fast, so other future research can be conducted on the newly published articles not highlighted in this review while considering the industry 5.0 implications, and social, technical, organizational, regulatory, and economic performance of the GM industries. In addition, further studies can greatly solve other environmental issues, such as preventing fraud in the supply chain, ensuring the sustainability, and traceability of manufactured products, reducing waste, reducing carbon emission, integrating BCT with other emerging technologies, developing standardized frameworks, and exploration new applications in GM with exploring the systematic way of adopting the GM in industries that will contribute to the sustainability of managing environmental impacts with considering the applicable standards like ISO 14001 (Environmental Management Systems standard) for enhancing the compliance to the requirements of sustainable GM in the industry ecosystem. Moreover, this review will add value to other existing research on BCT and will be the main key input for adopting blockchain to accelerate the GM industry.

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