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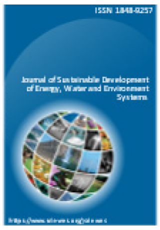

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Review Article

Blockchain Technology and the Circular Economy: A Systematic Literature Review

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ABSTRACT

This paper aims to offer an overview of the features in the existing state of research on blockchains in the circular economy. A total of 79 articles published up to 31 May 2022 have been extracted from Scopus and Web of Science. The research design has enabled us to identify what characterises the present state of research on the use of blockchains in the circular economy. It has also allowed us to obtain a new categorisation scheme of the research that has identified five themes and the contributions in each theme and has allowed us to highlight several research gaps. The review findings indicate that the literature revolved around five research themes, namely, the relationship between blockchains and Industry 4.0, the potential of blockchains for circular economy practices, the role of blockchains in energy management, the role of blockchains in waste management and the impact of blockchains on sustainability. This review suggests several future research opportunities and provides practical implications for researchers and practitioners. To the authors' best knowledge, this study represents one of the first attempts to investigate the interplay between blockchain technology and the circular economy.

KEYWORDS

Blockchain, Circular Economy, Industry 4.0, Sustainability, Waste, Energy.

INTRODUCTION

The circular economy (CE) concept has been advocated as an alternative to the existing linear economy that has the potential to support the transition toward sustainable development [1, 2]. CE seeks to establish a synergy between economic activities and environmental protection in a sustainable fashion [3]. Conceptually, the CE is a new business model that shifts from the conventional "make, use, dispose" approach and aims to reduce waste, maximise resource efficiency and realise harmony between the economy, environment and society. According to [3], the CE attempts to limit the depletion of natural resources and waste via its cyclical usage and promote cleaner production through the "reduce, reuse and recycle" (3Rs) activities. Within the loop, the CE strives to maintain resources, materials and products in circulation for the longest period by conserving their value [4]. Besides economic prosperity

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and environmental preservation, the CE also aspires to foster social equality [5] by increasing job creation and value proposition for all stakeholders [6]. As a result, firms are increasingly keen to implement the CE approach to incorporate sustainability into their operations [4].

Whilst the CE provides a unique opportunity to create value and valorise waste [7], it poses several issues connected with increased risk, responsibility and accountability linked with an organisation's ecosystem. As per [8], one must reform how organisations generate, deliver and capture value. For instance, organisations must expand their interactions and maintain stronger customer relationships across the product life cycle. Furthermore, the requirement for new capabilities, skills and business models necessitates reanalysis and evaluation of the broader firm ecosystem of how to integrate products to provide sustainable benefits with the maximum customer value [9]. According to [10], the transition toward a CE is a challenging task that requires the involvement of multiple sectors and stakeholders. Therefore, there is a need to leverage new technologies to adapt to increasingly changing conditions and respond to consumers' demands for sustainable and environmentally friendly products [11].

Technological advances manifested in the Fourth Industrial Revolution [12], or Industry 4.0, represent a key enabler for CE realisation [13]. In that context, the blockchain has been highlighted as a significant facilitator to overcoming hurdles toward a CE [12]. Integrating the technology to exchange information on materials and supply chain processes transparently can result in waste minimisation, more circular resource flows, and an enhanced platform for effective decision-making toward a CE [14]. The capabilities of blockchains have the potential to accelerate CE advancement in many ways. Information visibility, trustworthiness and automation offered by the technology can successfully leverage CE efforts. Information regarding materials sources, product provenance, processes, energy usage and involved stakeholders can be accessed and maintained in blockchain ledgers. Coupled with tracking devices such as global positioning systems (GPSs), blockchains can facilitate the traceability of raw materials and products throughout the supply chain. These prospective blockchain aspects can create the groundwork for reuse, upcycling, recycling initiatives and CE performance management. However, the utility of current blockchain systems has been questioned. The doubts concern high energy consumption levels and uncertainty about whether potential benefits can outweigh technology's downsides [15].

Considering the huge potential of blockchains in the CE domain [16, 17], comprehending what characterises the current state of research on blockchain use in the CE should be of great interest to both academia and industry. From the academic standpoint, one should study the blockchain-CE intersection to identify what has been researched so far and determine knowledge gaps that would provide opportunities for future research. For industry, the review aims to clarify how blockchains can be a key enabler to address challenges towards the CE and stimulate ideas for effective schemes and policies to adopt the technology to enhance overall firm performance.

It should be emphasised that the research on the blockchain's role in the CE and the relationship between the two concepts is in the nascent stage [14]. Regarding blockchains and the CE, a study [18] reviewed the current approaches for traceability in textiles and clothing value chains using blockchain technology and the Internet of Things (IoT). However, a systematic literature review (SLR) of the extant literature in a broader context is still missing. The lacking information prohibits a clear understanding of the early developments and extant research gaps concerning the nexus of the blockchain and the CE, which hinders further progress in the field. For this reason, the present research studies the current literature on the blockchain and the CE to examine the existing knowledge in this domain and suggest future research directions. Essentially, the SLR approach was applied to ensure a rigorous, valid and replicable procedure for selecting, assessing and reporting the current literature [19].

To attain the goals mentioned above, the remainder of this paper is structured as follows: Section 2 provides the theoretical background and conceptualisation of the blockchain, the CE, and the linkage between these two concepts. Section 3 presents the methodology used in this article. Section 4 shows the findings, including the descriptive statistics of the literature, categorisation and content analysis. Lastly, Section 5 briefly concludes and highlights the research implications and limitations.

THEORETICAL BACKGROUND

The blockchain origins have been attributed to Satoshi Nakamoto (pseudonym), who published a paper on the concept in 2008 [20]. In the paper, Satoshi proposed an open distributed ledger tool for the cryptocurrency bitcoin [21]. Beyond cryptocurrencies, the blockchain has received enormous attention for several applications [22, 23] and recognition as both a foundational [24] and disruptive innovation [25]. The main features of the blockchain are its distributedness, transparency, decentralised control, transaction immutability, robust design avoiding manipulation or tampering, openness, and accessibility [26]. Since its inception, three generations of blockchains have emerged, varying their application domains and technical properties [27]. The first generation of blockchains focused on cryptocurrencies and facilitating the exchange of electronic coins amongst dispersed users without a central authority such as a bank or a mint [28]. The bitcoin blockchain is generally a public blockchain in which unknown participants can use the system and interact with other members [29]. A blockchain relies on cryptography to manage a growing list of uniquely identified and linked transaction records called blocks [23]. Once a transaction is updated and verified by all the relevant participants in the blockchain, it becomes immutable and cannot be re-sequenced or over-written. As a result, this makes a blockchain a robust and secure ledger that provides all parties with identical, reliable and correct transaction records [30]. Moreover, the peer-to-peer nature of ledgers guarantees that modifications in any ledger are transparent and accessible to all network users. A blockchain is a continually increasing, distributed, shared ledger protected cryptographically through digital footprints [22].

Cryptocurrency mining is implemented to add new blocks to a blockchain. It requires solving a mathematical puzzle via complex computations until the desired value is obtained – an analogy to utilising a trial-and-error approach to obtain the correct hash code in the real world. Miners on blockchains compete against each other to be the first to successfully solve the computational problem and add blocks to the ledger [31]. In return, they are compensated for their work by new cryptocurrency. In blockchains, each block must include a proof-of-work, verified and validated by other network users, guaranteeing tamper-resistance and security of the whole chain [22]. A blockchain is designed such that there is a restriction on the amount of cryptocurrency put into circulation. Thus, the technology builds on the premise of synchronous collaboration and competition amongst network participants [32].

The second generation of blockchains involves smart contracts, which set the content of the contract and execution requirements in advance and automatically perform the contract when those requirements are fulfilled [33]. This automation demonstrates that one can use computer codes to establish a legally valid contract without the necessity for a trusted third party, which is crucial to the existing escrow mechanism. In general, the second generation of blockchains alters the conventional notion of supply chains since the implementation of smart contracts promises to reduce the cost of transactions and facilitate payment transactions [16]. This evolution phase leads to the third generation of blockchains, wherein the social elements of the technology are emphasised [34]. As a result, the blockchain has turned out to be the primary infrastructure of Industry 4.0 that has ushered in a novel industrial ecosystem in sectors as various as supply chain management [17], healthcare [35], tourism [36] and manufacturing [37]. This blockchain generation is interesting to many industries due to the technology's principles, including distributed storage, encryption, peer-to-peer interactions, strong security, and the possibility for secure and efficient automation.

A CE represents an economic system that aims to lower resource use, minimise waste, and achieve economic growth and prosperity. CE systems are established to reuse, remanufacture and recycle products within a closed system [38]. CE focuses on developing new business models that can reduce the influence on the environment [14]. To achieve this goal, the Ellen MacArthur Foundation proposed in 2015 a circularity model that indicates which activity cycle brings the most positive environmental effect [39]. The cycles concentrate on the next use of materials. The ideal next usage is to close a cycle rather than proceeding to a cycle with a lesser CE impact or ending up in the waste chain. The ultimate objective of the CE is to develop a cradle-to-cradle system, as stated in previous studies [40, 41], thus constituting a holistic approach that tries to develop zero-waste systems. In general, products and components are regenerated without deteriorating their quality and ending up in the waste chain. The CE concept is associated with the notion of industrial ecology, which confronts the prevailing belief that the environment and the industrial systems should be dealt with apart. The concept of industrial ecology aims to incorporate sustainability into the environmental and economic systems [42] by assisting policymakers in establishing a route to more environmentally sustainable development [43]. The main priorities of industrial ecology are to enhance the metabolic patterns of industrial activities and material usage, ensure dematerialisation of industrial output, reduce energy consumption and develop closed-loop ecosystems [44], thereby shifting from the linear economy and its coordination modes. Consequently, augmenting the scale of materials recycling promises considerable energy saving over different product life cycle phases [45].

The shift towards the CE necessitates a strong focus on energy and raw materials [46]. When making products, the emphasis should be on reducing the negative environmental impacts throughout the entire product lifecycle, from the initial phase of material extraction until the final disposal of products. In this regard, a study [4] explained how to tailor business model tactics and product design to a CE system. The operationalisation of a CE needs novel business models wherein one seeks opportunities by replacing the end-of-life concept with a cradle-to-cradle logic. The organisations assume life cycle responsibilities; move from unrenewable to renewable energies; opt for reuse, remanufacturing and recycling of their products; and enhance maintenance commitments [47]. This trend also implies that companies aiming to engage in a CE should strive to achieve a waste-free mode of production and consumption. According to [20], a move to servitisation represents a vital CE accelerator since it includes integrating physical products and services to respond to customer requirements.

In the CE context, the adoption of blockchain can support organisational processes. Large companies can benefit from the technology to efficiently manage their complex and fragmented facilities [48]. Using blockchain makes it possible to monitor and track resources as diverse as products, raw materials, energy, waste, etc. Therefore, digitising business operations provides a foundation for evaluating and managing green performance [16]. Excessively resource-intensive and wasteful activities in the CE can be eliminated or optimised using blockchain technology. CE adoption demands strong partnerships among supply chain parties, especially for closed-loop processes like reuse, remanufacturing, recovering, and recycling. In this sense, blockchain supports product recovery strategies, improves supply chain transparency, and assures product traceability. The technology is especially helpful for end-of-life processes, such as monitoring and tracing finished goods and raw materials throughout the circular supply chain [49]. Moreover, blockchain facilitates product sharing and reuse, decentralised manufacturing, and peer-to-peer resource circularity. Blockchain integration in CE initiatives can help reduce CE rebounds, which arise when total production, resource consumption, and environmental effects increase [50].

The facilitation of repair efforts is a recent strategy that has garnered considerable attention for accelerating the CE transition. Organisations must disclose their product blueprints so that customers and other organisations can effectively repair products and prolong their durability. Using blockchain, firms can easily share the information associated with product reliability, creating the potential for open innovation [51]. The ability to promote knowledge transfer for CE activities also presents intriguing opportunities for integrating circular processes across organisational boundaries and fostering business process innovation. In addition, blockchain technology can support product deletion policies by providing accurate and reliable information regarding shared products, resources, and services [16]. Throughout the lifespan of a product, blockchain excels at storing accurate and trustworthy information on its quality, location, and circularity performance. As a result, this increases the possibility of monitoring and tracking product performance, durability, and reusability. Overall, the cutting-edge technology of blockchain is regarded as a powerful force for the CE transition. The following section presents the in-depth research method used to review the intersection of blockchain technology and the CE.

MATERIALS AND METHODS

Despite the important impact of blockchains on the CE, current research on the intersection of both concepts is scarce [14]. The present SLR aims to investigate the existing literature on the blockchain and the CE. SLR is the approach utilised to map and review relevant publications; it follows generally accepted steps and hence permits evaluation and replication by other scholars [19]. The review procedure has been conducted following the rules and five steps suggested by [52]: (1) Formulate the research question, (2) Identify studies, (3) Select and evaluate the studies, (4) Analyse and synthesise and (5) report and discuss the results. Figure 1 shows the research procedure pursuing the five stages, which are detailed below.

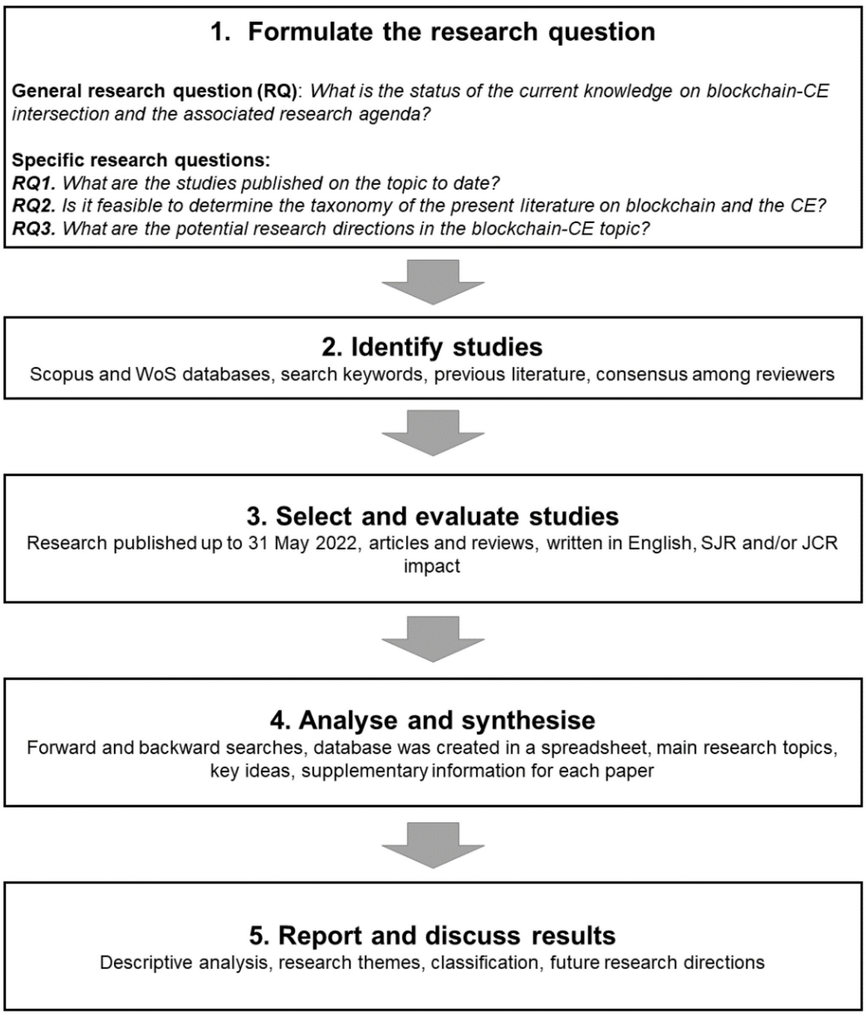

Figure 1. The research procedure

1) Formulate the research question: The main goal of this study is positioned at the intersection between blockchain research and CE research. Therefore, the search has been specially designed to identify studies in this junction area (see **Figure 2**). On this premise, the following research question (RQ) has been formulated to guide the current review:

RQ. What is the status of the current knowledge on the blockchain-CE intersection and the associated research agenda?

This broad research question has been divided into three interrelated sub-questions as follows:

RQ1. What are the studies published on the topic to date?

RQ2. Is it feasible to determine the taxonomy of the present literature on the blockchain and the CE?

RQ3: What are the potential research directions in the blockchain-CE topic?

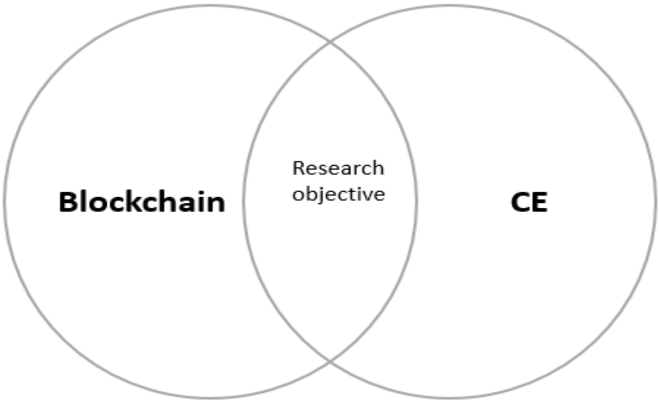

Figure 2. The blockchain-CE nexus

(2) Identify studies: Finding the most relevant studies constitutes the second step of the research procedure. Two main issues have thus been taken into consideration: search databases and search keywords. Concerning the former, The Scopus and Web of Science (WoS) databases have been consulted to locate the studies related to blockchains and the CE. Both databases are widely used in SLR due to their comprehensive coverage and high-quality content **[26]**. The unification process entailed considering the Scopus publications as the primary data source and adding to that source all WoS publications not included in Scopus. Furthermore, two complementary searches were conducted to check all references of the sampled publications (backward snowball search) and all publications that cited the articles included in the dataset (forward snowball search) by using Scopus and WoS as complementary databases for completeness. The research goal is in the nexus area of blockchains and the CE (**Figure 2**). An examination of search keywords in previous research **[53]** and a brainstorming session carried out by the authors aided in identifying the search terms connected to blockchains and the CE. As a result, a string query using Boolean operators (e.g., AND, OR) and truncated characters (e.g., "precise term" *) was created to locate the relevant studies in the databases. Moreover, the most frequent search keywords of the blockchain and CE literature were chosen to delimit and confine the nexus area. The terms and search query used are presented in **Table 1**. Multiple pilot tests were conducted on the databases to improve the search string and remove any false positives or false negatives. In both databases, the search fields "TITLE-ABS-KEY" and "TS" were selected as the tag of the searches, which means that the combination of keywords should be located either in the title, abstract, or the author keywords of the research papers. This search query returned 325 and 201 documents in Scopus and the WoS, respectively (see **Figure 3**).

Table 1. Keywords and search string

	Blockchain technology	CE
Keywords	Blockchain	Circular economy, circularity, closed-loop, zero waste, industrial symbiosis, cradle-to-cradle, recycling, reuse and remanufacturing
Search string	TS=(blockchain AND ("Circular economy" OR circularity OR closed-loop* OR "zero waste" OR "industrial symbiosis" OR "cradle-to-cradle" OR "recycling" OR "reuse" OR "remanufacturing"))	

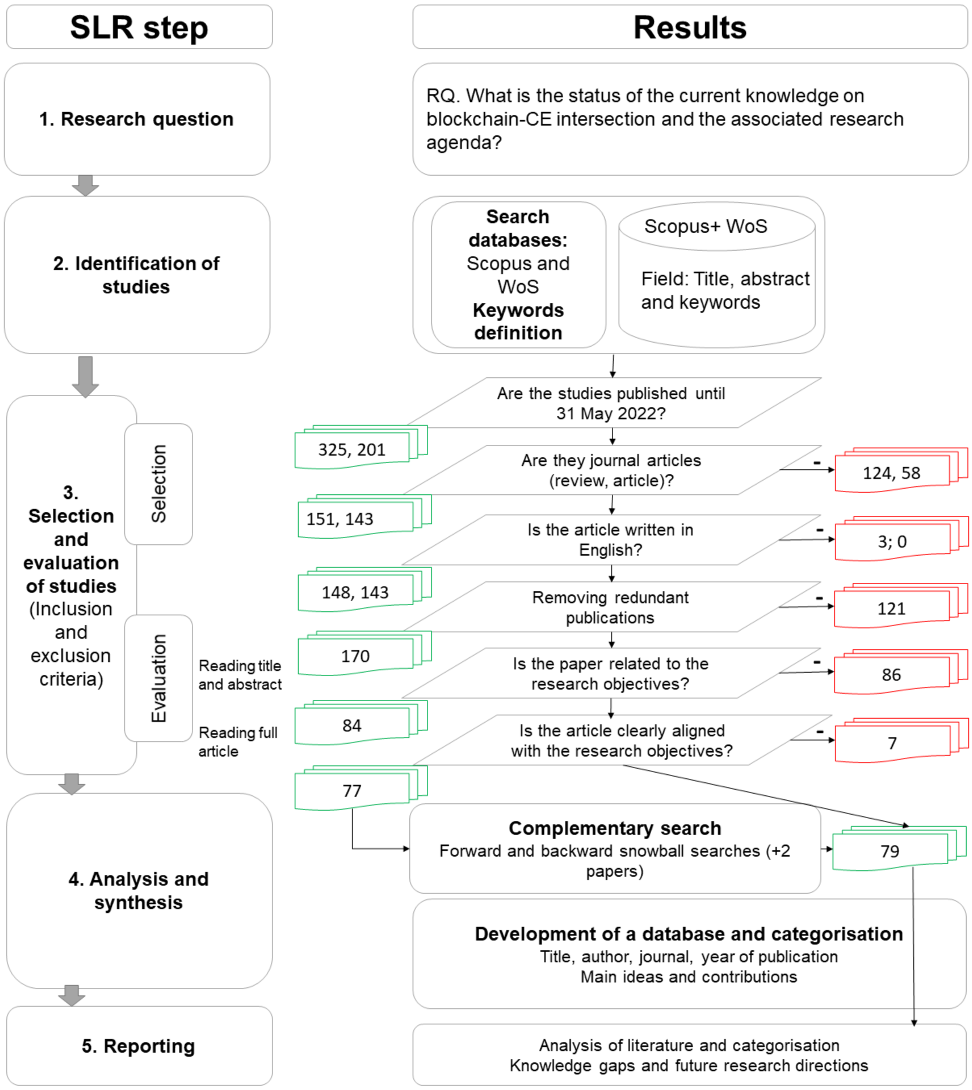

Figure 3. The SLR process

(3) Select and evaluate studies: Some criteria were identified to specify the publications that should be included (inclusion criteria) and those that should be eliminated [19]. Since the research was performed in May 2022, the search was limited to studies published up to 31 May 2022. Only English-speaking journal articles and reviews were considered. These filters helped decrease the total number of publications to 291 (148 papers from Scopus and 143 papers from the WoS). Next, 121 publications were redundant across the searches and were consequently excluded. The title, abstract and keyword fields were carefully read in the next phase, resulting in 86 papers being excluded due to their misalignment with the research topic. After this screening,

84 full papers were retained for a thorough reading to assess their relevance to the study's objectives. As a result, seventy-nine (79) papers were finally selected for this review. All these papers were published in journals indexed in Scimago Journal Rank (SJR) and/or the Journal Citation Reports (JCR), which confirms the quality of the selected documents. **Figure 3** depicts the publications that were excluded in each step and those retained after applying each of the exclusion criteria.

(4) Analyse and synthesise studies: In this phase, all papers chosen and evaluated in the earlier phase were analysed and synthesised by reading the entire paper and coding the content. The snowballing technique was used by performing forward and backward searches from the reference lists of the selected articles to capture any missing relevant articles. As a result, two additional papers were captured and added to the database to ensure the study's comprehensiveness **[54]**. This stage included pre-determined coding of the content to extract the main details in each publication and involved two researchers in the process **[55]**.

It was crucial to minimise single-researcher bias and to ensure the findings' reliability and validity **[56]**. Thus, the authors reached a consensus in the coding and data collection stage to obtain objective findings and reduce selection bias **[57]**. For the coding process of the articles, a database was created in a spreadsheet containing the main research topic of each paper, main ideas and other supplementary information (e.g., number of authors in a paper).

(5) Report and discuss the results: The final stage involved reporting the results from analysing and synthesising the literature. For this, the discussion of the results is presented in the next section.

RESULTS

The authors selected 79 articles to clarify the research at the intersection of the blockchain and the CE. This section provides a descriptive analysis of the publications, describes how the articles have been categorised in research themes using a new classification of the existing research, analyses the key findings of each research theme and identifies several directions for future research.

Descriptive statistics of the literature

Concerning the temporal evolution of research, **Figure 4** depicts the number of articles published from 2019–2022 (until 31 May). The figure demonstrates that this is an emerging research area that started recently. Scholars showed a significant interest in blockchain applications in the CE since the number of publications had witnessed more than a ninefold increase in 2021 compared to 2019. The authors anticipate that the attention given to blockchains and the CE will increase over time.

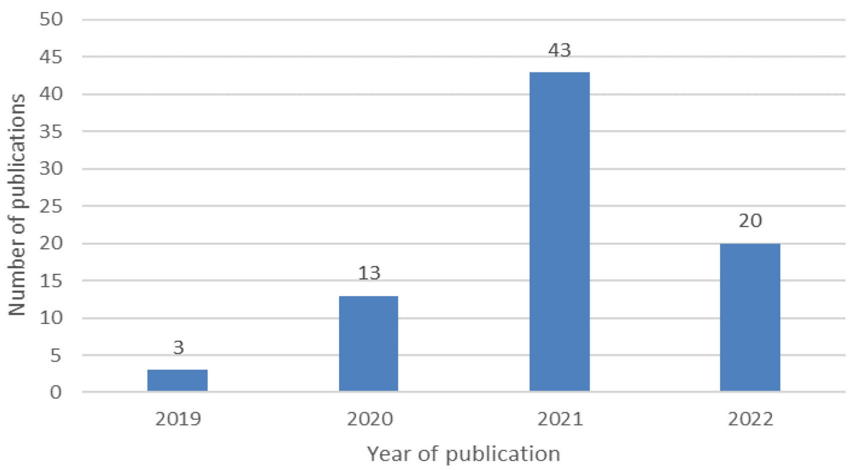

Figure 4. The annual distribution of publications

Regarding authorship, a total of 265 authors contributed to elaborating the 79 articles. Individual authors wrote five per cent of the articles, whilst two authors wrote 15%, three authors − 24%, and teams of four or more authors − 55% (see **Table 2**). In addition, **Table 3** shows the list of the most productive authors in the blockchain-CE literature, including Sarkis J., who stands out with eight articles, followed by Kouhizadeh M., Nandi S., and Yu Z., with three articles each. At the same time, the rest of the authors published either two articles or only one article.

Table 2. Classification by authors

Number of authors	Number of papers	Percentage
16	1	1%
8	1	1%
6	8	10%
5	10	13%
4	24	30%
3	19	24%
2	12	15%
1	4	5%

Table 3. The most productive authors

Author	Number of papers	Author	Number of papers
Sarkis J.	8	Teisserenc B.	2
Yu Z.	3	Sepasgozar S.	2
Nandi S.	3	Khan Sar	2
Kouhizadeh M.	3	Ramakrishna S.	2
Gong Y.	2	Bucea-Manea-Onis R.	2
Wang B.	2	Kazancoglu Y.	2
Rejeb A.	2	Ajwani-Ramchandani R.	2
Erol I.	2	Figueira S.	2
Peker I.	2	Torres De Oliveira R.	2
Searcy C.	2	Jha S.	2

Table 4 depicts the frequency of the papers published in the journals. Sustainability stood out with thirteen published articles (16%), followed by Business Strategy and The Environment and Journal of Cleaner Production, with six published articles each (8%). Industrial Marketing Management, International Journal of Production Research, and Resources, Conservation and Recycling published three articles each (4%). Compared to other journals on the list, Sustainability has a speedy review, which is a factor boosting article publications recently. The remaining journals published only two or fewer papers.

Table 4. The most relevant journals

Journal	Number of papers	Share
Sustainability	13	16%
Business Strategy and The Environment	6	8%
Journal of Cleaner Production	6	8%
Industrial Marketing Management	3	4%
International Journal of Production Research	3	4%
Resources, Conservation and Recycling	3	4%
Annals of Operations Research	2	3%
Buildings	2	3%
International Journal of Logistics Research and Applications	2	3%
International Journal of Productivity and Performance Management	2	3%
Resources Policy	2	3%
Sustainable Production and Consumption	2	3%
Technological Forecasting and Social Change	2	3%
Other Journals	31	39%
Total	79	100%

Categorisation and content analysis

The full reading of the articles and the database development permitted the researchers to identify five main research themes (T) in which the articles were positioned. Researcher consensus assured inter-coding reliability [56]. The identified thematic categories were the following: (1) blockchain and Industry 4.0, (2) blockchain and CE practices, (3) blockchain and energy management, (4) blockchain and waste management and (5) blockchain and sustainability. The articles could be grouped into more than one category. Figure 5 depicts the categorisation. Table 5 lists the articles situated in each of the thematic categories.

Whilst blockchain technology has made rapid inroads into several economic sectors, the integration of the technology in the CE is still at an embryonic stage [14]. As a result, research on blockchains and the CE is in the developing phase. The content analysis of the articles categorised into the identified research themes is presented below.

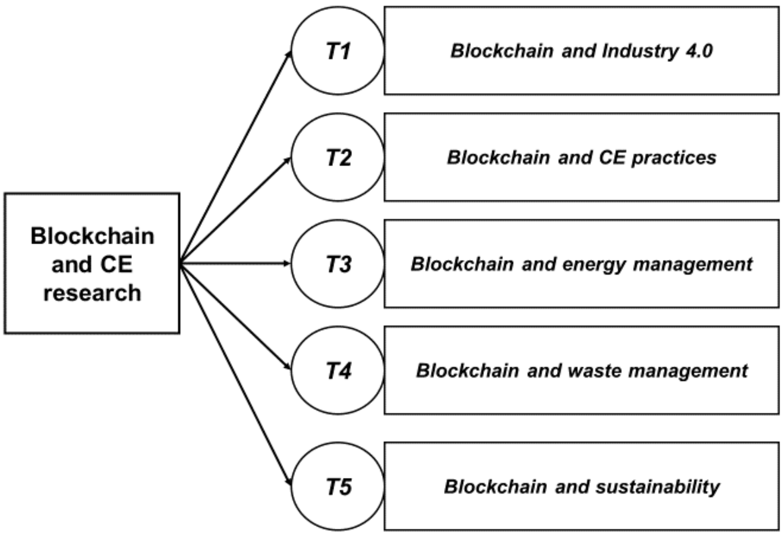

Figure 5. Research themes at the intersection of the blockchain and the CE

Table 5. Categorisation of the articles by research themes

Research theme	Articles
T1: Blockchain and Industry 4.0 (13 articles)	[11], [12], [58] – [68]
T2: Blockchain and CE practices (34 articles)	[14], [16], [17], [20], [62], [69] – [97]
T3: Blockchain and energy management (7 articles)	[82], [98] – [103]
T4: Blockchain and waste management (17 articles)	[20], [49], [88], [104] – [117]
T5: Blockchain and sustainability (17 articles)	[12], [32], [51], [60], [61], [69], [70], [88], [118] – [126]

Studies focused on the relationship between the blockchain and Industry 4.0

New technologies, evolving under the banner of Industry 4.0, offer organisations unique business opportunities. According to [12], blockchain technology represents one of the most critical elements of Industry 4.0 that can improve the level of information integration across supply chains and between different entities, increase transparency and support CE strategies. Blockchains streamline business transactions and collaboration between machines and stakeholders, a key characteristic and aim of Industry 4.0. The shift towards Industry 4.0 necessitates the interconnectivity and communication between smart objects such as IoT, sensors and transportation systems. Blockchains can increase the security of Industry 4.0 applications by improving transactional automation, saving time and resources, and reducing waste and inefficiencies. In this context, [62] introduced the industrial blockchain concept. It aims to combine the technology with IoT, machine-to-machine (M2M) communications and efficient consensus algorithms in the industry. The authors also argued that blockchains could provide an open yet secured information storage and sharing platform for CE stakeholders to achieve interoperability, openness and decentralisation in the Industry 4.0 era. A study [58] noted that a blockchain leads to effective decision-making processes and supports the ability of Industry 4.0 to achieve circularity and enhance performance. By storing records on a blockchain, CE stakeholders can improve circular design and innovation due to highly secure and transparent information flows. In addition, the blockchain accelerates the shift towards Industry 4.0 by increasing the ability of firms to respond to consumer needs for transparency in terms of product durability and repairability [11]. The possibility to gather reliable and updated product data allows firms to trace and evaluate the performance and durability of their products, thereby providing more durable products with greater future value. A recent study [61] stated that under the umbrella of Industry 4.0, one could connect blockchains to IoT, radio frequency identification (RFID), and global position sensors (GPS) to collect accurate data and overcome real-time traceability issues in the CE. The authors of [59] found that the blockchain is one of the most discussed Industry 4.0 tools to enable collaboration mechanisms in circular supply chains. Finally, [60] posited that digital technologies, including blockchains and IoT, could aid firms in tracking capital, managing resource use and optimising circular infrastructure.

In summary, the studies on the relationship between the blockchain and Industry 4.0 highlight the critical role of the technology in streamlining and securing information-sharing processes amongst CE stakeholders. This leveraging of the blockchain aims to alter organisational activities whilst requiring diverse skills and capabilities. Another pending question is how to effectively integrate blockchains with other Industry 4.0 technologies to sustain CE practices. The authors of [61] identified the shortage of empirical evidence that integrates the concept of blockchains at firm-level analysis.

Studies focused on blockchains and circular economy practices

The potential of blockchains for CE practices represents an innovative and emerging topic. Whilst circular supply chain management is necessary for organisations to shift from the linear economy model to a more sustainable CE, it is still challenging to trace the reuse of materials over several life cycles involving various stakeholders [84]. However, with the adoption of the blockchain, organisations can easily manage circular supply chain complexities and monitor the entire reverse logistic processes to reuse products and return components [16]. For example, [84] argued that the fashion industry could benefit from blockchain verification and authentication to reuse end-of-life materials, maximise the use of fast-fashion products, and reduce amounts of landfill waste. In the built environment, [82] revealed that blockchains could provide complete material and energy traceability, making it possible for users to predict the quantity of goods and materials for reuse. Blockchain could facilitate the traceability of product-related information through the lifespan, enabling subsequent reuse [20]. With the support of the blockchain, the record of products and materials at each plant and their current condition could allow proactive planning for their reuse in locations wherein such components and materials are most needed [82]. Therefore, the blockchain contributes to the development of adequate reuse strategies that limit the waste of potentially useful resources and minimise the consumption of materials.

Besides allowing manufacturers to determine which materials are to be reused and disposed of, blockchains significantly improve remanufacturing [61], which is vital to realising the CE due to its advantages in terms of energy savings, material conservation and emission reduction [78]. According to [124], the blockchain substantially impacted the CE by the three proxies of green supply chain management: green design, green manufacturing, and recycling and remanufacturing. The authors of [83] noted that the IoT-based blockchain could favour customer involvement in closed-loop supply chain operations, thus minimising the customers' hesitance and reluctance toward remanufactured products. Thus, the blockchain enables customers to obtain information concerning how their products were produced and remanufactured, whether they were sustainably sourced and securely maintained, and the ownership transfers. Furthermore, blockchains could be used to store remanufacturing knowledge and its related transactions and ensure the reliability and security of knowledge exchange [78]. Therefore, blockchains can be utilised in remanufacturing operations to extend the lifetime of products and delay the unavoidable step of recycling, thereby bringing considerable resource, labour and energy savings. Engaging in blockchain-enabled remanufacturing also provides a chance to retain and recover the economic value generally lost in the conventional linear economy.

The increasing production of recyclable goods and customer buy-ins are placing a great strain on recycling industries. For this reason, [76] argued that the recycling industry must embrace novel approaches and technologies to achieve growth and advancements. In this regard, the properties of the blockchain, such as traceability, transparency, security, accountability and reliability, could support the recycling of resources [100]. Automating the sorting and collection of wasted materials and products can be efficiently carried out using the blockchain since the technology could ensure end-to-end supply chain traceability and foster collaboration amongst stakeholders, waste collectors and recyclers [76]. Moreover, blockchains could enhance recycling performance by motivating consumers to recycle through rewards in the form of cryptocurrency tokens [80]. With the help of the blockchain, manufacturers could confidently procure more recycled materials and reduce their dependence on fossil fuels since the technology provides accurate information regarding the availability, quantity and quality of recycled materials [107]. The blockchain brings increased transparency to recycling processes [76]. It paves the way to regulated recycling, in which the technology makes a difference in several aspects during recycling, including transaction confirmation, waste material tracking and process regulation in re-production [62]. As a result, by leveraging blockchains in recycling, organisations could reduce the transaction hierarchy and overcome the uncertainty of key information, including the quantity, quality and type of recycled products [98].

Overall, the attributes of blockchains could set a strong foundation for CE implementation in terms of reuse, remanufacturing and recycling [14]. With the shift to the CE, there is an increased interest in examining the potential of blockchains for other CE activities such as repair and sharing. According to [49], a blockchain secures data from the ongoing traceability of products and materials in terms of availability, location and status, which might be utilised to assist in repairing and maintaining electronic products.

Studies focused on the blockchain and energy management

Energy management represents an approach that attempts to use the under-exploited potential of energy savings, address energy efficiency issues, and support the culture of energy savings and efficiency, thereby achieving reduced energy consumption within the firm without negatively impacting quality and productivity [127]. Incorporating blockchains in energy management brings several advantages from the CE and sustainability perspectives. The blockchain provides full energy traceability, including the amount of energy consumed in production, energy sources (renewable and non-renewable) utilised throughout the product lifecycle, and the influence of energy on the environment [82]. Furthermore, blockchains could facilitate energy financing, distributed trading and renewable energy expansion [101], so the funding process can benefit from blockchains to reduce transaction costs and increase efficiency. According to [100], blockchains are one of the leading digitalisation tools in energy management due to their ability to satisfy green energy needs and act as a control mechanism. The authors further argued that blockchains could strengthen the regulation of decentralised energy systems, enable peer-to-peer energy exchange and encourage energy self-production and self-consumption. Another study indicated that the blockchain is critical to optimising power distribution systems' financial and physical operations, ensuring distributed data storage and management, and fulfilling socio-economic needs for transactive energy management [78]. Therefore, the blockchain makes energy management more transparent, flexible and self-regulated. The technology also improves energy transactions and provides adequate infrastructure for data sharing and collaboration amongst stakeholders.

Studies focused on the blockchain and waste management

Waste management [128] plays a critical role in the transition towards a CE [129], where utilising design to minimise waste [130], restoring technological materials and regenerating biological materials are the fundamental principles [131]. Therefore, effective waste management is primordial for achieving sustainability and CE targets. As an emerging technology, the blockchain represents a plausible disruptor of waste management activities thanks to its ability to improve product recyclability across production and lifecycle management [112]. Blockchains could be applied to prevent overproduction, streamline supply chain processes and establish a more transparent and efficient system that aids in tracking the waste with the increased accountability of the CE stakeholders [109]. A recent study [106] proposed the adoption of blockchains to overcome the structural and economic challenges hampering the development of distributive strategies for electronic waste (E-waste) management that reduce toxic exposures and their negative impacts on human health and environmental quality. According to the authors, the blockchain offers incentives for E-waste aggregation and recycling through its effective management practices and process integration. In addition, [107] contended that the blockchain acts as a trust-based platform between plastic waste collectors, recyclers and recycled feedstock buyers, allowing improved resource efficiency and a profitable model for the CE of plastic waste. [111] explained how blockchains could be an important digital fraud prevention technology that helps to realise sustainability objectives in e-waste management and reduce costs of third-party supervision. [113] discussed the blockchain's role and digital twins to support e-waste management strategies. Likewise, [49] explored the fusion of IoT and blockchains to help overcome the deficiencies of the existing Extended Producers' Responsibility (EPR) system by preventing waste and extending the use phase for products. [109] suggested a blockchain-based solid waste management system that can assist municipalities in improving the efficiency of their waste management initiatives. The capabilities of blockchains provide a novel collaborative environment that allows regulatory bodies, governments and firms to cooperate and achieve effective and well-organised waste management.

Studies that highlighted the impact of blockchains on sustainability

Sustainability aims to overcome socio-economic [132] and environmental concerns [133] of this and future generations [132]. The need for sustainability is generally accepted since resources are limited, and pollution creates both climate change and a dangerous environment for people and other species [134]. Besides the sustainability concept, circularity and closing loops have been debated in the literature, given the increasing environmental awareness and the urge to conserve the planet [135]. To support sustainability and the CE agenda, organisations can use blockchains to increase their process efficiencies and achieve sustainable economic, environmental and social performance. From the economic perspective, blockchain supports sustainability by significantly reducing supply chain costs and streamlining business transactions [20]. The deployment of the technology in product recovery strategies (i.e., reuse, remanufacturing, recycle) could contribute to significant cost savings and revenue generation, thereby bringing higher margins and competitive advantages [70]. According to [12], blockchains could maximise a system's efficiency and reduce development and operational costs because the technology lowers the cost of networking and product verification across the supply chain. The disintermediation capability also makes blockchains a cost-effective and efficient platform that improves the capital flow and drastically enhances the resource productivity of products, their usage, and their associated environment [79]. From the environmental perspective, blockchain traceability and ecocentricity could optimise the environmental performance of CE stakeholders [61]. As such, the blockchain records assist in monitoring the environmental sustainability of the products manufactured [125], organising the production and consumption loops [32], and promoting green manufacturing [124]. Blockchain opportunities for the environment also include changing consumers' awareness of the environmental impact of products, promoting utilisation of recycled items, minimising waste and incentivising sustainable behaviour via cryptocurrencies [118]. Therefore, the blockchain has the potential to reduce resource consumption, promote greening practices and lower the overall cost of the environmental burden.

From the social perspective, the blockchain brings about several social changes manifested in social equality, increased supply chain coordination and knowledge sharing [125]. Under its openness, the blockchain creates an inclusive ecosystem that enables all CE stakeholders to be innovative [51] and create new offerings. The authors of [12] argued that the blockchain supports the development of new business models, such as the sharing economy, which relies on collaborative consumption and peer-to-peer resource sharing. According to [125], blockchain helps to assure the customers that neither child labour nor human rights violations occur in the CE processes. As a result, through its collaborative and knowledge-sharing capabilities, the blockchain is in the position to foster social sustainability in the CE.

CONCLUSIONS

This study represents an SLR on the applications of blockchains in the CE. Seventy-nine articles dealing with the topic have been identified in the Scopus and WoS databases. The shortlisted articles have been categorised into five research themes, namely: (1) studies focused on the relationships of the blockchain and Industry 4.0, (2) studies that highlight the role of the blockchain in CE practices, (3) studies focused on the blockchain and energy management, (4) studies on the blockchain and waste management and (5) studies focused on the impact of the blockchain on sustainability. Content analysis of each research theme evaluated the current state of knowledge on blockchains adoption in the CE and also provided future research directions.

The study findings indicate that the implementation of the blockchain in the CE is still in its infancy. Blockchain has become increasingly adopted in various business and functional areas. These include supply chain management, logistics, transportation, manufacturing and marketing; however, its applications in the CE are still in an emerging phase. One can extrapolate the main findings in the five research themes to a broader level.

Concerning the first research theme, sufficient knowledge has been produced on the potential of the blockchain for implementing the Industry 4.0 vision. The blockchain reduces the barriers to achieving the objectives of Industry 4.0 in terms of security, automation and transactional efficiencies. However, existing studies have overlooked the impact of blockchains on the performance of Industry 4.0 technologies in different contexts. Therefore, it is crucial to understand how the technology acts as an enabler or barrier to the successful integration of Industry 4.0 technologies and the accomplishment of CE objectives. Another research gap is the analysis of the role of the blockchain in developing smart factories and supporting the efficient use of resources, energy, capacities and logistics routes. Potential avenues of future research also include examining the potential of the blockchain to hasten the transition from Industry 4.0 to Industry 5.0, which is intended to harmonise the working environment and efficiency of workers and machines consistently.

With the support of the blockchain, organisations can facilitate their product recovery strategies, including reuse, remanufacturing and recycling. As such, organisations can use blockchains to trace the reuse of materials and products over several life cycles involving various CE stakeholders. Through the traceability and authentication of products, remanufacturing and recycling processes would be more efficient, transparent and flexible. Whilst several studies have demonstrated the potential of the blockchain for CE practices, researchers have not investigated how blockchain-enabled repairability and maintenance can reduce the environmental impacts of products. As more stakeholders are involved in the CE, there is a need to establish sharing economy platforms based on blockchains to simplify information verification and boost CE-friendly business models such as coopetition and prosumerism. The investigation of the user's acceptance of the blockchain in collaborative consumption and the sharing economy has been neglected in previous studies. As a result, there is a need to understand the conditions and factors influencing stakeholder involvement in these emerging business models. Developing more scalable and cost-efficient blockchain solutions in CE activities is another missing point in the literature. Future research should focus on modelling blockchain adoption enablers and challenges and suggesting blockchain systems tailored to CE practices that provide customised and robust privacy and security attributes.

Several studies have demonstrated the importance of the blockchain in promoting sustainable energy consumption, stabilising energy supply, and facilitating energy trading and sharing. However, the questions of integrating smart contracts and decentralising energy management while avoiding operational, economic and security issues remain ambiguous. Studies have also been silent on ways to incentivise stakeholders to engage in blockchain-enabled energy management under the CE context. Future studies also need to empirically explore the effects of the technology on energy management practices in CE activities to promote the blockchain. The factors that enable and hamper the successful adoption of blockchains in energy management also deserve more attention from CE scholars.

Regarding waste management, the technology has proved to be a promising alternative to reduce waste, strengthen collaboration amongst the partners of the waste supply chain, and facilitate the exchange of waste and recreation of value. Even though the current studies have advanced the understanding of the blockchain's role in waste management, they failed to examine how the technology contributes to proactive and preventive waste management efforts and brings environmental benefits. Consequently, research may also provide further insights into the enablers of blockchains for successful strategies for waste management and valorisation, as well as the barriers to reducing costs and emissions during the collection, processing, transportation and disposal of waste. Investigating the blockchain's potential to add waste exchange value and foster collaboration between recyclers and waste management firms is needed.

Finally, several important findings on the impact of blockchains on sustainability have been derived. For instance, the blockchain positively influences economic sustainability by bringing about cost savings, operational efficiencies and competitive advantages. From the environmental perspective, the technology fosters greening practices, reduces resource consumption and minimises the negative impacts of business activities. From the social perspective, the blockchain is set to radically alter CE activities by enforcing social equality and boosting coordination and resource sharing amongst CE stakeholders. The blockchain is also primed to enhance social sustainability by promoting collaborative consumption and a sharing economy. Therefore, the technology paves the way to an integrative or balanced approach between social sustainability and CE principles. Despite their contributions, previous studies did not examine the impact of blockchain-enabled product-service system (PSS) business models on economic and environmental sustainability. They also fell short in clarifying the role of blockchains in anticipating economic uncertainties, controlling economic ups and downs, and ensuring economic sustainability. Therefore, research may provide further insights into the blockchain's enablers for green supply chain management practices and environmental performance. From the social sustainability perspective, one potential contribution to such an endeavour is to examine the possibilities of the blockchain to generate new public services, drive local development, and promote social cohesion and product responsibility in the CE. Examining ways to incorporate social sustainability aspects into blockchain-enabled CE business models may inform CE practitioners about the social issues that should be addressed by adopting the technology in the CE transition.

Theoretically, this study has examined the current literature on the blockchain and CE. It has also identified several research themes related to the literature and categorised existing studies based on these themes. Moreover, the study conducted a content analysis of the publications grouped in each research theme. From the theoretical perspective, this work is one of the first attempts to examine the application of the blockchain in the CE. Both concepts are emerging topics in the embryonic stage. Blockchain-based digitisation enables tracing CE resources and creates the optimal and fast transition to a more sustainable CE. Evidence is provided concerning the advantages of implementing the blockchain in the CE and its implications. Also, from the theoretical standpoint, this study has provided several future research directions, which will be very valuable for scholars who devote their efforts to blockchains and the CE.

Practitioners can use this review to identify how the blockchain can benefit CE initiatives and boost sustainability. The current contributions will allow managers to imagine novel applications in their firms to achieve competitive advantages based on the blockchain. For instance, organisations can use blockchains to lessen their carbon-intensive practices and ensure accountability for their CE activities. The study findings can guide managers on how to strategise the adoption of the blockchain in the CE to achieve operational efficiencies and meet sustainability goals. Developing capabilities to manage CE practices effectively is primordial to ensure the successful integration of the blockchain in the CE. Therefore, future studies should refer to the experiences of prior implementations of blockchains to aid managers in carrying out their adoption strategies more effectively in a controlled manner. Lastly, the recommendation to managers is they can identify the most critical factors for successful blockchain adoption in CE activities.

Concerning the limitations of the review, the Scopus and WoS databases were the only data sources consulted, and journal articles with SJR and/or JCR impact only were included.

Nevertheless, this is a minor issue as both search engines are widely known for their comprehensive coverage and high-quality content. Although the selected studies underwent a rigorous and thorough peer-review process, one can include other relevant knowledge sources such as books, chapters and conference papers in future studies to gain additional insights.

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