SURVEY

A Tertiary Review on Blockchain and Sustainability With Focus on Sustainable Development Goals

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ABSTRACT Sustainable development is crucial to securing the future of humanity. Blockchain as a disruptive technology and a driver for social change has exhibited great potential to promote sustainable practices and help organizations and governments achieve the United Nations' Sustainable Development Goals (SDGs). Existing literature reviews on blockchain and sustainability often focus only on topics related to a few SDGs. There is a need to consolidate existing results in terms of SDGs and provide a comprehensive overview of the impacts that blockchain technology may have on each SDG. This paper intends to bridge this gap, presenting a tertiary review based on 42 literature reviews, to investigate the relationship between blockchain and sustainability in light of SDGs. The method used is a consensus-based expert elicitation with thematic analysis. The findings include a novel and comprehensive mapping of impact-based interlinkage of blockchain and SDGs and a systematic overview of drivers and barriers to adopting blockchain for sustainability. The findings reveal that blockchain can have a positive impact on all 17 SDGs though some negative effects can occur and impede the achievement of certain objectives. 76 positive and 10 negative linkages between blockchain adoption and the 17 SDGs as well as 45 factors that drive or hinder blockchain adoption for the achievement of SDGs have been identified. Research gaps to overcome the barriers and enhance blockchain's positive impacts have also been identified. The findings may help managers in evaluating the applicability and tradeoffs, and policymakers in making supportive measures to facilitate sustainability using blockchain.

INDEX TERMS Blockchain, sustainability, sustainable development goals, tertiary review.

I. INTRODUCTION

Sustainability is an essential concept with many definitions and has been receiving growing attention and commitments worldwide. The triple bottom line proposed by Elkington is a widely accepted concept that assesses sustainability from economic, environmental and social dimensions [1]. Urban

The associate editor coordinating the review of this manuscript and approving it for publication was Jolanta Mizera-Pietraszko.

sustainability has four defined dimensions — it adds a governmental dimension to the above three dimensions [2].

In 1987, the United Nations' (UN's) Brundtland Commission defined sustainability as meeting "the needs of the present without compromising the ability of future generations to meet their own needs" [3, pp. 16]. In 2015, the UN 2030 Agenda for Sustainable Development established 17 Sustainable Development Goals (SDGs) and 169 targets associated with them [4] as a call to action by all countries to end poverty, fight inequality, protect the planet

and ensure peace and prosperity for all people by 2030. The UN SDGs point out a path of sustainable development and set up a framework with priorities of a global action program for the people, planet, prosperity, peace and partnership [5]. The 17 SDGs are interrelated and call for balancing the three interdependent pillars (economic growth, social inclusion and environmental protection) of sustainable development.

Information and communications technologies (ICT) have been recognized as catalysts for all the three pillars of sustainable development [6]. ICT-enabled products, processes and organizational innovations empower companies to implement their sustainable development strategies. Many sustainable development initiatives have been developed to improve sustainability by integrating emerging ICT technologies such as artificial intelligence (AI), Internet of Things (IoT), big data and blockchain. Studies also indicate that technologies such as AI and blockchain have become significant decisive elements for a company's success or failure under the COVID-19 pandemic and in making a contribution to sustainability because such technologies might enhance the resilience of supply chains and businesses against the negative consequences of future pandemics and unforeseen interruptions [7].

Blockchain is decentralized information technology building on immutable, shared and distributed ledgers to store transactions and establish trust [8]. The benefits of blockchain include decentralization without central authorities, better information traceability, data transparency and security than classical technologies. Although blockchain is a rapidly evolving technology, it drives social change in many domains, expanding from the original application domain of finance [9] to smart cities [10], supply chain and logistics [11], energy [12], smart manufacturing and industry 4.0 [13], healthcare [8], maritime transport [14] among others. According to [7], food, agriculture and healthcare sectors have most commonly utilized blockchain technology to address the COVID-19 situation.

Research is increasingly being done on the application of blockchain technology to address sustainability. A recent example is a study investigating the application of blockchain to facilitate the implementation of the UN-promoted Principles for Responsible Banking [15]. Further, literature reports on blockchain's positive and negative impacts on sustainability. An example of the positive impacts is that blockchain's traceability can help unmask unethical suppliers and counterfeit products and better ensure human rights and fair working practices [11]. On the other hand, Proof-of-Work consensus algorithms are often considered environmentally unfriendly due to their high energy consumption. Getting a complete picture of the impacts of blockchain technology and its applications on sustainability can help people take advantage of blockchain technologies and address their drawbacks. There are studies reporting on the use of blockchain for the sustainable development of specific application domains, industries or aspects, for example, [2], [12], [14], [16], [17], and [18]. However, there

is no holistic analysis of blockchain's impacts on sustainability across domains or areas, particularly regarding its effect on the achievement of *all* SDGs. In addition, several papers have pointed out that the focus of most of the existing studies was not on sustainability and that it is essential to promote research on the implications of blockchain technology on sustainable development and performance [19]. Our work attempts to bridge this gap through a comprehensive analysis of all application contexts documented in literature.

The goal of our study is to investigate *how does blockchain technology contribute to sustainable development related to different SDGs*? Besides analyzing the impacts, we also want to know the reasons behind the impacts, the factors that drive or hinder the adoption of blockchain in practice, and the research gaps into enlarging blockchain's positive impacts and limiting the negative ones.

Fig. 1 illustrates the research framework for this paper. In detail, we aim to answer the following research questions (RQs):

- RQ1: What are the positive and negative impacts on SDGs of using blockchain technology in various applications?
- RQ2: What are the key drivers and barriers to adopting blockchain technology to satisfy SDG goals? We aim to understand the drivers and barriers to blockchain adoption in the context of SDGs from system-level, intra-organizational, inter-organizational and external or societal dimensions [11].
- RQ3: What are the research gaps to facilitating sustainability when using blockchain technology?

Several reviews, for example, [2], [9], [10], [11], [12], [13], [14], [16], [17], and [18], cover this topic from different angles. Therefore, we decided to perform a tertiary review to answer our research questions [20]. A tertiary review, or a tertiary study, is "a review of secondary studies related to the same research questions" [21, pp. vii], i.e., a review of systematic literature reviews. We used thematic analysis methods [22] to extract information from existing reviews to answer our research questions. We have analyzed and consolidated information from 42 review articles, 36 of which were published since 2019. The main contributions of this study are:

- We identified 76 positive and 10 negative linkages between blockchain-based applications and *each of the 17 SDGs* through a holistic and systematic analysis of blockchain's impacts on SDGs at the *SDG target level*.
- We identified 45 factors that drive or hinder the adoption of blockchain technologies to satisfy SDGs. We classified the factors into four categories: system-level, intra-organizational, inter-organizational and external or societal. Furthermore, the drivers/barriers have been linked to the identified impacts that blockchain has on SDGs and ranked by their relative degrees of importance.
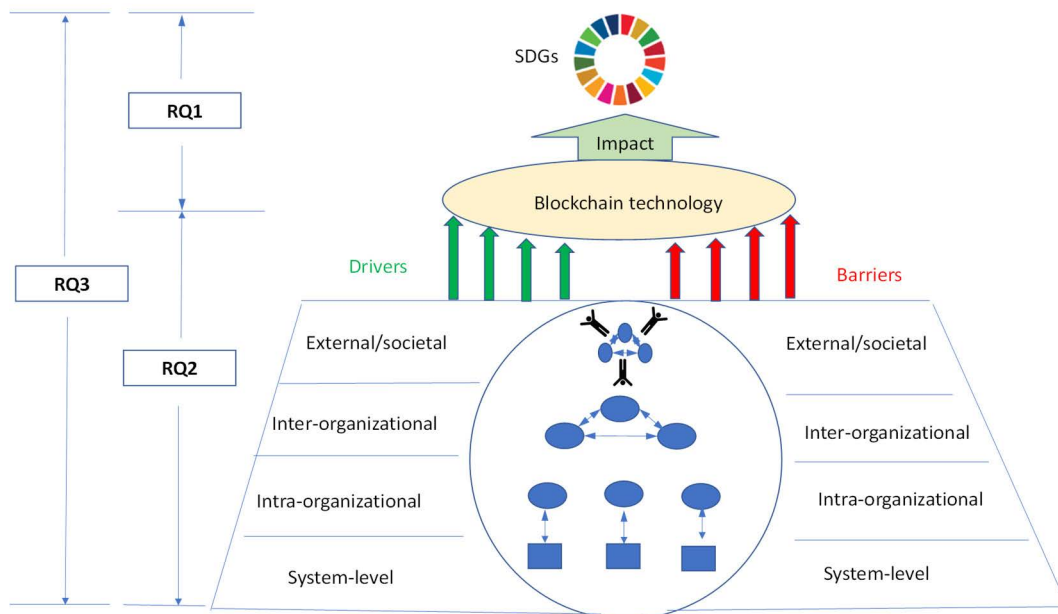
FIGURE 1. Research framework on blockchain and SDGs.

- We also recognized six research gaps and directions to motivate further development of blockchain technology to promote SDGs.

The remainder of the paper is organized as follows: Section II provides background information related to sustainability and the critical features of blockchain. Section III describes the methodology of the study. The findings of this study are presented in Section IV. Section V discusses the results. Finally, Section VI concludes the paper and proposes future work.

II. BACKGROUND

A. SUSTAINABILITY AND SUSTAINABLE DEVELOPMENT GOALS

The SDGs in the UN 2030 Agenda are meant to function as a global framework for cooperation to address economic development, social inclusion, and environmental sustainability. Achieving SDGs requires transnational multi-stakeholder collaboration that will give an imperative for stakeholders to act according to collective rationality, leading to a potential renunciation of intra- and inter-state interests for the common good. However, there is a strong doubt as to whether this is feasible, and it has proved challenging to get all parties adequately involved and anchored on the SDGs. A recent example is the United States' withdrawal, albeit temporary, from the Paris Agreement. This example showcases the imminent risk associated with political constellations, such as the replacement of administrations or individuals, resulting in a shift or even termination of interests or consensus, thus creating an inherent lack of predictability and trust.

The UN SDGs offer solid and important guidelines for various topics at governmental, organizational, technical and personal/societal levels. The SDG goals depend on each other and are indivisible. Nilsson et al. gives an example showing such interdependency: "educational efforts for girls (goal 4) in southern Africa would enhance maternal health outcomes (part of goal 3), and contribute to poverty eradication (goal 1), gender equality (goal 5) and economic growth (goal 8) locally" [23, pp. 321]. The UN 2030 Agenda has *policy coherence* as one of the SDG targets to highlight such interactions. Regarding this, [23] has proposed a seven-point scale of SDG interactions to systematically determine the influences of SDGs to help policymakers to create coherent policies and strategies that can enhance positive interactions / impacts and minimize negative ones.

B. BLOCKCHAIN TECHNOLOGY AND BLOCKCHAIN-BASED APPLICATIONS

Blockchain technology comprises a multitude of underlying technologies and protocols, which are referred to as "blockchain technology" or simply "blockchain" in this paper. A blockchain is a decentralized digital ledger that provides transparency and immutability of encrypted records or digital events. A blockchain records every transaction on a block across multiple copies of the ledger that is shared with many parties without the need of intermediaries or centralized control and where everyone has access to the data (transparency). The data is stored using a unique identifier, a cryptographically secure hash, which depends on the data stored in the last and previous blocks [24]. The hash acts as the main guarantee for data integrity in the blockchain, and "a change in a single block in the blockchain results in invalidating all the following blocks" [12, pp. 86748]. Security is enhanced by verifying transactions via multiple nodes in the blockchain through a consensus algorithm before a block is added to

the blockchains. There exist several consensus algorithms, such as Proof of Work (PoW), Proof of Stake (PoS), Proof of Authority, Practical Byzantine Fault Tolerance (PBFT), Delegated Proof of Stake, and many more [25]. Trust can then be established among parties who do not trust each other, and no external intermediary is needed to validate the data.

Blockchain can be grouped into permissioned or permissionless categories based on who can access the blockchain network. It can also be classified into public, private, and consortium blockchains based on how the permissions to write to the blockchain network are assigned [26]. There also exist hybrid blockchains with deferred and limited access to specific datasets for as long as the cryptographically selected methods are valid.

Blockchain can register, store and transfer any type of assets [9], including cryptocurrencies. Blockchain can thus be used, for example, in proof of identity and ownership as well as in protection of digital rights [2], [11], [27], [28], although it works best with small data that can easily be serialized.

Fundamental blockchain technology exhibits a few key features that can bring significant benefits:

- *Decentralization* – Blockchain is a peer-to-peer distributed system that allows the participation of all parties and their access to data without the need of central authorities or intermediaries (no supervision), which provides robustness, resilience (no single point of failure), trustworthiness and durability [29].
- *Consensus mechanism* – Blockchain allows for self-organization and provides coordination mechanisms.
- *Data integrity* – The hash values in the blocks make it easy to identify a data compromise.
- *Privacy mechanisms* – Blockchain provides pseudonymity for privacy preservation.
- *Smart contract and autonomy* – Smart contracts can execute a predefined logic automatically when the terms on the contract are fulfilled. Blockchain smart contracts can be executed without a trusted third party. Blockchain has advantages such as "transparency, accuracy, speed, security, efficiency, and trust" [30, pp. 15].
- *Data transparency, accountability and traceability support* – Stored data cannot be altered. Blockchain provides a complete history of transactions, allowing data to be shared/exchanged securely and in a trustworthy manner in a low-trust environment without a third party's supervision or intermediation.
- *Cryptocurrency and social currency* – Blockchain provides incentive mechanisms and financial innovations.

Blockchains can be divided into three theoretical stages: Blockchain 1.0, 2.0 and 3.0 [31]. This evolution of blockchain denotes the technological transition from the simple described ledgers into applications outside Fintech.

- Blockchain 1.0 started with the release of bitcoin and its functionality as an asset. The main applications were cryptocurrencies and associated payment systems.
- Blockchain 2.0 became a term used to show the core technology as a programmable trust infrastructure

supporting functionalities such as smart contracts, decentralized applications and decentralized autonomous organizations (DAOs).

- Blockchain 3.0 denotes the current trend where blockchain applications are replacing existing technologies and optimizing the core technology itself, with emphasis on the consensus protocol in sensitive applications. The blockchain applications extend to domains outside Fintech, such as supply chain management, health, energy, government, science and art.

More technical details on blockchain technology are out of the scope of this paper, but interested readers can refer to literature, such as [32], [33], and [34].

III. RESEARCH METHODOLOGY

We followed the tertiary review guidelines described in [21] for our study. Fig. 2 shows the process used for identifying and selecting the papers included in the survey. We scanned the Scopus and Web of Science databases using the search terms "blockchain" AND "sustainability OR sustainable" (see the search criteria in the database search boxes in Figure 2). We included only journal papers and (systematic) reviews written in English. We did not limit the period of the search, and all publications by end of July, 2022 were included. Furthermore, for a paper to be included, it had to address the use of blockchain technologies for sustainability; a paper was excluded if full paper access was not available, or the paper was solely about blockchain technology.

One hundred and twenty-one papers from Scopus and 92 papers from the Web of Science published between 2017 and July 2022 were returned after the search, and, of these, 159 were kept after removal of duplicate records. After abstract screening, 78 papers were included for full-text assessment. Thirty-eight out of the 78 papers were found to be relevant to our research questions. Four more papers were identified using backward snowballing from the 38 papers. Finally, 42 papers were included in the qualitative synthesis.

Afterwards, we followed the thematic analysis methodology [22] and used a qualitative analysis tool "Dedoose"0F[1] to code the papers. The codes were analyzed and synthesized in an iterative process. Three authors with different backgrounds and expertise, ranging from software engineering, sociology and engineering, were involved and conducted a *consensus-based expert elicitation* process for the analysis, as documented by previous studies on SDGs [35], [36], [37]. Each selected paper was reviewed by one of the authors and coded with regard to the RQs. At least one other author validated the result of each paper. We had consensus meetings when discrepancies arose.

To answer RQ1, we extracted documented blockchain impacts on sustainability (as codes in Dedoose) and mapped them to concrete SDGs at the target level. We considered it acceptable evidence when there was a documented use case, implementation, or proposal on potential impacts on

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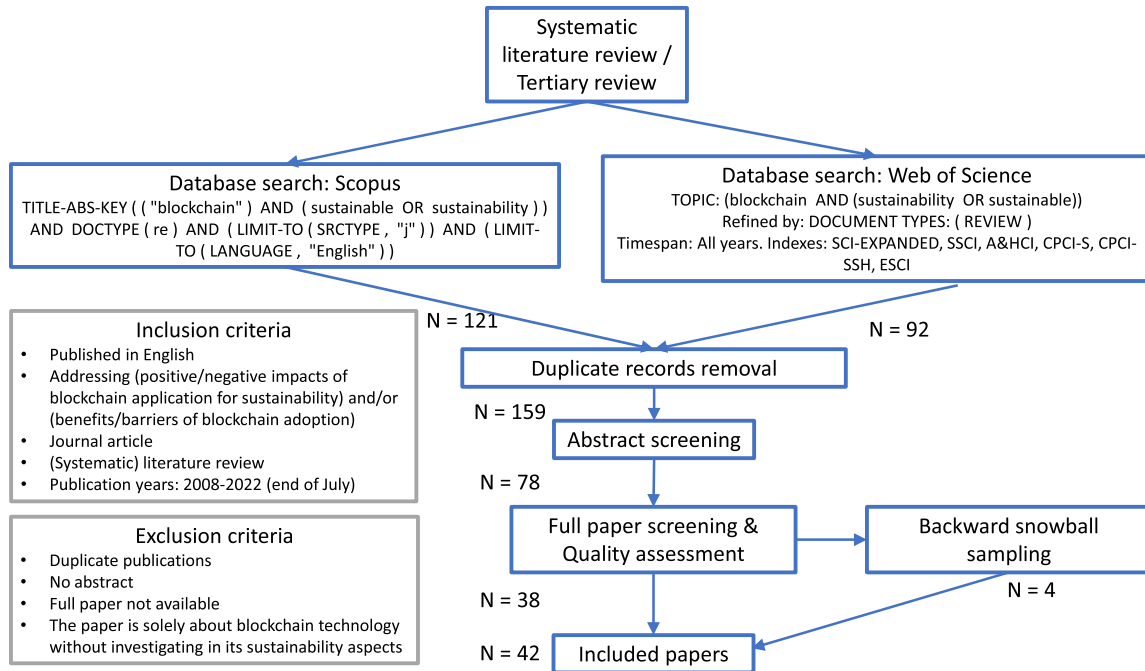[1]The Dedoose tool, see: https://www.dedoose.com/

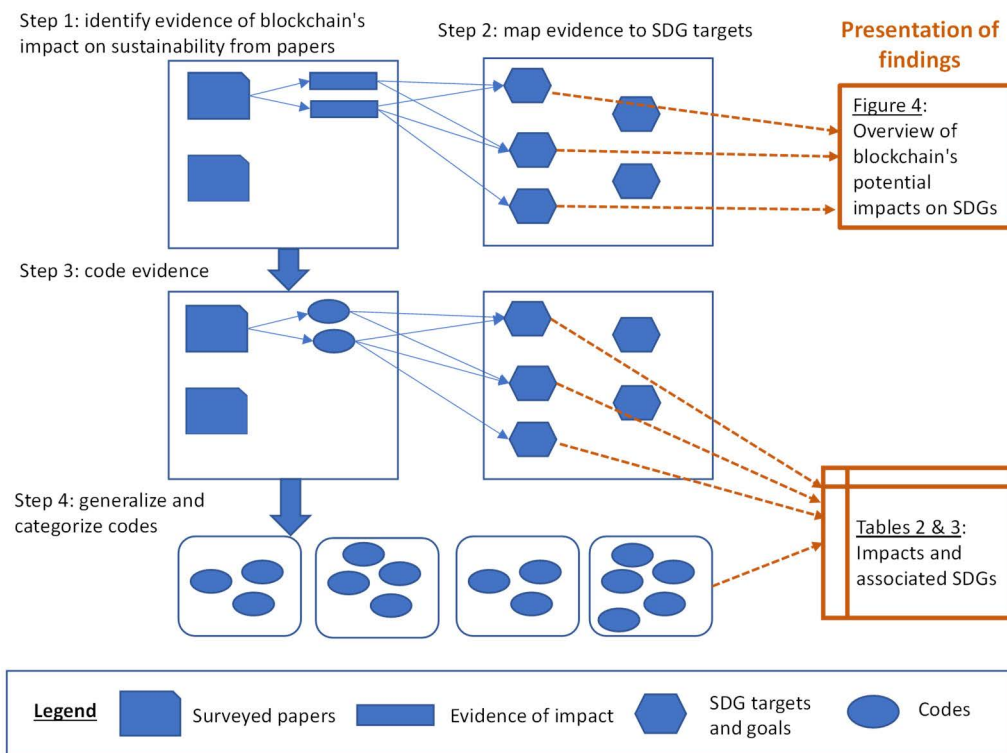**FIGURE 2.** Process for identification of relevant papers.

FIGURE 3. Data analysis process for RQ1.

sustainability from the surveyed papers. As shown in Fig. 3, we first identified evidence of blockchain's impact on sustainability from survey papers and mapped the evidence to SDG targets based on SDG descriptions. The results are shown in Fig. 4. We then associated the evidence with codes

by either selecting a suitable code from the existing codes established through analysis of other papers or creating a new code. This resulted in more than 130 codes referring to potential impacts on SDGs. After that, we generalized or merged codes by analyzing their similarities and differences

FIGURE 4. Overview of blockchain's potential impacts on SDGs based on the reviewed papers.

following the thematic analysis guideline [22]. This resulted in 29 high-level codes on impacts, which have been further divided into economic, environmental, social, governmental, legal and regulatory categories. The high-level codes and their categories are summarized in Table 2 and Table 3. As an example, blockchain's transparency and traceability contributes to the mitigation of Illegal, Unreported and Unregulated (IUU) fishing as illustrated in the Provenance case described in [38]. This evidence was mapped to SDG targets 14.1–14.5 and associated with the code "Potential to end unethical and illegal practices, e.g., slavery and IUU fishing". This code was merged under "(So.5) Fraud and corruption prevention" belonging to the "social impact" category.

To answer RQ2, we identified and extracted drivers and barriers from the descriptions in the papers. Drivers and barriers are factors that motivate or hinder the adoption of blockchain for sustainable development. They are often two sides of the same coin. For example, blockchain is a driver when it is used to solve specific domain challenges or needs. Blockchain's key features are also considered technical drivers. In some cases, we extracted barriers from the challenges, threats and weaknesses listed in a paper and extracted drivers from benefits, strengths and opportunities in the *Strengths, Weaknesses, Opportunities and Threats* analysis (e.g., [39]). The coding refinement process is similar to RQ1.

To answer RQ3, we used a thematic analysis and summarized research gaps and challenges proposed in the surveyed papers.

TABLE 1. Overview of the reviewed papers and their topics.

Topics	Paper	Number of papers
Application domain		
Supply chain and logistics	[11], [16], [24], [30], [38], [40],[41][2], [42], [43], [44], [45], [46], [47][3], [48][4], [49], [50], [51]	17
Energy	[12], [39]	2
Smart cities	[2], [10], [27], [52], [53]	5
Manufacturing and industry 4.0	[13], [17]–[19], [54]	5
Transportation	[14], [29]	2
Finance /bitcoin	[9], [55]	2
Smart villages	[56]	1
Forestry	[57]	1
Cross-domain themes		
Traceability	[41], [48], [58], [59][5]	4
Circular economy	[47], [59], [60]	3
Standards	[61]	1
Law and policy	[62]	1
Research topics	[8]	1
Fairness	[63]	1

IV. RESULTS AND FINDINGS

The papers analyzed focus on summarizing blockchain and sustainability in different application domains. The main

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[2]This paper addressed agri-food traceability; therefore, we placed it under both "supply chain and logistics" and "traceability".

[3]This paper discussed food supply chain under the circular economy context; therefore, we placed it under both "supply chain and logistics" and "circular economy".

[4]This paper addressed supply chain traceability, therefore, we placed it under both "supply chain and logistics" and "traceability".

[5]This paper addressed blockchain for traceability and circular economy; therefore, we placed it under both "traceability" and "circular economy".

application domains the papers focused on are shown in Table 1. Seventeen out of the 42 papers focus on the supply chain and logistics. Five papers are about manufacturing and industry 4.0. Five papers are on smart cities, covering several sub-domains, such as energy, transport, health, and waste management. In addition, energy, transportation and finance (including Bitcoin) domains each has two papers. Smart villages and forestry each has one paper. A few of our analyzed papers focus on a particular theme. Four papers focus on studying the traceability aspect of blockchain while three papers discuss blockchain from the circular economy perspective. The other themes studied by one paper include standards, law and policy, fairness, and research topics. Four of the 42 papers addressed two topics in Table 1.

All the papers were published in journals. Eight of the studied papers were published in 2022, 7 published in 2021, 11 published in 2020, 10 published in 2019, 4 published in 2018 and 2 published in 2017. The rapid increase in the number of surveys in recent years shows a growing interest in blockchain and sustainability. Table 6 in the Appendix summarizes the included papers.

A. THE RESULTS OF RQ1

Blockchain's potential impacts on SDGs are summarized in Fig. 4, where the numbers in the boxes represent the targets of the SDG. "G" in a box represents the SDG in general. The green box indicates a positive impact on a specific target of the SDG or the SDG in general, while the red box indicates a negative impact. A white box indicates that no impact (either positive or negative) has been identified from the reviewed papers. The results show that blockchain has positive impacts on all 17 SDGs, with direct impacts on 76 SDG targets while negative impacts are experienced in 10 SDG targets of 8 SDGs3F.[6] The impacts are summarized in Table 2 and Table 3. A complete list of papers that show blockchain's impact on SDGs is given in Table 4 and Table 5 in the Appendix.

1) POSITIVE IMPACTS ON SDGS

Blockchain's positive impact on sustainability can be classified into many codes, 24 categories, and 5 high-level themes: economic, environmental, social, governmental, and legal and regulatory, as shown in Table 2.

Below, the blockchain's impact for each SDG is presented in detail with concrete examples.

a: SDG 1 – NO POVERTY

This SDG "*calls for an end to poverty in all its manifestations by 2030*" [64]. To explain SDGs and put the discussion in context, as with this SDG, each subsection later starts with an introductory paragraph on the specific SDG based on the definitions from the online SDG explorer [64].

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[6]We counted only the specific targets with direct impacts. If blockchain only impacts an SDG in general (i.e., "G" boxes in Figure 4), it is not included when counting.

TABLE 2. Thematic overview of blockchain's positive impacts on sustainability[7].

Category	Codes of the positive impacts on sustainability	SDGs (SDG targets)
Economic impact (Ec)	**(Ec.1) Cost reduction** for companies and institutions[14], [16]: elimination of paper records [14]; automated supply chain certification processes [38], [48]; reduced regulatory compliance and verification costs [38], [49]; cost reduction and improved efficiency due to the removal of intermediaries from the market [14], [57].	8 (8.2)
	(Ec.2) Increased dependability of systems and processes and reputation enhancement [11]: enforcement of service level agreement between participants [13]; product quality ensured by data integrity and traceability [13], [19]; fraud prevention in trade [38]; improved food safety [42]; higher resilience [17]; cyber resiliency [18]; proof of sustainable practices [38]; provenance of products and ingredients/components [38]; transparency and visibility of data provenance [11], [50], [53].	2 (2.4), 9 (9.2), 12 (12.6, 12.8)
	(Ec.3) Improved efficiency [42]: traceability and recall efficiency [24], [49]; process efficiency, for example, in sustainable supply chain management [16], smart manufacturing [17], water management [27]; efficient resource allocation and use [38], [50]; reduced transaction delays [14]; increased efficiency in trade contracts and harmonization of conflicting objectives [14]; improve energy efficiency [10].	6 (6.4), 7 (7.3), 8 (8.1, 8.2, 8.4), 9 (9.4, 9.5)
	(Ec.4) Industrial sustainability: enabling secure and reliable manufacturing systems with automated workflows and efficient operations [10], [19].	9 (9.1, 9.2, 9.4)
	(Ec.5) New and inclusive financial services, financial inclusion of SMEs: for example, microfinance or remittance for rural farmers [55]; smart contract-based financial loan management facilitating inclusion of SMEs [54].	1 (1.4), 2 (2.3), 8 (8.3, 8.10), 9 (9.3), 10 (10.2), 17 (17.3)
	(Ec.6) New businesses models: support of sharing economy and circular economy [2], [11], [53], [59]; boosting the local economy, for example, based on recovered solid waste [2]; extended revenue streams and financing modes [17].	7 (7.1, 7.2), 12 (12.5)
Environmental impact (Ev)	**(Ev.1) Improved measurability and awareness of the environmental impact and enhanced capacities for climate actions**: for example, tracking carbon footprints and environmental impacts [27], [50]; facilitating impact assessment and evaluation [27], [38], [48], [53], [59].	11 (11.6), 12 (12.8), 13 (13.2, 13.3)
	(Ev.2) Improved monitoring and protection of sustainable use of natural resources and ecosystems, for example, monitoring terrestrial [24], [54], [57] and oceanic ecosystems [16], [38].	2 (2.3), 13, 14 (14.1–14.5), 15 (15.1–15.7)
	(Ev.3) Improved resource efficiency and waste reduction: recycling and management [11]; circular economy enabler [17], [59], [60]; reduced food waste [41], [42], [50].	2 (2.1, 2.3, 2.4), 8 (8.4), 11 (11.6), 12 (12.2-12.5), 13
	(Ev.4) Reduction of pollution and environmental degradation: energy saving as a result of faster tracking and reduced paperwork [14]; fossil fuel usage and emission reduction due to improved and efficient planning [14], [19].	11 (11.2, 11.6), 13 (13.1-13.3)
Social impact	**(So.1) A secure and trustworthy infrastructure:** secure systems for healthcare [2], energy [12], transport [29], supply chain and value chain	3 (3.8), 7 (7.2, 7.3), 9 (9.4),

TABLE 2. *(Continued.)* Thematic overview of blockchain's positive impacts on sustainability[7].

	management [11], [16], manufacturing [13], [17] and sustainable building development [52], [53].	11 (11.2), 16 (16.6)
	(So.2) A tool for fighting poverty [55]: social currency [55]; assistance in humanitarian aid [12]; fairer distribution of value [2], [63].	1 (1.1, 1.3, 1.4), 2 (2.1)
	(So.3) Awareness-raising and promotion of transition to sustainable practices: improved awareness of environmental impacts [2], [60]; engaging and motivating users/the public [16], [29], [50], [57], [60].	4 (4.7), 11 (11.6), 12 (12.8), 13 (13.3)
	(So.4) Enhanced trust and collaboration [14]: enhanced multi-stakeholder partnerships [42], [51]; enhanced collaboration for autonomous agents [2]; enhanced trust in a low-trust environment [29], [48]; improved interchain coordination of IT outsourcing [45].	16 (16.6), 17 (17.16, 17.17)
	(So.5) Fraud and corruption prevention: monitoring and ensuring human rights, fair trade and fair working practices [14], [19], [49]; potential to end unethical and illegal practices, such as, slavery and Illegal, Unreported and Un-regulated (IUU) fishing [16], [38] and illegal logging [57]; monitoring and overseeing sustainable conditions and regulatory policies [14], [48]; implementing and managing corrective activities [61]; ensuring fair pricing [54], [63].	1 (1.4), 2 (2.3), 7 (7.1, 7.2), 8 (8.5, 8.7, 8.8), 11 (11.1), 14 (14.1, 14.4), 15 (15.7), 16 (16.1–16.5), 17 (17.10–17.12)
	(So.6) Improved access to affordable and reliable resources: facilitating secure, reliable and efficient energy trading in energy systems [12], [27]; improving access to affordable and reliable water resources [2], [27].	6 (6.4), 7 (7.1)
	(So.7) Improved product safety, quality and traceability: ensuring product (food, drink, drug, wood, etc.,) provenance and quality [19], [29], [38], [48], [49], [56], [59], [63]; anti-counterfeiting [38], [48], [50], [51]; traceability for sustainable agriculture [42], [56] and a sustainable supply chain (medical, food, agri-food, etc.) [46], [48], [50], [51], [56]–[58].	2 (2.3, 2.4), 3 (3.5), 6 (6.3, 6.5), 9 (9.4), 11 (11.6), 12 (12.4, 12.5), 15 (15.1-15.7)
	(So.8) Improved road traffic safety and sustainability [2], [18], [29]: improved road traffic safety; reduced congestion; reduced energy consumption and pollution.	3 (3.6), 11 (11.2, 11.6), 13
	(So.9) Improved social inclusion and equality [61], [63]: inclusions of low-income, marginalized or restricted-market groups.	5, 8 (8.2, 8.5, 8.7, 8.8, 8.10) 10 (10.2, 10.5,10.6, 10.7)
Governmental impact (Go)	**(Go.1) Collaborative urban/participatory decision-making** [2]: facilitating citizen engagement and democratization.	16 (16.6, 16.7, 16.9, 16.10)
	(Go.2) Smart administration and governance [2], [10]: enhanced e-voting, e-residency, taxation, government document sharing, etc.	16 (16.4–16.7, 16.9, 16.10)
Legal and regulatory	**(Lr.1) Automatic compliance to regulatory and standards requirements:** automatic verification and enforcement of compliance to regulations with auditable data and smart contracts [14], [38], [48]–[51].	3 (3.3, 3.5, 3.9)
	(Lr.2) Catalyzing development of policy and	17

TABLE 2. *(Continued.)* Thematic overview of blockchain's positive impacts on sustainability[7].

	regulations [42]: facilitated determination and shaping of rules and governance norms at various levels (transport, logistics and supply chains) [14].	(17.14)
	(Lr.3) Proof of ownership and intellectual properties and digital rights management [2]: avoidance of double registration of properties [27]; immutable and auditable certificates of learning achievements [10].	4, 9 (9.5), 11 (11.1)

Blockchain contributes to SDG 1 through indirect impacts, such as preventing fraud and corruption in distributing food (So.5[8]). Blockchain technology holds potential for mitigating corruption and can ''break down the barriers that have impeded previous attempts to end poverty'' [61, pp. 235]. For example, a UN humanitarian aid project distributed food in rural areas of Pakistan, utilizing blockchain to register funds and all types of transactions to assure transparency and security in the process [12]. Another example is the application of blockchain in the delivery of food vouchers to Syrian refugees [40], [65].

Cryptocurrency and blockchain's decentralization feature aid in the fight against poverty (So.2) [65] claims that a blockchain-based social currency may contribute to SDG 1. An example from Cyprus where people began converting money in their bank accounts to Bitcoin when the government planned to seize cash in the country's bank accounts has been proclaimed to show the potential of using cryptocurrencies as a potential tool to fight poverty [55].

Blockchain can address power imbalance and allow for a fairer value distribution of the supply chain (So.2, So.5). The Bext360 coffee project deployed blockchain to address poverty and secure fairer and faster payment to smallholder farmers [40]. Reference [39] gives an example of favorable policy support compliant with the poverty alleviation strategy, which encourages the development of blockchain-based distributed photovoltaic (PV) projects, allowing PV owners to sell energy through secure trading platforms and ensure a steady income.

b: SDG 2 – ZERO HUNGER

The aim of this goal is ''*to end hunger and all forms of malnutrition by 2030''*; and further, to achieve *''universal access to safe, nutritious and sufficient food throughout the year''* [64].

Blockchain leads to reduced food waste (Ev.3, Ec.2). An untargeted food recall is the main cause of food waste [42]. Blockchain-based traceability can improve recall efficiency and significantly reduce food waste and loss. It is an efficient tool to meet consumers' concerns about the origin of

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[7]We give only one or two reference papers for each code in this overview table. For details, please refer to the description in Section IV.A.1.

[8]The number here and in the following subsections refers to the code number in Table 2.

their food and drinks and improve traceability and integrity in global food supply chains. Tracking food products can also help in the fight against fraud and counterfeiting of products, ensure food quality and reduce food recall and waste [38], [41], [42], [44], [46], [47], [48], [56], [58], which contributes to secure access to safe, nutritious and sufficient food (SDG target 2.1). Several use cases related to traceability in the food supply chain have been analyzed in [38], for example, Alibaba ("Food trust framework" in global food supply chains), Walmart (tracking of Chinese pork and U.S. mango), Intel (seafood supply chain) and Bext360 (coffee supply chain).

Blockchain facilitates sustainable agriculture (So.7). Blockchain technology combined with IoT and big data analysis can improve crop or food production and encourage food producers to pursue sustainable practices in agriculture (SDG targets 2.3 and 2.4) [56]. Reference [54] recommends using blockchain and smart contracts in the plantation, in harvesting and in the milling process in the palm oil industry, for instance, using blockchain to enhance product traceability across the supply chain and using smart contracts to decide the premium price of products with good quality. Belagricola tracks grains and ensures their quality with the help of IoT and smart contracts, where warnings can be sent via a smart contract to prevent further damage when abnormal conditions are detected by IoT sensors [42]. References [56] and [66] have analyzed blockchain's main applications in the agri-food value chain, namely, in traceability, manufacturing, information security and sustainable water management (e.g., water trading for smart irrigation and water control systems for sustainable irrigation); and outlined blockchain's potential and implications for performance improvements in the agri-food value chain, for example, regarding food safety, quality and traceability.

c: SDG 3 – GOOD HEALTH AND WELL-BEING

This third SDG aims to "*ensure health and well-being for all, at every stage of life*" [64].

Blockchain supports secure and trustworthy infrastructure for healthcare applications (So.1). This impact is brought about by blockchain's ability to ensure the transparency of medical data and improve trust in transactions in the medical value chain. A good number of applications, such as [2], [10], [29], [38], [56], and [65], in the healthcare domain (contribute to SDG target 3.8) are related to this factor. Blockchain can significantly reduce the development cost for new drugs and diagnostic tools due to improved transparency and trust [2]. Example use cases include medical data-sharing among cloud service providers using blockchain-enhanced data security [55], medical data access control associated with tracking sensitive data and enhanced security utilizing the immutability and autonomy of blockchain and improving clinical trial processes with security mechanisms to avoid unauthorized manipulation [2].

Blockchain leads to automatic medical regulatory and standards compliance (Lr.1, So.7). IoT-integrated

blockchain traceability can be used to monitor and track conditions (including pollution) in the food and medical product supply chain while smart contracts can automatically verify and enforce compliance to quality control and regulatory requirements [46]. These capabilities contribute to several targets in SDG 3, including SDG targets 3.3, 3.5 and 3.9. Examples include the Chronicled, Modum and Gemalto use cases illustrated in [38]. A blockchain-enabled system focused on real-time tracking of cannabis plants from production to destination to prevent their diversion to illegal markets [2] is an example that touches on SDG 3.5 (drug abuse).

Blockchain can create transparent, interoperable and connective networks, which could make COVID-19 "a compelling case for the wider integration of blockchain", according to the World Economic Forum (WEF) [67, pp. 1]. For example, Spanish researchers piloted using a blockchain App to monitor the pandemic outbreak and support health officials in making smart decisions [10], [68]. Blockchain also facilitates systems in improving municipal health indices, reducing garbage deposited in a municipal landfill, and potentially reducing diseases [65] (impacts on SDG targets 3.3 and 3.9). Furthermore, blockchain-empowered origin tracking and traceability in the food supply chain can ensure food safety and address the challenge of foodborne outbreaks for retailers [44], [49].

d: SDG 4 – QUALITY EDUCATION

This SDG aims to "*ensure inclusive and equitable quality education and promote lifelong learning opportunities for all*" [64].

Blockchain provides immutable and auditable certificates of learning achievements (Lr.3). Blockchain ensures secure and tamper-proof storage of educational data and documents and facilitates secure and privacy-preserving sharing and verification of learning achievements. Various applications of blockchain-based systems for education and learning have been proposed, for example, [2], [10], and [56], to keep an immutable and secure record of the educational process, including data-sharing and storage, verification of student records, and accreditation. The purpose is to improve digital platforms for decentralized learning and in particular, those related to life-long volunteering in personal development (the so-called volunteer services [2]), protect copyrights and digital rights, maintain the trustworthiness of educational certificates and intellectual rights and mitigate fraud and establish a scholarly reputation.

Blockchain improves awareness and transition to sustainable practices (So.3). Regarding SDG target 4.7, an example is an application [65] which utilized blockchain to create awareness among young people and children about ecologically correct behavior and encourage recycling solid domestic wastes by motivating and training people.

e: SDG 5 – GENDER EQUALITY

This fifth SDG aims to "*achieve gender equality and empower all women and girls*" [64].

Blockchain contributes to inclusion and equality (So.9). The literature studied did not provide examples and use cases directly related to this SDG. However, the blockchain implementation could influence or catalyze democratization processes besides promoting transparency and accountability in institutions and amongst stakeholders. Blockchain can verify and authenticate human identity, provenance and transactions and offer transparency and accountability, contributing to breaking down the barriers to reduce inequality [61], thus having potential positive impacts on gender equality.

f: SDG 6 – CLEAN WATER AND SANITATION
This SDG aims to "*ensure the availability and sustainable management of water and sanitation for all*" [64]. This domain is said to be at "*the very core of sustainable development*" because access to clean water is critical to the survival of people and the planet in general [64].

Blockchain improves access to affordable and reliable water resources (So.6, So.7, Ec.3). Combined with IoT, blockchain's ability to improve the monitoring and tracking of products and processes also applies to water quality and consumption. Regarding SDG targets 6.3, 6.4 and 6.5, blockchain can be used to monitor water quality and consumption, and regulate water usage for different areas, with benefits like enhanced security and transparency, reduced operational cost and overall efficiency [27], [46], [56], [69]. A blockchain-based gaming platform for water consumption efficiency was mentioned in [2], where blockchain mechanisms were utilized to engage users and ensure correctness and privacy-preservation in water consumption reporting.

g: SDG 7 – AFFORDABLE AND CLEAN ENERGY
This SDG aims to "*ensure access to affordable, reliable, sustainable, and modern energy for all*" [64].

Blockchain provides a secure and trustworthy infrastructure for energy systems (So.1). Energy is a domain where many blockchain-based use cases and systems have been proposed and implemented [2], [10], [12], [27], [29], [39], [54]. Blockchain technology can overcome the obstacles that have hindered previous attempts to deliver sustainable energy. Reference [12] proposed a blockchain applications framework in smart grid security and data protection with blockchain as a cyber-layer, illustrated blockchain-based microgrid automation and analyzed blockchain's readiness in the smart grid. As real-life examples, the paper also listed corporations that play the role of retail energy intermediaries and exploit blockchain to become more affordable and competitive. Blockchain has been adopted as a countermeasure to cyber-physical attacks, enhancing the power grid's security, privacy and robustness [12]. Blockchain also guarantees smart meter readings' transparency and data security in Smart Energy Grids [2], [27].

Blockchain improves access to affordable and reliable energy resources (So.6). Regarding SDG target 7.1 (access to affordable and reliable energy services), blockchain has been used to facilitate and enhance energy services and new business models, such as peer-to-peer (P2P) energy trading, electric vehicle (EV) applications, grid security applications, microgrid operations, and control applications [12], [56]. The increasing installation of distributed energy systems (such as rooftop solar photovoltaic (PV) panels, micro-wind or hydro generation systems) leads to the increase of microgrids and the emergence of prosumers, who produce and consume electrical energy in a local area. Microgrids increase the utilization of local energy generation, as they can reduce energy loss and thus improve energy efficiency. Microgrids are considered more resilient than traditional centralized power plants and are also referred to as citizens' utilities due to the energy generation and distribution at citizen level [12], [55].

Blockchain enables new energy business models (Ec.6, So.5). Blockchain plays a significant role in energy trading, for example, for prosumers, energy storage systems and EVs. It also supports new business models on P2P energy trading transactions [2], [12], [27], [56]. Regarding SDG target 7.2 (increasing the share of renewable energy), blockchain supports secure, reliable and efficient energy trading of distributed renewable energy (e.g., PV, wind and hydro) based on P2P decentralized architecture, smart contract and automatic negotiation, verifiability and traceability. Two papers have analyzed the role of blockchain in improving the competitiveness and sustainability of distributed PV [39] and palm oil industries [54]. Replacing fossil diesel with palm-derived biodiesel can effectively reduce CO_2 emissions and alleviate fossil fuel dependency [54]. Blockchain can be used by multiple stakeholders to make the palm oil industry sustainable by utilizing blockchain's features related to traceability, cybersecurity and smart contracts for fair pricing.

Blockchain enables improved energy efficiency (Ec.3). Regarding SDG target 7.3 (improving energy efficiency), blockchain offers transparency and real-time information and improved traceability, enabling reliable real-time data analysis of energy transactions and strengthening energy resource planning and management [10], [27].

h: SDG 8 – DECENT WORK AND ECONOMIC GROWTH
This SDG aims to "*promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all*" [64].

Blockchain improves efficiency and reduces cost (Ec.1, Ec.3). Blockchain has been used to ensure security, privacy-preservation and transparency in real-time information-sharing and to reduce information asymmetry between stakeholders [14], [16], [18]. Transparency, visibility and real-time information can enable efficient resource-allocation and improved decision-making. Disintermediation and smart contracts can automate business processes and improve process and operational efficiency. Together, they contribute to cost-reduction related to, for example, execution of payments, automatic change of goods ownership in the supply chain, execution of energy-trading transactions as well as processes in smart manufacturing related to "searching, negotiation, transaction, and tracing, and carrying out

integration'' [17, p. 3]. Blockchain enables fine granular traceability, reducing recall costs significantly [24], [29]. Furthermore, it can automate supply chain certification processes and reduce regulatory compliance costs [29], [38]. Automation eliminates paper records, saving time and cost. Blockchain can enhance coordination and improve efficiency in supply chains. [14] has detailed the benefits of blockchain adoption, which, among others, include enhanced job performance, reduced rework and recall, reduced transaction delay, increased efficiency in trade contracts and harmonization of conflicting objectives.

Blockchain enables inclusive financial services (Ec.5). Blockchain has created new jobs and business models, for example, within supply chain finance domains [16] and has also extended revenue streams [17]. Blockchain has been exploited to enable new business models and new services, for example, P2P models in P2P lending, leasing and financing, P2P energy trading as well as connected vehicle services and other new types of business models for the automotive industry [2], [18], [56]. Furthermore, blockchain's inherent features promote a collaboration-based sharing economy and provide even value distribution [16]. For example, blockchain presents a secure and transparent infrastructure for a social production model where the created value and rewards are distributed fairly among the contributors through a cryptocurrency-based economy [2]. All the above contribute to industry competitiveness, economic productivity and growth as well as resource efficiency, impacting SDG targets 8.1–8.4.

Blockchain's decentralization and cryptocurrency leads to financial inclusion (Ec.5, So.9). Blockchain allows for re-balancing of power and fairer value distribution, enabling innovations in financial services and contributing to financial inclusion. This has positive impacts on several SDG targets which address financial inclusion from various aspects: 1.4 (equal rights to economic resources and financial services), 2.3 (small-scale food producers' access to financial services), 8.3 (encourages SMEs' growth through access to financial services), 8.10 (inclusive access to banking, insurance and financial services), 9.3 (increased small-scale industrial enterprises' access to financial services), and 10.2 (economic inclusion of all). As the same examples and use cases can illustrate blockchain's impacts on these differing targets, we present them together in the following paragraph to avoid repetition.

The original applications of blockchain and cryptocurrency were in the finance and banking sector. However, the applications have been extended to other sectors where blockchain is used to enhance e-commerce platforms and ownership management systems [2]. Using blockchain technology to support cryptocurrencies is instrumental in facilitating the adoption of microfinance or remittances for rural smallholder farmers and their families as transaction costs can be reduced by eliminating intermediaries [55], [56]. Notably, blockchain-based financial service platforms are beneficial to SMEs, which generally have difficulty raising funds. Examples of

such platforms include Chained Finance and IBM's financial services platform for supply chains [40]. Reference [65] described an example of a blockchain-enabled system that offered additional earnings to low-income families and boosted the local economy via green money circulation. Blockchain's decentralized network, consensus mechanism and data integrity allow everyone to generate content, participate in the entire product lifecycle and collaborate efficiently, promoting the inclusion of SMEs and consumers in matters such as collaborative product design and open and social manufacturing [17]. Smart contracts have been piloted in financial transactions and settlements, such as the digital wallet blockchain initiative for automated payment in EV charging and automatic payment for the transfer of cargo ownership in supply chain management [40]. Smart contracts have been applied to financial loan management to process loans or subsidies among SMEs or people in rural areas [56], for example, lower interest rates are given to companies committed to fulfilling the CSPO standard based on the CSPO certification status [54].

Blockchain ensures human rights and fair working conditions and reduces unethical and illegal practices (So.5). This impacts SDG targets 8.5, 8.7 and 8.8, for example, through monitoring and tracking sustainable conditions and implementing or managing suitable corrective activities [14], [19], [30], [38], [46], [61]. Blockchain is a tool for verifying sustainability with meaningful and quantifiable indicators [16]. Blockchain-empowered traceability can monitor and verify working conditions and practices, such as child labor, modern slavery in industry, and other discrimination or inequality related conditions. Therefore, blockchain can secure human rights, fair working practices and fair trade and potentially stop unethical and illegal practices. This also contributes to reducing inequality and eliminating discrimination.

i: SDG 9 – INDUSTRY, INNOVATION AND INFRASTRUCTURE
This SDG aims to ''*build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation*'' [64].

Blockchain leads to industrial sustainability (Ec.4, Ec.2, Ec.3, So.1, So.7). Blockchain's impact on SDG target 9.2 (inclusive and sustainable industrialization) comes through enabling secure and reliable manufacturing systems with automated workflows and efficient operations [10]. Smart and sustainable manufacturing is based on the industrial IoT that utilizes ad-hoc connections of numerous sensors and connected devices to monitor and track product life cycle and automate workflows. Blockchain provides a resilient and sustainable ICT infrastructure for smart manufacturing and industry 4.0 [10], [13], [17], [19], [38], [46], [60] and helps address challenges in sustainable manufacturing and product life cycle management [17].

The application of blockchain in software-based manufacturing can increase productivity and quality control, reducing costs, such as tracking in inspections, inventory management,

maintenance or recycling tasks and ownership issues. The Renault use case [18] is an example of implementation that connects each car's maintenance book to the vehicle's blockchain-enhanced digital twin, where blockchain offers benefits like tamper-proof data, traceability and visibility.

Blockchain helps in verification of intellectual properties and digital rights (Lr.3). Regarding SDG target 9.5 (scientific research and innovation), blockchain can encourage, support and enhance open innovation and open science in accessing to the scientific results and the scientific process. For example, blockchain is used to credit researchers for their respective scientific work and protect authors and software owners' intellectual properties and digital rights, ensuring the sustainability of scientific research and innovation [2]. Blockchain facilitates the management of digital copyright and helps to protect design from plagiarism and theft, contributing to sustainable buildings [52].

j: SDG 10 – REDUCED INEQUALITIES

The aim of SDG 10 is to "*reduce inequality within and among countries*" [64]. This SDG emphasizes inequalities in income and those based on age, sex, disability, race, ethnicity, origin, religion, or economic or other status within countries. Regarding inequalities among countries, this goal addresses "*those related to representation, migration and development assistance*" [64].

Blockchain promotes social equality and inclusion (So.9). A blockchain network has inherent equality and inclusion in theory. All participants have similar power. There is no central authority. Everyone has access to an identical copy of data (transparency and information symmetry) and everyone can participate in decentralized decision-making based on consensus mechanisms. This allows for re-balancing of power and fairer value distribution, offering opportunities, for example, for small businesses [40].

Corruption and manipulation of reputation data or ratings in centralized services, including banks and governments, impedes the trust needed to ensure equal and fair distribution of power and wealth in any society or economy. Blockchain creates trust between users and content and facilitates fair trade by coordinating conflicting interests towards common goals [61]. It can secure and establish good trust among parties involved in the value chain based on decentralization, accountability and transparency, trust and risk-reduction. Decentralization and transparency supported by blockchain can benefit less powerful parties in the supply chain [40], [70]. This has the potential to socially integrate low-income, marginalized or market-restricted groups into the formal market [65].

Regarding political inclusion and decision-making, blockchain allows for collaborative and decentralized decision-making, for example, e-voting [27], collaborative product design and crowdsourcing in manufacturing [17] and collaborative urban decision-making [2]. Blockchain's applications in banking and financing systems based on cryptocurrencies have social implications in changing

organizations, and this has a bearing on SDG targets 10.5 and 10.6.

k: SDG 11 – SUSTAINABLE CITIES AND COMMUNITIES

This goal aims to "*make cities and human settlements inclusive, safe, resilient and sustainable*" [64]. It is specifically targeted at urban areas, based on the rationale that cities and human settlements can function as incubators for innovation and ingenuity, driving sustainable development.

Smart contracts prevent fraud and double registration of properties (Lr.3, So.5). Regarding SDG target 11.1 (access to adequate, safe, and affordable housing), [27] discussed how smart contracts could facilitate property, land and housing registration and, in general, support property development processes, particularly to avoid issues related to fraud and double registration.

Blockchain improves road traffic safety and sustainability (So.8, So.1, Ev.4). Blockchain provides privacy protection, secure and privacy-preserving data exchange and communication. It can *solve trust* challenges for vehicle networks and Intelligent Traffic Systems (ITS), providing a basis for a large number of sustainable and safe transport services, systems and business models through innovations based on *electric*, *connected* and *autonomous* vehicles [2], [18], [27], [29]. Compared to the mainstream centralized ITS system, blockchain is expected to enable a decentralized, secured, and trusted autonomous ITS ecosystem and facilitate the management of digital and physical assets [2]. Blockchain smart contract enables automatic negotiation for EV charging services, stimulates EV market growth and reduces greenhouse gas (GHG) emission [2], [12], [18], [29]. Blockchain's transparency and security mechanisms facilitate fraud reduction in vehicle information management and remote vehicle software version updates [2]. Furthermore, blockchain's features of secure data storage and verification of digital identity can address problems caused by the rise of the sharing economy and collaborative consumption, such as trust issues and *stranger-sharing*. For example, in ride-sharing services, blockchain can securely verify the digital identities of the drivers or customers and grant them access to the data of shared vehicles through verified digital identities [27]. Cryptocurrency can be used as a financial incentive for urban transportation sustainability, for example, by motivating urban cycling [2].

Blockchain promotes environmentally friendly practices (So.3, Ev.1). Regarding SDG target 11.6 (environmental impact of cities, focusing on air quality and waste management), blockchain's traceability and transparency are used for protection against fraud and waste reduction and management [2], [17], [27], [53], [65]. Blockchain's visibility and transparency and cryptocurrency can motivate a transition to sustainable practices, such as recycling and efficient (solid and electronic-) waste management as well as sustainable behavior among motorists and other road-users [2], [29].

In combination with IoT, blockchain technology can be used for transparent and secure monitoring and tracking of

the level of pollutants, increasing awareness of environmental impacts, for instance, regarding air quality and pollutants, thus contributing to CO_2 emission reduction [2], [27].

l: SDG 12 – RESPONSIBLE CONSUMPTION AND PRODUCTION

This SDG calls for ensuring *"sustainable consumption and production patterns"*. Here, it is emphasized that *"economic growth and development require the production of goods and services that improve the quality of life"*, and that *"sustainable growth and development require minimizing the natural resources and toxic materials used, and the waste and pollutants generated"*, throughout the production process as well as during consumption [64].

Blockchain encourages responsible consumption and production (Ev.3, So.7, Ec.6). Blockchain applications can improve decision-making based on real-time data collection and analysis and facilitate the efficient use of natural resources (SDG target 12.2) [2], [13], [14], [16], [17], [19], [38], [46], [48], [50], [51], [52], [53], [57]. Regarding SDG target 12.5, blockchain's data transparency and traceability can enable a circular economy [47], [56], [59], [60], and reduce waste through better decision-making and planning based on product life cycle data [60]. For example, using an IoT-integrated blockchain system, accurate and tamper-proof data on product life cycle can be provided as reliable information for effective circular economy planning regarding product recycling and remanufacturing [17]. In addition, waste reduction and management as described under SDG 11.6 (see Section IV.A.1.11), and in particular, a solid waste management and an e-waste handling system using blockchain [2], [29], are examples of blockchain's potential impacts on SDG targets 12.4 and 12.5.

Blockchain enhances the reputation of companies following sustainable practices (Ec.2, So.7, So.3, Ev.1). This impacts SDG target 12.6 (encourage companies to adopt sustainable practices and incorporate sustainability information in the reporting cycle) and 12.8 (*"ensure relevant information and awareness for sustainable development and lifestyles in harmony with nature"*). Blockchain has the potential to enable sustainability verification through more quantifiable and meaningful indicators [38].

Blockchain's transparency and traceability enhance the visibility of information related to sustainability, such as carbon footprints in the supply chain, and can thus improve the awareness of environmental impacts. Examples include emission-trading based on carbon footprints in fashion apparel manufacturing [17], using cryptocurrency as a reward mechanism to motivate the recycling of solid domestic waste [56] and plastic waste [60] and enabling efficient waste management [2], [56], [65].

Awareness-raising can encourage people and organizations to adopt sustainable behavior (SDG target 12.8). Traceability as a strategic tool to monitor environmental impacts and regulatory compliance can encourage companies to be more

sustainable (SDG target 12.6). As an example, blockchain traceability provides tamper-proof data for carbon tax calculation, which will encourage companies to restructure their supply chains to have lower carbon footprints [27]. In addition, companies in global supply chains face pressure for increased traceability as they need to adapt to different policies in different areas. "By applying blockchain, globalized standardization can be adaptable for all countries and regions, and they can save companies from duplicative works" [42, pp. 5]. Furthermore, blockchain traceability is an affordable mechanism for the differentiation of sustainable products and practices from non-sustainable ones [54] and the facilitation of verification of eco-labelling and certifications [43]. Thus, it adds value and enhances the reputation of companies that adopt sustainable practices [57]. Further examples include using blockchain and smart devices to advance carbon emission compliance and trading, for example, in the fashion apparel manufacturing industry [2], [17], [41], [59], and a reputation-based mechanism using blockchain to encourage the adoption of a long-term solution for reducing emissions [2]. By enabling users to precisely monitor their energy use and the corresponding energy mix composition, for instance, through trading certificates, blockchain can help prevent energy wastage, promote the use of green energy and decrease the use of fossil fuels [10].

m: SDG 13 – CLIMATE ACTION

This SDG call for *"urgent action to combat climate change and its impacts"*. Climate change is called *"the single greatest threat to development"*, and its impacts *"disproportionately burden the poorest and most vulnerable"*. Thus, combating climate change and minimizing its disruptions is considered integral to successful SDG implementation [64].

Blockchain contributes to pollution reduction and helps reduce environmental degradation (Ev.4, Ev.1, Ev.2, Ev.3, So.3). Blockchain boosts an organization's capability for combating climate change (SDG target 13.1). For example, in a blockchain-enabled sustainable supply chain and logistics [14], [16], [42], [51], efficient resource allocation and improved decision-making based on visibility and transparency of data lead to a reduction in fuel and energy consumption, lower greenhouse gas (GHG) emissions and alleviation of pollution and environmental degradation [8]. In the energy domain, blockchain supports low-carbon energy systems integrated with renewable energy as well as high energy efficiency, such as the adoption of renewable energy (see description of SDG 7 in Section IV.A.1.7) and the substitution of conventional diesel with palm-derived biodiesel [54]. For low carbon mobility, smart contracts enhance EV charging services and stimulate the EV market, and blockchain-empowered new ITS and services reduce road traffic congestion, improve safety, and reduce energy consumption and pollution [29]. Other examples of blockchain's contribution to pollution-reduction include improved carbon emission compliance and trading [2], [14], constructive involvement of citizens in environmental quality monitoring

to boost awareness on city health [2], and waste reduction and management [2], [29], [50], [65].

Regarding SDG target 13.2, from a policy perspective, blockchain transparency improves visibility, which can bring attention to the need for regulations within and between countries and catalyze the development of policies and regulations for sustainable development [42].

Concerning SDG target 13.3 (awareness-raising and early warning), building on blockchain's features of information sharing, transparency and decentralization, blockchain applications are used in monitoring and tracking the level of pollutants, improving air quality and pollutant awareness and contributing to CO_2 emission reduction [2], [27]. Blockchain's traceability also makes eco-labelling and certifications related to sustainability verifiable and trustworthy [43].

n: SDG 14 – LIFE BELOW WATER
This SDG calls for conservation and sustainable utilization of "*oceans, seas and marine resources for sustainable development*". Apart from playing a significant role to the 37 % of the global population living in coastal communities, "*coastal and maritime resources contribute an estimated USD 28 trillion to the global economy each year*". Further, oceans "*help regulate the global ecosystem by absorbing heat and carbon dioxide from the atmosphere and protecting coastal areas from flooding and erosion*" [64].

Blockchain improves the monitoring and protection of sustainable use of the oceanic ecosystem (Ev.2, So.5). A pilot project on blockchain-based traceability in the Indonesian fishing industry is described in [38]. The traditional seafood source tracking system is based on paperwork, and full quality control of seafood trade from hundreds of boats is challenging. It lacks supervision and is plagued by corruption, questionable practices and problems such as fraud, overfishing and *illegal, unreported, and un-regulated* (IUU) fishing. Blockchain helps mitigate against IUU fishing and stop illegal practices, including slavery, through traceability, transparency and stakeholder engagement [16], [38], [71], thus contributing to fulfilling targets 14.1 to 14.5 [16], [71].

o: SDG 15 – LIFE ON LAND
This SDG aims to preserve diverse forms of life on land, calling for efforts to "*protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss*" [64].

Blockchain facilitates monitoring and sustainable use of the terrestrial ecosystem (Ev.2). For example, a blockchain-based approach was used to monitor the sand resource supply chain from mining to trading to prevent illegal sand mining, thereby contributing to combating desertification (SDG target 15.3) [2]. The sustainable palm oil industry example mentioned in Section IV.A.1.7 can also contribute to checking deforestation (SDG target 15.2) [54].

Blockchain is also used for the traceability of wood products along the supply chain [16], [24], which has an impact on targets 15.1–15.4. [57] categorized blockchain applications in the forestry sector into traceability of forest-based products, forest management and forest fire detection, showing potential in sustainable forestry, conserving biodiversity and minimizing illegal logging (impact on targets 15.1-15.7).

p: SDG 16 – PEACE, JUSTICE AND STRONG INSTITUTIONS
The goal of SDG 16 is to "*promote peaceful and inclusive societies for sustainable development, provide access to justice for all and build effective, accountable and inclusive institutions at all levels*". It rests on the rationale that "*peace, justice, and effective, accountable and inclusive institutions are at the core of sustainable development*" [64].

Blockchain prevents unethical and illegal practices and promotes peace (So.5). This has impacts on SDG targets 16.1–16.5, for example, by reducing all forms of violence, combating crimes, reducing corruption and bribery, and uncovering and ending unethical and illegal practices (e.g., fraudulency, unethical use of natural resources, child labor) [27], [38]. As an example, Everledger's diamond certificate system uses the blockchain traceability of diamonds' provenance as a measure to eliminate the flow of diamonds mined inside conflict zones for financing wars [38].

Blockchain leads to more accountable institutions at all levels (Go.2, So.1, So.4). Blockchain guarantees accountability with timestamped, immutable and auditable data and ensures transparency in value chains and amongst stakeholders [2], [18], [30], [44]. Blockchain thus has a noticeable impact on society, law, and governance at various institutional levels. For example, blockchain allows for the creation of a DAO, which has a potential impact on organizational design [16]. The previous sections on SDG 8 and 9 have described blockchain's positive impacts on various companies and organizations (manufacturers, supply chain partners, energy providers, farmers, etc.) regarding their effectiveness (improved efficiency), accountability and inclusiveness, which are also good examples illustrating blockchain's impacts on SDG target 16.6.

Blockchain facilitates smart administration and governance with collaborative urban decision-making (Go.1, Go.2). Blockchain's transparency and accountability impact smart governance and administration [2], [27]. It imparts, for example, improved efficiency (lower administrative cost, etc.) in public administration regarding service delivery and operation, accountable and transparent document-sharing, and corruption and fraud-prevention based on enhanced transparency.

An example of SDG target 16.4 (combating organized crime) is Estonia's e-residency and government-banked cryptocurrency (Estcoin) planned use as a measure against counterfeiting and illegal use of digital currency [55]. Another example is blockchain-empowered digital identity and proof-of-ownership and digital rights [2].

Regarding SDG target 16.5 (corruption and bribery reduction), governments can reinforce transparency and avoid corruption [27], [38] by utilizing blockchain to store and interconnect government records (incomes, expenses, contracts, etc.), as well as to secure online transactions [16]. Blockchain is considered a peace engineering tool in the context of e-voting [72]. For example, blockchain was used in decentralized e-voting systems [10], [27] to eliminate voter fraud. Blockchain ensures the anonymity, privacy, transparency and traceability of the voting process, contributing to SDG targets 16.5, 16.6 and 16.7. Blockchain-based applications for taxation can prevent tax revenue losses and prevent duplicated tax refunds [11].

Regarding SDG target 16.7 (inclusive and participatory decision-making), blockchain's decentralization eliminates central authority and control. It allows everyone to access the same data and participate in a consensus-based decentralized decision. At the same time, blockchain's transparency and immutability ensure transparency and integrity of government information. This increases citizens' trust and encourages stronger inclusion and participation in democratic decision-making and collaborative urban policy-making [10]. For example, in a disease spread scenario, blockchain helps manage individual health data more transparently and ethically, facilitating evidence-based collaborative decision-making [2].

Regarding SDG target 16.9 (legal identity for all), digital identity is one key application of blockchain and also the basis for many other applications, for example, using blockchain to securely store, share and authorize information on digital identity and other information related to citizens, such as national identity, passports, birth and death registration as well as health and employment records [27], [56].

Regarding SDG target 16.10 (ensuring public access to information and fundamental freedoms), various blockchain-based systems, such as Dubai's e-Democracy [27], have been proposed to ensure that government documents can be shared with the public more securely and reliably [2].

q: SDG 17 – PARTNERSHIPS FOR THE GOALS

This final SDG builds on the rationale that to achieve the SDGs, a revitalization and enhancement of global partnerships, bringing together governments, civil societies, the private sector, the UN system and other actors, is required. This SDG aims to *"strengthen the means of implementation and revitalize these global partnerships for sustainable development"* [64].

Blockchain facilitates the building of multi-stakeholder partnerships (So.4). Blockchain provides computational trust, reduces cyber-risks, assures information transparency and symmetry for all participants, facilitating transparency and accountability of the value chains and reducing risks. Thus it can build trust and enhance collaboration and cooperation with multiple stakeholders [2], [13], [16], [17], [24], [30], [38], [40], [43], [45], [61], [73]. Using smart contracts can improve trust and greatly speed up transactions, substituting

the *letter of credit* and securing partnerships [42]. In particular, blockchain facilitates the establishment of trust in a low or no-trust environment and facilitates greater collaboration, for example, among potential partners that have never met before or may be far away from each other in complex global supply chains [29]. This has positive impacts on targets related to cooperation and collaboration and facilitates the building of multi-stakeholder partnerships in pursuing sustainable development globally; for example, as in SDG targets 17.16 and 17.17. Examples of applications of this advantage include securing and establishing good trust among parties involved in the value chain, reducing custody risk and securing ownership registration and cross-border asset transfers, transaction verification, theft prevention, tracking disruption roots and propagation, addressing the holistic sources of risk and reducing inefficiencies in capacity reservations and backup sources [13], [14], [17], [29], [38], [42].

Blockchain catalyzes the development of policies and regulations (Lr.2). This has positive impacts on SDG target 17.14. Blockchain offers instruments for mapping norms, frameworks and policy-making [61] and helps in the establishment of appropriate legal systems and environmental regulations [47]. For example, improved visibility facilitates the determination and shaping of rules and governance norms at various levels such as transport, logistics, and supply chains, allowing for effective government supervision and enhancing policy coherence for sustainable development of the transport and logistics industry [14]. Blockchain can also help in the achievement of global alignment in traceability and conservation of natural resources, supporting global standardization adapted to all countries [42].

Blockchain improves fair trade (So.5). Blockchain can potentially solve the challenges related to fake customers and personal reputation records falsification through transparency and verifiability, thus facilitating e-commerce [24], [44]. Blockchain can also simplify international trade finance through global interoperability [61]. Benefits brought by blockchain's application in the supply chain and its role in enabling trade, as estimated by the World Economic Forum (WEF), "could increase worldwide GDP by almost 5% and total trade volume by 15%" [44, pp. 8]. These will have positive impacts on SDG targets 17.10, 17.11, and 17.12.

2) NEGATIVE IMPACTS ON SDGS

Blockchain's negative impacts on sustainability are summarized in Table 3.

Compared to blockchain's positive impacts on SDGs, we found very few discussions on negative impacts related to sustainability although the challenges of blockchain technology were sometimes mentioned. Below is our summary of the main negative impacts of SDGs from the surveyed papers.

Some blockchain technologies' energy intensiveness leads to wasted resources and high carbon footprints and GHG emissions (Ev.5, Ev.6). Proof of Work (PoW) algorithms like Bitcoin are considered environmentally costly due to their energy intensiveness and wasted resources related to

TABLE 3. Thematic overview of blockchain's potential negative impacts on sustainability[9].

Category	Codes of negative impacts on sustainability	SDGs
Economic impact	**(Ec.7) High infrastructure investment and implementation cost** [14], [38]: expensive to operate the blockchain-based system.	2 (2.3), 8 (8.3), 9 (9.2), 10 (10.2)
Environmental impact	**(Ev.5) High carbon footprints and greenhouse gas emissions** [29]: PoW consumes high energy. **(Ev.6) Wasted resources** [9], [55]: PoW consumes high energy.	7 (7.1, 7.3), 8 (8.4), 12 (12.2), 13
Social impact	**(So.10) Job losses and job-reskilling**, for example, due to the removal of intermediaries [40]. **(So.11) Social inequality:** not affordable for developing or underdeveloped countries, SMEs and smallholder farmers [40], [55]. **(So.12) Potentially used for illegal activities:** for example, cryptocurrency may be linked to drug and weapon-trading [9].	2 (2.3), 8 (8.3, 8.5), 9 (9.2), 10 (10.2), 16 (16.4)

mining, validation of transactions and maintaining consensus [9], [14], [18], [29], [55], [56], [62]. Thus, it has potential negative impacts on SDG 7 (targets 7.1 and 7.3) regarding energy consumption and energy efficiency, SDG 8 (target 8.4) and SDG 12 (target 12.2) regarding resource use and efficiency as well as SDG 13 regarding carbon footprints and GHG emission.

Costs and infrastructure, and training investment lead to inequality (Ec.7, So.10, So.11). Blockchain requires a high degree of computation, which affects its availability and scalability. The adoption of blockchain technology requires server infrastructure investment (including Internet connectivity) and additional implementation costs. Hardware and software upgrades are needed, resulting in increased costs associated with devices, operation, maintenance and training. In addition, lack of expertise and skilled personnel is another barrier to the adoption of blockchain. These may hinder blockchain as an affordable technology for all and, in particular, for developing or underdeveloped countries, SMEs and small farmers with poor infrastructure and constraints in finance and skill [38], [40], [46], [55], [56]. It would thus be difficult to realize the full potential of blockchain in the global supply chain, which depends on the participation of partners in the whole supply chain. Such economic and knowledge barriers have a potential negative impact on SDG 2 (target 2.3) regarding the accessibility of smallholder farmers, SDG 8 (target 8.3) and SDG 10 (target 10.2) regarding economic inclusion and SDG 9 (target 9.2) regarding affordability and inclusiveness as well as increased consumption.

Anonymization and cryptocurrency may potentially be used for illegal activities (So.12). Blockchain's

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9We give only one or two reference papers for each code in this overview table. For details, please refer to the description in Section IV.A.2.

permissionless public systems might be used for illegal activities due to its anonymization. For example, cryptocurrencies have been linked to drug and weapon trading, money laundering and terrorism financing [9], [40], [55]. This indicates potential negative impacts on SDGs; such as SDG target 16.4.

Blockchain can lead to job losses and job-reskilling (So.10). Blockchain is based on disintermediation and distributed consensus. Blockchain adoption may result in job losses for current intermediaries in the short term and job-reskilling as new intermediaries offering new blockchain-based services emerge [40], thus impacting SDG 8 (target 8.5).

These negative impacts on SDGs highlight sustainability aspect of the cost of adopting blockchain – the high infrastructure investment and implementation cost, the required training for needed knowledge and expertise as well as potential negative environmental impacts. The adoption of blockchain in practice will need an assessment of the trade-off between the benefits that it may bring and its associated cost.

B. THE RESULTS OF RQ2

In RQ2, we tried to identify the key drivers and barriers to adopting blockchain technology in practice to satisfy SDG goals. The drivers are factors that motivate, enable and facilitate the adoption of blockchain while the barriers are factors that hinder its adoption.

We followed the approach in [11] and classified the drivers and barriers into four high-level themes: system-level (related to the blockchain technology itself or the blockchain-based systems), intra-organizational (related to internal activities of organizations), inter-organizational (related to relationships and collaboration with partners) and external (related to external stakeholders, industries, institutions and governments that are not directly affected by an organization's activities).

1) DRIVERS TO ADOPTING BLOCKCHAIN
1.1) System-level drivers (Dsys)
- *(Dsys.1) Security and privacy mechanisms to address cyber-security threats* [2], [13], [14], [17], [18], [27], [29], [39], [46], [52], [54], [56]. Blockchain technology provides a good security and privacy assurance mechanism and algorithms.
- *(Dsys.2) Functions that can be implemented using smart contracts* [14], [40], [42], [46], [48], [50], [51], [54], [56], [60], [63]. Smart contracts enable automation and self-execution of predefined and mutually agreed contractual conditions.
- *(Dsys.3) Transparency and accountability (immutability) of recorded data* [14], [19], [42], [50], [51], [52], [53], [56], [57], [59], [61], [63]. Blockchain's feature to provide transparent and trustworthy data address many SDG challenges.
- *(Dsys.4) Tamper-proof and finer-granular traceability* [13], [14], [17], [18], [19], [27], [29], [30], [38], [42], [44], [46], [48], [51], [53], [56], [57], [59],

[60], [63]. The greater transparency and efficiency in blockchain-based traceability motivate people to use blockchain in improving sustainability tracking system.

- *(Dsys.5) Decentralized architecture and governance* [18], [50], [51], [52]. Blockchain's decentralized architecture means high network resilience and no single point of failure, enabling many SDG applications.
- *(Dsys.6) Digital certification, verifiable digital documents, and indicator measurements for assessing indicators of sustainability and quality* [16], [38], [46], [48], [51], [53], [59]. This provides the possibility to verify sustainability with meaningful and quantifiable indicators.
- *(Dsys.7) Cryptocurrency, social currency and financial services* (microfinance etc.) [9], [40], [46], [50], [55], [56], [60]. These enable and support many blockchain-based applications.
- *(Dsys.8) Possibility of being combined with disruptive technologies (IoT, Big data, AI, etc.)* [14], [42], [46], [50], [56], [59]. Combing blockchain and disruptive technologies improves the applicability of blockchain in different domains.
- *(Dsys.9) Addressing the challenges due to an increase in smart and connected devices* [27], [29], [44]. Blockchain is a communication technology with a secure and decentralized architecture that offers secure solutions which traditional cyber-security approaches cannot solve.

1.2) Intra-organizational drivers (Dintra)

- *(Dintra.1) Upper-level management support* [17]. On one hand, blockchain is an emergent technology and needs upper-level management support to be adopted. On the other hand, it can help businesses succeed through effective management of the organizational culture (goals, strategies, structures and shareholders) [47].
- *(Dintra.2) Key resource transparency* [17]. Blockchain applications need more visible, traceable, and dis-intermediary access to key resources.
- *(Dintra.3) Decentralized decision-making within an organization* [17]. A decentralized decision mechanism will ease the adoption of a blockchain-based application.
- *(Dintra.4) Automated business processes and handling* [14], [16], [38], [44]. Having real-time information-sharing, verification, and compliance checking could smoothen the use of smart contracts.

1.3) Inter-organizational drivers (Dinter)

- *(Dinter.1) Transparency, visibility and real-time information sharing* among different parties [2], [14], [17], [18], [29], [30], [38], [41], [42], [44], [45], [48], [49], [50], [51], [54], [56], [58], [59], [60], [63]. Transparency in value chains and amongst stakeholders and timely sharing of data enables blockchain-based applications.

- *(Dinter.2) Computational trust across multiple entities* [17], [40], [47], [48], [53], [56], [63]. "Trust is the most influential factor driving interest in the blockchain within supply chain management" [40, p. 71], and, here, *computational trust* refers to "the reliability of the information provided by trade partners, or the safety and security of the data managed by a central authority" [40, p. 71]. Blockchain applications need high-quality data inputs to deliver value.
- *(Dinter.3) Decentralization across organizations* [29]. Many blockchain-based applications need efficient information exchange and transactions, high data availability, decentralized decision-making, and self-organized collaboration.

1.4) External drivers (Dext)

- *(Dext.1) Policy and regulation support* [39], [47]. From a policy perspective, it is necessary to have favorable policies, such as the requirements supporting the development of blockchain applications in distributed photovoltaic (PV) industry, for blockchain adoption [39]. Furthermore, blockchain technology provides secure and transparent information for governmental bodies and businesses to support appropriate legal systems and environmental regulations for sustainable development [47].
- *(Dext.2) Regulatory and standards requirements related to product quality, public safety and security* [2], [11], [14], [24], [29], [38], [40], [42], [43], [48], [49], [54]. This is related to requirements of environmental regulations and rules touching on things such as medicine transportation and storage requirements. These are requirements related to food and medicine safety, water and waste management.
- *(Dext.3) Consumers' increasing concern about product provenance (i.e., origin) and demands on sustainable products and practices* [11], [17], [19], [24], [29], [38], [42], [43], [46], [48], [49], [54], [57], [59]. Increasing expectations on traceability lead to higher demands for blockchain-based applications.
- *(Dext.4) The increasing social awareness on sustainability* [30], [39], [43], [54], [59]. This puts high demand on blockchain to get more real-time and trustworthy information related to environmental protection and sustainable practices.

Fig. 5–Fig. 8 summarize the relationship between the drivers of blockchain and it's impacts on SDGs. The drivers considered very important (**) or important (*) are marked with stars. This prioritizing is based on i) the weighting of the respective driver in the reviewed literature (how much emphasis it is given), and ii) its diffusion in the research mapped (e.g., the number of works referring to it, how often it is mentioned).

In general, there are a higher number of drivers related to system level and relatively few intra-organizational drivers as compared to the other categories of drivers. Blockchain-enhanced traceability is one of the most widely adopted use

cases for blockchain, especially in supply chains. Therefore, the system-level driver of tamper-proof traceability (Dsys.4) and the inter-organizational driver of transparency and information sharing (Dinter.1) are most emphasized in the reviewed literature. External drivers related to regulatory requirements (Dext.2) and consumers concern (Dext.3) regarding product quality and security are also pointed to as major drivers for blockchain adoption for sustainability purpose. System-level drivers like security and privacy (Dsys.1), smart contracts (Dsys.2), transparency and accountability (Dsys.3) and decentralization (Dsys.5) are based on the key features of blockchain and are important factors for blockchain adoption for sustainability. Automated business processes and handling (Dintra.4) enabled by the adoption of blockchain and smart contracts is an important driver for businesses and organizations to achieve economic sustainability.

2) BARRIERS TO ADOPTING BLOCKCHAIN

2.1) System-level barriers (Bsys)

- *(Bsys.1) Access limitation to the required technology, tools, and infrastructure* [11], [16], [24], [38], [51], [59], [60]. Internet connectivity is a challenge to rural areas or open seas with a lack of or limited access to broadband Internet.
- *(Bsys.2) Immature technology* in an early development phase [8], [14], [16], [18], [29], [44], [46], [53]. The immaturity leads to technological vulnerabilities and the perception of insecurity or unreliability, thus impeding stakeholders' readiness for adoption. There are a number of technical challenges to be tackled, such as those related to resource-intensive and inefficient consensus algorithms [9], [13], [17], [24], [44], [55]; the energy intensiveness of processing, key algorithms and computations within the blockchain [9], [13], [14], [24], [44], [55]; scalability and performance challenges [2], [8], [9], [12], [13], [14], [16], [17], [18], [24], [29], [41], [42], [44], [46], [48], [50], [55].
- *(Bsys.3) Negative effect of immutability on erroneous data* [11], [16], [29], [40]. Mistakes are irreversible and may increase transaction costs.
- *(Bsys.4) Lack of new business models, standard tools, methods, best practices and indicators* [11], [14], [16], [17]. This can hinder the implementation and measurement of new solutions and sustainability practices.
- *(Bsys.5) Cyber-security challenges* [9], [11], [17], [18], [40], [41], [46], [50], [53], [59]. Although blockchain-based applications are more secure than some IT technologies, there are still many blockchain-related vulnerabilities to cyber-attacks that need to be addressed.
- *(Bsys.6) Reduced privacy due to transparency* [8], [9], [13], [14], [17], [24], [44], [46], [53]. Blockchain technologies still have many data privacy-related challenges that need to be addressed.
- *(Bsys.7) Lack of standards leads to interoperability issues* [11], [14], [16], [17], [18], [24], [40], [41], [46],

[48], [50]. Standards are needed to guarantee interoperability between blockchains and facilitate their integration with third-party or legacy systems. This lack of standards hinders cooperation.

- *(Bsys.8) Risks related to raw data manipulation, human errors, compromised data users and physical manipulative activities* [9], [11], [12], [13], [14], [16], [17], [18], [29], [38], [40], [42], [48], [60]. Input data quality affects transparency and accountability. Blockchain ensures cyber-security, data immutability and integrity, but it is a challenge to guarantee the quality and correctness of the input information and ensure that the digital layer (data) corresponds to the physical layer (assets represented by the blockchain).

2.2) Intra-organizational barriers (Bintra)

- *(Bintra.1) Investment in infrastructure and additional resources* [11], [14], [16], [17], [24], [29], [38], [42], [46], [48], [49], [51] [53], [55], [59]. Implementing a blockchain-based application incurs an additional implementation cost besides requiring hardware and software upgrades.
- *(Bintra.2) Lack of knowledge and expertise* [8], [11], [14], [16], [18], [24], [29], [40], [42], [44], [48], [55], [60]. Insufficient knowledge may lead to exaggerated faith in blockchains and misinformation regarding them, such as associating Bitcoin with fraud and illegality. A lack of understanding of blockchain potential can significantly impact stakeholders' attitudes and their willingness to change.
- *(Bintra.3) Lack of management awareness and commitment* [11], [14], [16], [17]. This holds back transitioning to more sustainable practices using blockchain-based applications.
- *(Bintra.4) Lack of new organizational policies regarding the use of blockchain technology* [11], [14], [16]. Blockchain adoption may change or transform existing organizational culture or hierarchy. New policies need to be defined regarding the new roles, responsibilities, and expertise for the transition.
- *(Bintra.5) Stakeholders' hesitation and resistance to change* [11], [14], [16], [17], [18], [24], [29], [40], [44], [48], [53]. This can be due to skepticism towards the transparency of blockchain, doubt or resistance to changes in organizational culture or hierarchy resulting from a transition, a reluctance to change to new systems due to inertia of legacy systems, a fear of losing revenue models and intermediaries' fear of being removed from the value chain.

2.3) Inter-organizational barriers (Binter)

- *(Binter.1) Organizational and cultural differences* [11], [16], [29]. The differences can lead to communication challenges.
- *(Binter.2) Unwillingness to share valued information* [11], [14], [16], [40]. This can be caused by
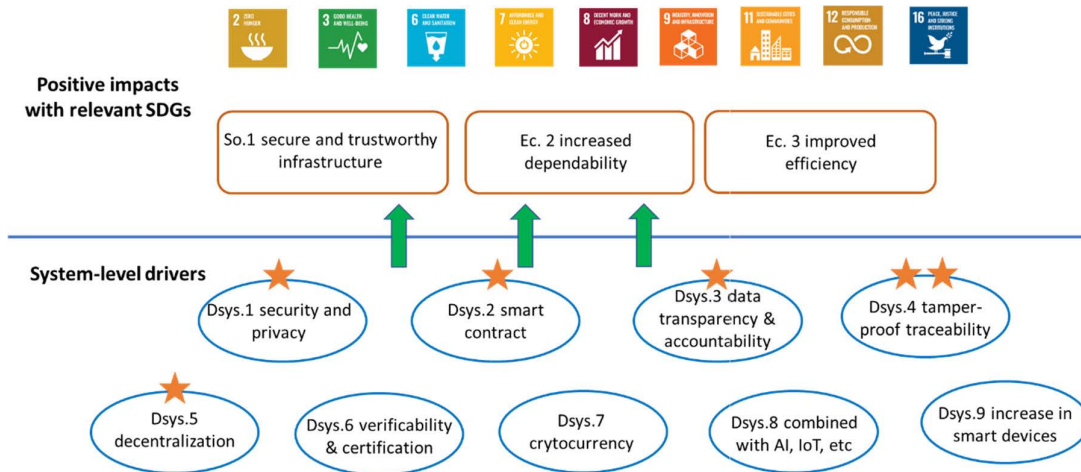
FIGURE 5. System-level drivers and impacts on SDGs.

a concern about reduced privacy or information assumed to give a competitive advantage.

- *(Binter.3) Lack of policy and robust rules regarding information-sharing or addressing lost or stolen data* [11], [14], [16], [29]. Missing such support can affect the collaboration and adoption of blockchain.
- *(Binter.4) Lack of customers' awareness and intention to contribute to sustainability* [11], [16], [17], [24]. People may not understand the benefits of green certification schemes and may have a low willingness to pay more for sustainable products or products produced with greater transparency.
- *(Binter.5) Interest conflicts/lack of effective collaboration* [11], [14], [16], [17], [18], [42]. Different stakeholders have different needs, requirements, and premises. There is a lack of collaborative mindset and a lack of effective collaboration mechanisms among stakeholders with conflicting operational goals and priorities.
- *(Binter.6) Lack of central authority* [14], [16], [29]. This leads to a lack of trust and "lower confidence about the effectiveness of a trustless distributed paradigm" [14, pp. 11].
- *(Binter.7) Network effect* [14], [18], [38], [40], [42], [46]. This is related to the required critical mass of adoption and technology diffusion.

2.4) External barriers (Bext)

- *(Bext.1) Lack of or unclear governmental policies and regulations to guide and support sustainable and safe practice* [8], [9], [11], [14], [16], [18], [29], [41], [42], [44], [48], [50]. This is related to regulatory uncertainty due to the existence of several regulatory environments with various rules, such as the adoption of some aspects of smart contracts potentially being overregulated or considered illegal [14], [44].

- *(Bext.2) Lack of external stakeholders' involvement.* This is related to missing ethical and safe practices and the promotion of blockchain for sustainable value creation [11], [16], [29], [50].
- *(Bext.3) Market competition and demand uncertainty for sustainable products* [11], [16]. Competition and unpredictable customer behavior make it uncertain about recouping investments in sustainable practices and new technology.
- *(Bext.4) Lack of rewards and encouragement programs associated with the application of blockchain technology* [11], [16], [50], [53]. People are skeptical about giving financial incentives to data validators in a blockchain-based system because ethical concerns reduce the opportunities to use well-established blockchain technologies.
- *(Bext.5) Implementation of blockchain-based solutions in global supply chains is a complex task* [38], [40]. This is because it has to conform to various laws, regulations and institutions.

Most barriers to SDGs, influencing the adoption of blockchain in general, are generic. However, some barriers have specific consequences to SDGs as illustrated in Fig. 9. These barriers considered are marked with stars to indicate their relative degree – very important (**) or important (*) – in a similar way as done for the drivers.

The biggest barriers to adopting blockchain for sustainability are the system-level barrier related to the level of immaturity and technical challenges of blockchain technology (Bsys.2), with special emphasis on issues related to scalability, and the external barrier related to unclear governmental policies and regulations (Bext.1). In addition, intraorganizational conditions related to the lack of knowledge (Bintra.2) and investment costs (Bintra.1) as well as the infrastructure requirement (Bsys.1) are considered major barriers to adopting blockchain.
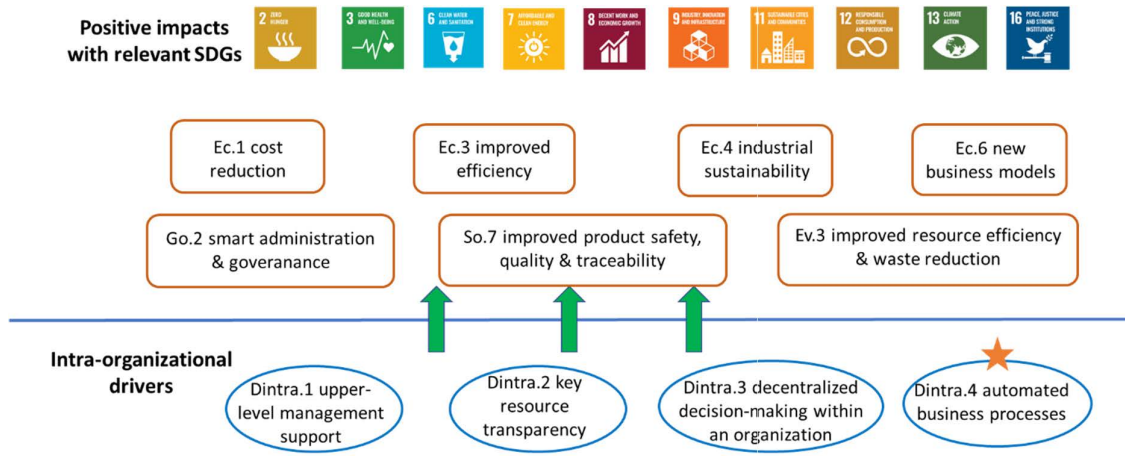
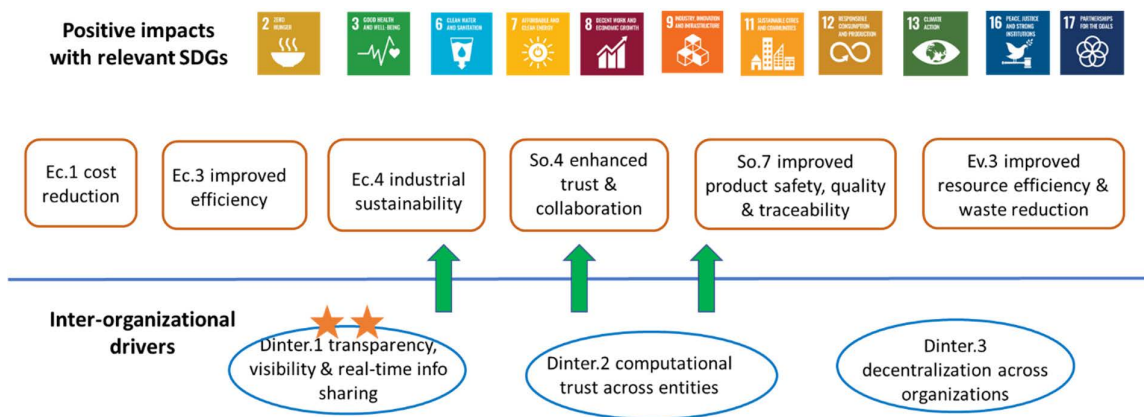**FIGURE 6.** Intra-organizational drivers and impacts on SDGs.

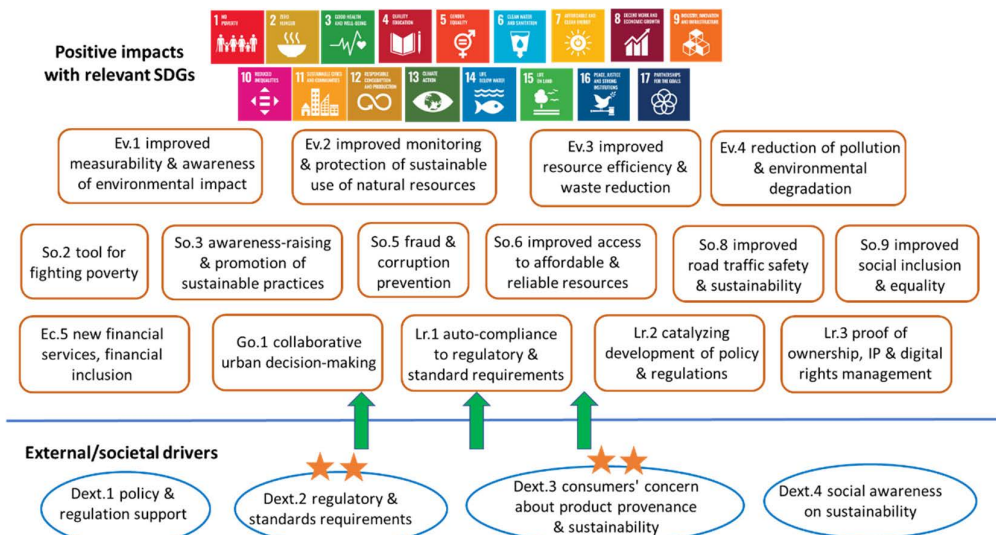**FIGURE 7.** Inter-organizational drivers and impacts on SDGs.

FIGURE 8. External drivers and impacts on SDGs.

C. THE RESULTS OF RQ3

Beyond blockchain's negative impacts on SDGs shown in Section IV.A.2 and barriers explained in Section IV.B.2, we summarize other research gaps in this section.

D. LEGAL FRAMEWORKS AND STANDARDS

Standards can contribute to industrial and societal acceptance of the application of blockchain, for example, in the food supply chain [46]. Adopting shared standards for certain
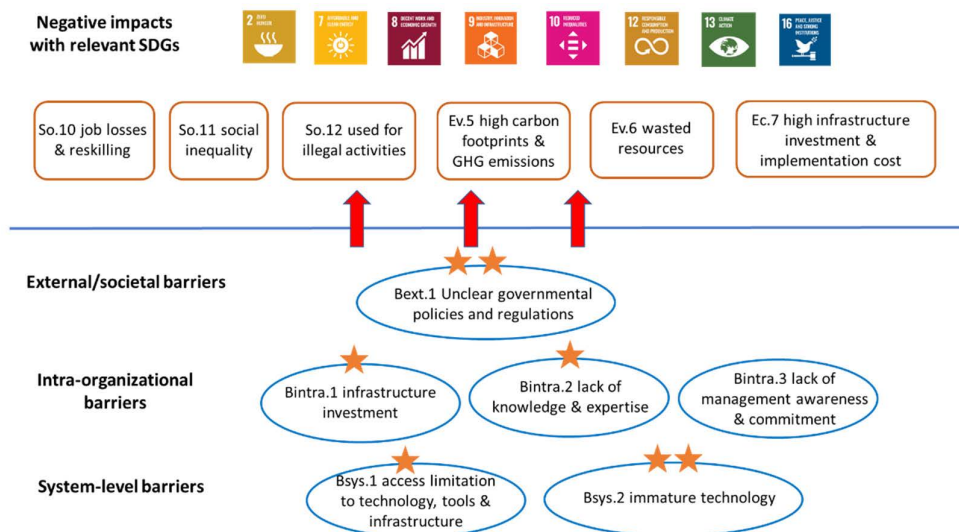
FIGURE 9. Barriers and impacts on SDGs.

methods and practices by supply chain actors may substantially benefit supply chain traceability [48]. Standards also facilitate interoperability. A lack of regulations and standards creates uncertainty and risks for companies and holds back their transition to blockchain technology. For example, there is uncertainty regarding the legal validity and enforcement mechanisms of smart contracts when disputes arise [40]. A legal framework is necessary for blockchain to reach its full potential. To constrain data manipulation, appropriate legal framework and policies may be defined. This could include regulations such as:

- using certificates and regular checks to ensure raw data authenticity,
- ensuring traceability or regulatory monitoring to encourage companies to take responsibility for their products and provide authentic information,
- mechanisms to prevent fraud and money laundering activities,
- policies supporting data-sharing between parties in law enforcement against some cyber risks,
- putting in place criteria to guarantee the legal validity and enforceability of smart contracts [40].

E. SOFTWARE ENGINEERING TOOLS AND METHODS

Further research is needed to tackle the absence of standard tools and methods for implementing blockchain applications, particularly software engineering methodologies and frameworks for developing blockchain-based systems. Reference [74] pointed out some software engineering research directions, for example, user involvement in defining and eliciting software requirements, flexible architectures, verification of functional and non-functional system properties, and empirical evaluation methods and criteria. References [75] and [76] reported on research and experience regarding requirement engineering to identify user needs and system requirements for blockchain-based energy demand-response

systems and understanding the values in P2P energy-trading systems. More research of this kind is desirable to bridge the research gap regarding software engineering theory and practices for blockchain implementation to achieve SDGs. [40] also suggested research directions for design science-based development of generic actions, processes, and systems operationalized in various contexts. Domain specific tools and methods are needed, for example, to support blockchain's fully integration with Building Information Modelling (BIM) platforms for sustainable building [53].

F. EVIDENCE-BASED KNOWLEDGE ON LARGE-SCALE AND LONG-TERM EFFECTS

We observed that the negative impacts of blockchain on sustainability are not addressed to a considerable extent in the surveyed papers. Most papers addressed the *challenges*, *barriers*, *problems* related to the adoption of blockchain, but they did not talk about its *negative effects* on sustainability. Therefore, we were not able to link negative impacts to most SDG targets. This may be due to the current state of blockchain as an emerging technology since most discussion about it is theoretical or hypothetical without significant reference to use cases and experience from real deployment. Studies [12], [29], [46], [48], [49], [57], [74], [77], [78] point out the lack of real experiments and the need for empirical studies on blockchain for sustainable development. In particular, large-scale and long-term measurements are needed to give evidence of the impacts of blockchain on SDGs.

Empirical studies depend on frameworks for comprehensive evaluation of outcomes with *well-defined metrics and methodology*. Such a framework will facilitate a critical reflection on the current investments and experimentations and empirical evidence concerning the long-term effects, unanticipated and detrimental impacts, as well as limitations of blockchain in these contexts. Firstly, there is a need for *meaningful and quantifiable sustainability indicators*.

Blockchain-empowered traceability can be used to monitor activities in various contexts and verify sustainability indicators in a meaningful and quantifiable way [16]. However, the lack of standard indicators and methods hinders the effective monitoring and verification of sustainability practices. Secondly, there is a need for *comprehensive* evaluation of blockchain's impacts, for instance, from economic, social and environmental aspects or from the viewpoint of SDGs. Finally, a *benchmark on software sustainability* is desirable to compare the sustainability of software technologies (such as blockchain implementations) and their impacts on SDGs [48]. For example, PoW has been criticized for its negative impacts on energy intensiveness and its environmental footprint while other blockchain protocols, such as PoS and PBFT are more efficient and consume less energy. An evaluation of whether blockchain consumes more energy than other technologies may depend on the metrics used to measure the sustainability impact.

G. ETHICAL RESEARCH
Research on ethical issues associated with blockchain and its applications is also essential for preventing its potential negative consequences. Reference [79] has described a roadmap to further research on the ethics of blockchain. The legal and ethical implications of SDGs should be considered.

H. DECISION-MAKING FRAMEWORK
A reference framework is needed to support stakeholders to "make more informed decisions as to whether to invest in the development of the technology, (…) as well as how to design its architecture to meet their demands" [80, p. 27]. Based on the lessons learned and experience gained from previous initiatives and experimentations as well as the empirical evidence on the impacts of blockchain on SDGs, this framework should comprise of, among others, best practices and guidelines on the selection of relevant blockchain technology to meet SDGs, patterns or anti-patterns for its design and implementation as well as examples and use cases.

I. SUSTAINABILITY ASSESSMENT
Life Cycle Sustainability Assessment (LCSA) is a systematic and integrative methodology to evaluate the impacts of the three pillars of sustainability throughout the life cycle of a product or service. Reviewed literature pointed out a lack of research on the integration of blockchain technology with LCSA [53]. Future research can explore blockchain as a plausible solution offering data traceability and integrity to facilitate a more effective LCSA process and help minimize the negative impacts generated, for example, during the construction life cycle [53].

V. DISCUSSION
A. COMPARISON WITH RELATED WORK
Innovations through digital technologies such as AI and blockchain may influence the ability to meet the SDGs

defined in the UN 2030 Agenda. The assessment and governance of sustainability is a central challenge for our society since sustainable development is crucial to securing the future of humanity [6]. Existing literature reviews usually investigate blockchain's role in sustainability in specific application areas, such as sustainable supply chain management [16], smart cities [10] and sustainable manufacturing [13], [17]. Only a few of these reviews, for example [16], [73], and [74], touched on several SDGs and none of them documented connections between blockchain and the UN SDGs holistically, not to mention the detailed targets in each SDG. There is work [35] that systematically assessed the potential impact that AI might have on all aspects of sustainable development in terms of the 17 SDG goals and 169 targets. However, to date, there is no similar published study assessing blockchain's potential impact on all these SDG goals and targets. Our work attempts to bridge this gap.

In addition, our study has consolidated the barriers and drivers to blockchain adoption from existing literature and categorized them into system-level, intra-organizational, inter-organizational, and external or societal dimensions. Furthermore, we have analyzed the relationship between these barriers/drivers and blockchain's impacts on SDGs, thereby providing a link between RQ1 and RQ2. To the best of our knowledge, no other work has linked the barriers and drivers to blockchain with their impacts on SDGs.

Finally, this study has identified research gaps and proposed directions for further research to ensure that the potential of blockchain can be fully exploited and its negative impacts minimized.

B. IMPLICATIONS TO ACADEMIA AND PRACTITIONERS
1) FOR RESEARCHERS
Our work contributes to the body of knowledge about blockchain's role in meeting SDGs and indicates research gaps and directions for further development of blockchain technology with respect to SDGs. Some SDGs have more use cases and applications built upon blockchain, while others may need more research, for instance, regarding innovative applications and their impacts. Our study provides a comprehensive overview of the impact of blockchain adoption on SDGs, not only on selected SDGs. For researchers, our work offers a systematic approach to understanding the blockchain potential vis-à-vis the principles of SDGs and the opportunities to identify unexplored SDGs areas.

Our study highlights that negative impact of blockchain implementations on SDGs is not adequately addressed in the current literature. Most of the research on blockchain has so far been at a hypothetical or conceptual level, where the research has been concerned with investigating the potential effect of blockchain on SDGs, focusing mostly on the positive as such. Thus, future research should aim also on elucidating the potential or actual negative effects of blockchain, beyond the ever-recurring focus on e.g., the energy consumption of some blockchains (such as PoW) and the high implementation cost. However, the reviewed articles do point to

some negative impacts of blockchain technology which needs to be mitigated both in order to ensure its relevance as a tool to contribute positively to reaching SDGs, and further, its relevance for companies and organizations considering blockchain implementation.

Results of RQ3 suggest some research directions in this regard. In particular, future research should aim to fill the research gaps in order to support practitioners and policy-makers. The reviewed literature emphasizes that the lack of policy and regulations is a major barrier for the utilization of blockchain technology, and that legal frameworks and standards, as well as decision-making framework, must be developed in order to fully utilize the possibilities of blockchain. Thus, future research should aim to develop knowledge that can serve as input and provide foundation for governments and policymakers that are responsible for the development of such frameworks.

Furthermore, a lot of the current research on blockchain is on a hypothetical, conceptual level, and there is a need for more empirical studies that can provide evidence-based knowledge on the effects of blockchain implementations, in general and on SDGs in particular.

The nature of blockchain technology also requires new business models, and thus, new ways of managing the stakeholders, and distribution of risk and responsibility, in a given value chain. Researchers should aim to provide input for the development of models for stakeholder management in these novel contexts, for governments, policy- and decision-makers, and companies to use.

2) FOR COMPANIES USING BLOCKCHAIN

Substantial work concerns the use of blockchain technology to improve conditions for companies, for example in sustainable production. Blockchain can enable new services and applications and enhance or transform existing processes, systems, or services. A multitude of use cases for innovations are available in various domains. Blockchain is still in a growth stage, and significant progress and new opportunities can be expected shortly. The analysis of this paper may shed light on new directions and solutions that would assist companies and customers integrate their needs through blockchain. In addition, the analysis of barriers and drivers highlights the need for a cultural change and managerial awareness and support to embrace this new technology. Managers are recommended to carefully define strategies and policies for integrating blockchain technology in existing operational and managerial settings.

In particular, although it seems promising that blockchain adoption can enhance sustainability and impact SDGs positively, it may not be suitable for all contexts and needs. Many alternative blockchain technologies exist, and there is no "one-size-fits-all" solution. Some well-known decision trees with questions that help evaluate the applicability of blockchain technology are available in the literature [12], [18], [41], [80], [81], [82], [83], [84], [85]. However, [2] highlighted inconsistencies between the reported use cases

and the well-known decision rules. Even if some decision rules are not passed, the blockchain technology or a specific type of blockchain can still be used in a concrete use case because the application may focus on exploiting different features that blockchain offers. There are different design choices for implementing the same function. A systematic analysis such as the one suggested in [2] may help.

Our work offers managers an understanding of the benefits of investment in blockchain technology, blockchain's role in addressing the challenges of implementing sustainable practices and possible adoption barriers. Managers should pay attention to the importance of adequately evaluating blockchain's suitability and applicability for their needs as well as the tradeoff between potential benefits and the associated cost. The above mentioned literature and techniques can help managers in this process. A greater awareness among managers about the impact of blockchain technology on sustainable development may motivate them to support the adoption of this technology. In particular, managers should gain a knowledge of blockchain technology and the advantages it offers to sustainability in various fields and an awareness of the intra-organizational and inter-organizational barriers to the adoption of blockchain in order to lift the managerial awareness and commitment and incentivize the creation of new organizational policies and other aspects needed to create a favorable environment for this transition.

3) FOR POLICYMAKERS

For policymakers, our work provides insight and understanding of the technology and its impacts on SDGs besides the legal and regulatory barriers against its adoption, thus facilitating the establishment of the needed supportive legislation and governance framework.

In particular, the lack of policy and regulation for blockchain adoption within and across complex ecosystems of stakeholders is emphasized as a major barrier to blockchain adoption for sustainability [14], [16], [18], [29], [41], [42], [44]. Thus, policymakers should aim to provide the legal and regulatory frameworks demanded from practitioners. In addition, policymakers can contribute with financial incentives for technology adoption, for instance, [49] emphasized the role of policymakers in encouraging the participation in blockchain programs by giving tax incentives. Furthermore, policy- and decision-makers can contribute with financial funding for empirical and/or multidisciplinary projects aiming to address the underdeveloped research areas in blockchain research.

C. IMPLICATIONS TO SUSTAINABILITY

The UN SDGs are a comprehensive framework which calls for actions covering a wide spectrum of activities related to social, technical, socio-technical, business/economic, legal/regulation, ethical, and socio-economic issues. The SDGs cannot be simply met by implementing digital technologies and blockchain is only one of the enablers for fulfilling SDGs. We found a number of other enablers mentioned

in the literature that can help facilitate the achievement of sustainable development. For example, AI may have a positive impact on all SDGs by offering technological improvement in different sectors while negative effects on SDGs may be experienced if certain aspects of AI are not addressed [35]. From a business perspective, [86] investigated the role of AI in implementing sustainable business models (SBMs) in light of SDGs and highlighted the implications of AI concerning SDG 12 and the importance of managerial awareness about strategies to achieve SDGs. Reference [87] reviewed the literary corpus regarding the role of intellectual capital for sustainable and innovative development of organizations towards the creation of SBMs linked to SDGs. Reference [88] investigated the role of accounting and accountability models on the transition towards a circular economy and waste management and the contribution of digital transformation in this aspect from the viewpoint of SDGs.

Several researchers have also studied the relationships and interdependency between SDGs. For policymakers and planners, the implementation of SDGs needs to take into account the interactions between SDGs as illustrated in [23] which has proposed a *goal-scoring* framework with a seven-point scale of SDG interactions to help policymakers make coherent policies and strategies towards sustainable development pathways that can enhance positive interactions while minimizing negative ones.

D. THREATS TO VALIDITY

Our work is a tertiary review that is based on a systematic review of the reviews on the selected topic. Thus, the results are limited by the scope of the included papers. There may be a bias in selecting papers and the documented evidence in the included papers may not be exhaustive. As the literature seldom explicitly provided a linkage between blockchain and SDGs, specifically at the SDG target level, we did a mapping based on our understanding of the impact of blockchain and the SDGs. The results may be biased or limited by our knowledge and understanding. Nevertheless, as described in the methodology section, we have tried to mitigate this limitation by consulting literature on SDGs, adopting the expert consensus method, verifying the results using at least two authors in the process, and reviewing the mappings in several iterations.

In Fig. 4, some SDG targets are not marked with positive or negative impacts as we have not found evidence of potential impacts from the literature we reviewed. However, this does not mean that there is no relationship between blockchain and the remaining SDG targets. An additional literature search and future research may indicate further interlinkage between blockchain and the unmapped SDGs in Fig. 4.

VI. CONCLUSION AND FUTURE WORK

Blockchain is a disruptive technology and a driver for social changes. Combined with other technologies, like AI, big data and IoT, blockchain has a great potential to empower numerous innovative applications and provide technological

TABLE 4. Surveyed papers with evidence on blockchain's potential positive impacts on SDGs.

SDG	Reference paper
SDG 1 – No poverty	[12], [14], [16], [38]–[40], [55], [56], [61], [63]
SDG 2 – Zero hunger	[11], [12], [16], [29], [38], [40]–[44], [46]–[50], [54]–[56], [58], [61]
SDG 3 – Good health and well-being	[2], [10], [16], [29], [38], [40]–[42], [44], [46], [48]–[50], [55]–[58]
SDG 4 – Quality education	[2], [10], [16], [56]
SDG 5 – Gender equality	[61]
SDG 6 – Clean water and sanitation	[2], [27], [46], [56]
SDG 7 – Affordable and clean energy	[2], [10], [12], [27], [29], [39], [50], [54]–[56], [61]
SDG 8 – Decent work and economic growth	[2], [14], [16]–[18], [24], [29], [30], [38], [40], [44], [46], [49], [52], [54]–[57], [61], [63]
SDG 9 – Industry, Innovation and Infrastructure	[2], [10], [13], [14], [16]–[19], [38]–[40], [44], [46]–[48], [52]–[54], [59], [60]
SDG 10 – Reduced inequalities	[2], [16], [17], [27], [38], [40], [54]–[56], [61], [63]
SDG 11 – Sustainable cities and communities	[2], [10], [12], [16]–[18], [27], [29], [46], [51], [52], [53]
SDG 12 – Responsible consumption and production	[2], [10], [11], [13], [14], [16], [17], [19], [24], [27], [29], [30], [38], [40]–[44], [46]–[54], [56]–[61], [63]
SDG 13 – Climate action	[2], [8], [14], [16], [27], [29], [30], [42], [43], [49], [50], [51], [53], [54], [57], [59], [61]
SDG 14 – Life beneath water	[16], [38]
SDG 15 – Life on land	[2], [16], [24], [54], [57]
SDG 16 – Peace, justice and strong institutions	[2], [10], [11], [14], [16], [18], [27], [30], [38], [40], [44], [49], [53], [55], [56], [61], [63]
SDG 17 – Partnerships for the goals	[2], [13], [14], [16], [17], [24], [29], [30], [38], [40], [42]–[45], [61]

TABLE 5. Surveyed papers with evidence on blockchain's potential negative impacts on SDGs. Only the SDGs that blockchain has negative impact on are included.

SDG	Reference paper
SDG 2 – Zero hunger	[38], [40], [55]
SDG 7 – Affordable and clean energy	[9], [14], [18], [29], [55], [56], [62]
SDG 8 – Decent work and economic growth	[9], [38], [40], [46], [55], [56], [62]
SDG 9 – Industry, Innovation and Infrastructure	[38], [40], [55]
SDG 10 – Reduced inequalities	[38], [40], [55], [56]
SDG 12 – Responsible consumption and production	[9], [55], [56], [62]
SDG 13 – Climate action	[29], [55], [62]
SDG 16 – Peace, justice and strong institutions	[9], [40], [55]

improvement or enhancement to overcome limitations or domain challenges. Therefore, it can act as a catalyst to achieve potentially all SDGs defined in the UN 2030 Agenda and has already exhibited its great potential to promote sustainable practices.

TABLE 6. Summary of the surveyed papers with their focus area, search query, articles reviewed by each paper and the main outcomes. "N/A" means no explicit information provided in the paper.

Paper	Focus area	Search query	Articles reviewed	Main outcomes
[11]	Supply chain and logistics	N/A	N/A	Examined blockchain's potential application to supply chain management. Classified blockchain technology adoption barriers into 4 categories: inter-organizational, intra-organizational, technical and external barriers.
[16]	Supply chain and logistics	"blockchain"+"sustainable supply chain management"	187 out of 1102 papers from EBSCO Host, ProQuest, Directory of Open Access Journals, Springer Link, Emerald Open Access, Harvard Business Review, MDPI, and Science Direct published after 2015.	Provided a classification framework (ETLCL) for surveying emerging technologies and applied this to blockchain technology. The study highlighted transparency and traceability as the main benefits of adopting blockchain technology.
[24]	Supply chain and logistics	N/A	N/A	Identified challenges and requirements such as technical issues, government requirements and regulations and consumer acceptance, that need to be addressed in order to enable transparency in food supply chains via technologies including IoT and blockchain.
[30]	Supply chain and logistics	"blockchain in supply chain", "P2P network", "blockchain impact on supply chain transparency", "blockchain impact on supply chain traceability", "blockchain impact on supply chain sustainability", "blockchain impact on supply chain trust", and "blockchain impact on supply chain cost-efficiency"	52 out of 109 articles from Google Scholar and ScienceDirect, published from 2015 to 2019.	Highlighted blockchain's potentials in improving supply chain performance in terms of traceability, transparency, sustainability, trust and cost-efficiency.
[38]	Supply chain and logistics	Multiple case studies	N/A	Provided early evidence on blockchain's role in achieving key supply chain objectives and the blockchain-based mechanisms for increasing transparency and accountability through 11 case studies.
[40]	Supply chain and logistics	"blockchain" or "distributed ledger" or "digital ledger" or "shared ledger"; "supply chain", "logistics", "demand chain" and "value chain"	29 out of 227 articles from ABI Inform Global, Emerald, IEEE Explore, Jstor, Science Direct, Scopus, Springer, Taylor and Francis and Web of Science, from 2008 to 2017.	Trust was the predominant factor driving blockchain's early adoption in supply chains. Adopting blockchain for supply chain management contributes to supply chain digitalization and disintermediation, extended traceability and visibility, smart contracts and improved data security.
[41]	Supply chain and logistics, traceability	"blockchain AND food traceability/supply chain" or "blockchain AND information security" or "digital AND food traceability/supply chain" or "smart contract AND agriculture/food"	Articles from Google Scholar, Web of Science, ScienceDirect (Elsevier), IEEE Xplore, ProQuest (ABI/ INFORM), CNKI and other online resources, from 2005 to 2019.	Reviewed blockchain technology applications on food supply chain related to sustainable traceability management. Proposed an architecture design and analysis tools for application of such systems. Highlighted benefits and challenges of implementing blockchain based food traceability systems.
[42]	Supply chain and logistics	blockchain, food supply chain	26 articles from Web of science, Scopus, and Ebsco (57 from initial search).	Proposed benefits (transparency, information authenticity, sustainability, efficiency) and challenges (such as lack of understanding, immature technology, stakeholder cooperation, trade secrets, raw data manipulation, regulation deficiency) for blockchain adoption within food supply chain.
[43]	Supply chain and logistics	sustainable AND "supply chain" AND "food OR agri-products OR agri-food OR agriculture OR farm"	84 out of 128 articles from Web of Science for the period from 2000 to 2017.	Proposed a data-driven application framework for agri-food supply chain and identified the supply chain visibility and supply chain resources as the key driving factor for data analytics development and sustainable performance outcome. Identified blockchain's potential in achieving better integration of supply chain resources.
[44]	Supply chain and logistics	N/A	N/A	Explained the use of blockchain in logistics processes, its impact on business transparency and benefits and challenges of the application of blockchain in logistics.
[45]	Supply chain and logistics	Combination of AND and OR between the terms in each bullet point: • IT outsourcing, sourcing, vertical outsourcing, outsourcing chain, IT outsourcing blockchain,	146 articles from Web of Science, ScienceDirect, AISeLibrary, Scopcus, Sage Journals, Google Scholar and IEEE Xplore databases, considering the period from 2009 to 2019.	Identified mechanisms for IT outsourcing chains' management, interchain coordination and sustainability, and interchain activities' cohesion. Interchain coordination can be improved by the application of blockchain economy and by enterprise architecture modelling.

TABLE 6. *(Continued.)* Summary of the surveyed papers with their focus area, search query, articles reviewed by each paper and the main outcomes. "N/A" means no explicit information provided in the paper.

		multi-sourcing • Supply chain, relation changeability, communication, compensation and compliances in outsourcing, contracting, stakeholder, decision-making, governance, integration, performance measurement, project management in outsourcing and strategic considerations of outsourcing, • Vertical software development, vertical integration, vertical cooperation, distributed systems • Model, theory, survey, case study, field study, review.		
[46]	Supply chain and logistics	"blockchain" OR "distributed ledger" AND "food supply chain"	69 articles from IEEE Xplore, ScienceDirect, Springer Link, Taylor and Francis Online, Wiley Online Library published until (including) December 2020.	Identified the challenges of scalability, privacy and security of blockchain applications as well as current practices to cope with them, and proposed future research directions and their relevance to the SDGs as well as contribution towards more sustainable, transparent and traceable food supply chains.
[47]	Supply chain and logistics, circular economy	("barriers of circular economy" OR "circular economy barriers" OR "challenges of circular economy" OR "circular economy challenges") AND ("food supply chain") AND ("closed-loop economy" OR "circularity" OR "implementation of circular economy" OR "application of circular economy") AND ("reuse" OR "reduce" OR "recycle" OR "recover" OR "repair" OR "remanufacture" OR "repurpose" OR "rethink")	136 out of 501 articles from WoS and Scopus.	Classified circular economy barriers in the food supply chain under seven categories: cultural, regulatory and governmental, business and business finance, technological, managerial, knowledge and skills, supply-chain management. These barriers to circular economy transition can be overcome using Industry 4.0 technologies, for example, blockchain and big data analytics to support the legal systems and enhance environmental regulations.
[48]	Supply chain and logistics, traceability	"TITLE-ABS-KEY (blockchain OR "distributed ledger" AND "supply chain" AND traceability)"	72 out of 668 articles from Scopus published from 2018 to 2021.	Classified blockchain-specific supply chain traceability implementations based on their domains, applied methodologies and covered sustainability perspectives. Outlined technical characteristics and implementation maturity details of the available implementations. Discussed implementation issues, research gaps and open issues related to blockchain-specific supply chain traceability implementations.
[49]	Supply chain and logistics	"certification" or "blockchain" or "sustainability" AND "halal" or "halal food"	54 out of 253 articles from Web of Science published from 2001 to 2021.	Demonstrated that certification and blockchain could enhance the traceability, reliability and sustainability of Halal foods, assuring fair trade, green animal breeding, ethical business and environmental economics.
[50]	Supply chain and logistics	("Sustainability" OR "Sustainable" OR "Green") AND ("Logistics" OR "Supply chain" OR "Reverse logistics") AND ("Blockchain" OR "Internet of Things" OR "IoT")	174 out of 488 articles from Scopus published from 2011 to 2020.	Investigated the individual and integrated impact of blockchain and IoT on sustainable forward and reverse supply chain management. Findings showed that blockchain and IoT can improve sustainability dimension in almost 18 sectors, but also disclosed the need for more research on social sustainability of supply chain.
[51]	Supply chain and logistics	Combinations of: • "physical internet" OR "intermodal freight transport"; • "logistics" OR "International cooperation" OR "supply chain" OR "shipping" OR "Multimodality" • "intermodal logistics" OR "synchromodality" OR "hyperloop" OR	74 secondary studies from Scopus, Web of Science and Emerald Insight published from 2016 to 2022.	A tertiary study on the application of disruptive technologies (including blockchain) and Physical Internet on supply chain management. Identified the key activities, strategies and knowledge areas in supply chain management where disruptive technologies and Physical Internet are game-changing. Presented a conceptual framework summarizing the relationships between supply chain key activities, Physical Internet themes and disruptive technologies.

TABLE 6. *(Continued.)* Summary of the surveyed papers with their focus area, search query, articles reviewed by each paper and the main outcomes. "N/A" means no explicit information provided in the paper.

		"autonomous vehicles" OR ("belt" AND "road initiative") OR "silk road" OR "Transport networks" OR "Industry 4.0" OR "blockchain" OR "artificial intelligence" OR "big data" OR "internet of things" • "systematic review" OR "systematic literature review"		
[12]	Energy	N/A	N/A	Reviewed key blockchain applications in smart grid, including the advantages, approaches, and technical challenges and frameworks. Showed the use of blockchain as the cyber-physical layer for smart grid.
[39]	Energy	N/A	N/A	Provided SWOT analysis for China's distributed PV development. Identified the application mode of blockchain to the distributed PV industry. Provided policy proposals to support formulation of industry regulations in China.
[2]	Smart cities	"blockchain" and "city or urban"	159 articles from ACM, ASCE, IEEE, e-Government Research Library (EGRLv13.5), JSTOR, ScienceDirect, Scopus, Springer, Web of Science, Wiley	Organized blockchain application-oriented use cases by 9 sectors. Proposed role-based and business model-based methods for cross-sector blockchain use case classification. Proposed a component-based analysis framework that helps identify gaps for applying blockchain use cases. The review can be used to evaluate the implication of blockchain applications for urban sustainability goals.
[10]	Smart cities	blockchain AND "smart cit*"	73 articles from Web of Science published from 2016 to 2020.	Identified 9 application fields of blockchain in smart cities. Addressed how blockchain may benefit the urban development, and derived propositions for future research.
[27]	Smart cities	N/A	N/A	Identified five key blockchain application areas in smart city for achieving sustainability. Proposed a smart sustainable city-blockchain integration framework.
[52]	Smart cities	'Building Information Modeling', 'Sustainable Building', 'Sustainable Building Construction', 'Sustainable Building Operation', 'Sustainable Building Design', and 'Blockchain'.	1305 articles from WoS published between 2011 and 2020 for bibliometric analysis followed by micro scheme analysis of 61 articles.	Explored the potential impact of integrating blockchain and Building Information Model (BIM) for sustainable building across the construction project life cycle in smart cities, highlighting their interrelationships, and identifying gaps and trends.
[53]	Smart cities	Combinations of: • "blockchain", "digital ledger technology" • "sustainability", "sustainable" • "built environment", "construction sector", "construction industry", "real estate", "real property", "construction project", "building project"	90 out of 1384 documents from SciVerse Scopus published from 2016 to 2022.	Classified 6 main blockchain application areas for sustainability: supply chain, smart city, commerce, smart power grids, cryptocurrency and agri-food sector. Identified 6 key blockchain applications for the built environment: BIM security, construction management, contract management, real estate, payment automation and smart city. A conceptual framework summarizes the challenges and future exploratory directions for the integration of blockchain in the built environment to achieve sustainable buildings.
[13]	Manufacturing and industry 4.0	"blockchain" and "industry 4.0"	22 out of 109 articles from ScienceDirect, Emerald Insight, Taylor & Francis Online, Wiley Online Library, IEEE Xplore, Sage Publications and Springer Link published from 2018 to 2020.	Classified vital cyber-attacks in Industry 4.0 and performed a comparative study of the application of blockchain for cyber-threats in Industry 4.0. The review indicated that the integration of blockchain in industry can ensure data integrity, confidentiality, availability and privacy.
[17]	Manufacturing and industry 4.0	"blockchain", "sustainable product lifecycle", "sustainable manufacturing", and "Industry 4.0"	183 articles from Science Direct, IEEE Xplore, Taylor & Francis Online, Springer, Wiley InterScience, Emerald Insight, AIS Electronic Library, Georgia Tech Library, and MDPI	Defined and discussed metrics for adopting blockchain in different situations to achieve sustainability from the product lifecycle management and the manufacturing system perspectives. Summarized challenges for adopting blockchain in manufacturing applications.
[18]	Manufacturing and industry 4.0	N/A	N/A	Analyzed the potential of applying blockchain to addressing current challenges in the automotive industry focusing on cybersecurity features. Summarized main blockchain use cases, and proposed recommendations for future cyber-resilient automotive industry development based on SWOT analysis.

TABLE 6. *(Continued.)* Summary of the surveyed papers with their focus area, search query, articles reviewed by each paper and the main outcomes. "N/A" means no explicit information provided in the paper.

[19]	Manufacturing and industry 4.0	("Sustainab*" OR "environ*" OR Green OR "Societal" OR "CSR" OR "eco*" OR "Social") AND ("Blockchain" OR "distributed ledger" OR "Smart Contract")	21 out of 883 articles from Scopus	Explained the potential contributions of blockchain technology to the social, economic and environmental performances of manufacturers and the supply chains. Illustrated how blockchain can influence manufacturers' sustainable performance through transparency, real-time information sharing, traceability, and security of the data capabilities.
[54]	Manufacturing and industry 4.0	N/A	N/A	Adopted HAZOP literature review approach to investigate the potential integration of Industry 4.0 technologies in the palm-based energy, food and chemical production processes. Proposed 23 recommendations to enhance the palm oil industry with Industry 4.0 technologies (including blockchain) to achieve a better sustainable production. Identified 13 Industry 4.0 features as development gaps for the palm oil industry.
[14]	Transportation	"Blockchain AND Sustainability", "Blockchain AND Document exchange", "Blockchain AND Information exchange", "Blockchain AND Transport", "Blockchain AND Sustainability AND Transport", "Blockchain AND Maritime transport", "Blockchain AND Maritime industry", "Blockchain AND Shipping", "Blockchain AND Seaport", "Blockchain AND Port"	99 sources, from Web of Science and Scopus, from 2015 to 2020.	Identified several barriers and challenges, yet it finds that blockchain technology has potential to improve information exchange between stakeholders, positively affecting several aspects of sustainability.
[29]	Transportation	"blockchain AND traffic", "blockchain AND logistic", "blockchain AND supply chain", blockchain AND airport", "blockchain AND transport", "blockchain AND transportation"	371 articles from Scopus, from 2006 to 2019.	Found that blockchain technology is "extremely promising", but at a very early stage of development. Blockchain technology may trigger several sustainability-related improvements, such as reducing resource consumption and waste.
[9]	Finance/bitcoin	"blockchain", "FinTech" or "financial technology"	49 articles from Web of Science Core Collection published from 2016 to 2019.	The analysis indicated that the main challenges for blockchain application in FinTech are associated with scalability, latency, security, privacy, legal and regulatory.
[55]	Finance/bitcoin	"bitcoin", "digital currency", "cryptocurrency" and "virtual currency", with "sustainability"	Literature search in Scopus, Web of Science and Google Scholar.	The literature search showed that generally a small number of publications considered the sustainability of bitcoin and cryptocurrency. High energy consumption and GHG emission associated with mining has negative impact on environmental sustainability.
[56]	Smart villages	Blockchain, rural, rural development, rural banking, rural incentivization, rural education, rural healthcare, rural environment, rural energy, agriculture, farming, livestock, traceability, supply chain, developing countries, and smart village	112 out of 157 articles from ACM Digital Library, IEEE, Elsevier, Springer, Science Direct, Google Scholar published from 2010 to 2021.	A systematic literature review of key applications and areas implementing blockchain for smart villages to achieve sustainable rural development. Identified major issues in rural development and blockchain's potential to address them. Explored existing platforms, software and tools for blockchain implementation in rural development. Identified research gaps and future directions for using blockchain to realize smart villages in rural development.
[57]	Forestry	("blockchain" OR "blockchain-based" OR "block chain") AND ("forest*" OR "timber" OR "wood*")	21 out of 570 articles from Scopus, Web of Sciences, ACM digital library, and IEEE Xplore published from 2017 to 2022.	Categorized blockchain applications/solutions in the forestry sector into three domains: traceability of forest-based products, forest management and forest fire detection. Identified benefits, challenges and opportunities for blockchain application in forestry. Showed blockchain's potential in sustainable forestry, conserving biodiversity and minimizing illegal logging. Identified research gaps and future research directions on the blockchain application in forestry.
[58]	Traceability	N/A	N/A	A functional traceability system must meet a variety of regulations and laws as well as consumer value and perspective associated with the regions it operates. AI and blockchain are among the promising technologies available to modernize traceability systems. Blockchain has potential to improve traceability across the food supply chain. It is vital to adopt common traceability systems to maintain the sustainability of the significant trade links that positively impact the EU and China economies.

TABLE 6. *(Continued.)* Summary of the surveyed papers with their focus area, search query, articles reviewed by each paper and the main outcomes. "N/A" means no explicit information provided in the paper.

[59]	Traceability, circular economy	'traceability system', 'Blockchain-based traceability', 'IoT-based traceability', 'Fashion' or 'Textile and Clothing', 'Circular Economy'	96 documents from Google Scholar.	Current approaches and key technologies for traceability and the promotion of circular economy in the textiles and clothing (T&C) value chain are identified. Blockchain is considered essential for registering traceable items' activities through the value chain. Benefits and challenges for blockchain implementation on the T&C value chain are identified.
[60]	Circular economy	(blockchain OR bitcoin OR ledger) AND "circular economy"; (blockchain or ledger or bitcoin) and "circular economy"; #blockchain AND #circulareconomy	57 documents (30 articles from research review from Scopus and Google Scholar and 27 records from practice review from Google and Twitter)	Three key findings: 1) There is a lack in research for a clear terminology of blockchain types and technical properties and benefits, 2) Verification and trust are major potential benefits but they also create challenges, and 3) It is crucial to have a closer examination of potential benefits and challenges of blockchain application for the circular economy in light of sustainable development.
[61]	Standards	N/A	N/A	Blockchain standards will enhance the reputation of blockchain as a useful technology layer for the tracking and auditing of data and transactions, and make blockchain a critical tool for achieving trust and transparency in sustainable development efforts.
[62]	Law and policy	N/A	N/A	Identified regulations and legal tools that may limit energy consumption of digital currencies, without harming the blockchain sector.
[8]	Research topics	N/A	N/A	Illustrated the main blockchain-based components and industrial applications. Identified blockchain's potential role in the sustainable development and the implementation challenges.
[63]	Fairness	Step 1&2 (academic and grey literature): • Fairness, justice, agr*, chain • Step 2 Upstream Agro-food chain focus: producer*, farmer*, fair price • Step 2 Downstream Agro-food chain focus: consumer*, behav* Step 3 (business applications): • Fairness, justice, agr*, chain • For Upstream Agro-food chain: producer*, farmer*, fair price, blockchain, business model*, tech*, fair trade • For Downstream Agro-food chain: consumer*, behav*, dynamic pricing, dual entitlement	Step 1&2: 79 papers; 5 reports; 1 website from Scopus, WOS, Google Scholar, International institutions' websites. Step 3: 36 papers; 10 reports; 4 websites from Scopus, WOS, Google Scholar, International institution reports and websites, Researchers, Experts, Website search, Consultancy reports.	Defined three types of fairness: distributive fairness, procedural fairness and interactional fairness. Identified 12 key upstream fairness-enabling practices and 5 downstream fairness-enabling practices. Explained blockchain's role to contributing to the three fairness types.

This tertiary study, built upon existing systematic reviews on the relationship between blockchain and sustainability, has investigated the potential positive and negative impacts on SDGs that blockchain may bring about. Positive impacts on all 17 SDGs with direct impacts on 76 SDG targets have been identified from the surveyed papers. Our study also reveals that most blockchain applications are with low maturity, e.g., as prototypes, new deployments, or even only at a conceptual level, therefore, their real influence and long-term effects are hard to be concluded.

Based on thematic analysis from identified systematic reviews, this study further presents a systematic overview of drivers and barriers to blockchain adoption for sustainable development, categorized into system-level, intra-organizational, inter-organizational, and external/societal dimensions. Implications of these barriers and drivers on SDGs have been provided as well.

Blockchain is still an immature technology. Its deployment is in its early stages and has been largely experimental. Our study acknowledges issues that need to be addressed before the potential of blockchain can be fully exploited and the negative impacts can be minimized. Our future work is to follow empirical evidence of real impacts and investigate how software engineering theories and practices can help the development of blockchain-based systems for sustainable development.

Finally, blockchain is only one of the enablers to achieve SDGs. The UN 2030 Agenda has set up a comprehensive framework for sustainable development and the achievement of SDGs not only calls for the implementation of driving technological solutions, but also needs to address social, ethical, legal, business, socio-technical, and other issues to balance the three pillars of sustainable development.

APPENDIX

See Tables 4, 5, and 6.

ACKNOWLEDGMENT

REFERENCES

[1] J. Elkington, "Accounting for the triple bottom line," *Measuring Bus. Excellence*, vol. 2, no. 3, pp. 18–22, Mar. 1998, doi: 10.1108/eb025539.

[2] C. Shen and F. Pena-Mora, "Blockchain for cities—A systematic literature review," *IEEE Access*, vol. 6, pp. 76787–76819, 2018, doi: 10.1109/ACCESS.2018.2880744.

[3] United Nations. (1987). *Report of the World Commission on Environment and Development: Our Common Future*. [Online]. Available: https://sustainabledevelopment.un.org/content/documents/5987our-common-future.pdf

[4] United Nations. (2015). *Transforming Our World: The 2030 Agenda for Sustainable Development*. [Online]. Available: https://sustainabledevelopment.un.org/post2015/transformingourworld/publication

[5] N. D. P. A. Filho, "The agenda 2030 for responsible management education: An applied methodology," *Int. J. Manage. Educ.*, vol. 15, no. 2, pp. 183–191, Jul. 2017, doi: 10.1016/j.ijme.2017.02.010.

[6] O. Kostoska and L. Kocarev, "A novel ICT framework for sustainable development goals," *Sustainability*, vol. 11, no. 7, p. 1961, Apr. 2019, doi: 10.3390/su11071961.

[7] M. Nabipour and M. A. Ülkü, "On deploying blockchain technologies in supply chain strategies and the COVID-19 pandemic: A systematic literature review and research outlook," *Sustainability*, vol. 13, no. 19, p. 10566, Sep. 2021, doi: 10.3390/su131910566.

[8] Y. Lu, "Blockchain and the related issues: A review of current research topics," *J. Manage. Anal.*, vol. 5, no. 4, pp. 231–255, 2018, doi: 10.1080/23270012.2018.1516523.

[9] S. Fernandez-Vazquez, R. Rosillo, D. De La Fuente, and P. Priore, "Blockchain in FinTech: A mapping study," *Sustainability*, vol. 11, no. 22, p. 6366, Nov. 2019, doi: 10.3390/su11226366.

[10] H. Treiblmaier, A. Rejeb, and A. Strebinger, "Blockchain as a driver for smart city development: Application fields and a comprehensive research agenda," *Smart Cities*, vol. 3, no. 3, pp. 853–872, Aug. 2020, doi: 10.3390/smartcities3030044.

[11] S. Saberi, M. Kouhizadeh, J. Sarkis, and L. Shen, "Blockchain technology and its relationships to sustainable supply chain management," *Int. J. Prod. Res.*, vol. 57, no. 7, pp. 2117–2135, Apr. 2019, doi: 10.1080/00207543.2018.1533261.

[12] A. S. Musleh, G. Yao, and S. M. Muyeen, "Blockchain applications in smart grid—Review and frameworks," *IEEE Access*, vol. 7, pp. 86746–86757, 2019, doi: 10.1109/ACCESS.2019.2920682.

[13] S. B. ElMamy, H. Mrabet, H. Gharbi, A. Jemai, and D. Trentesaux, "A survey on the usage of blockchain technology for cyber-threats in the context of industry 4.0," *Sustainability*, vol. 12, no. 21, pp. 1–19, 2020, doi: 10.3390/su12219179.

[14] M. Jović, E. Tijan, D. Žgaljić, and S. Aksentijević, "Improving maritime transport sustainability using blockchain-based information exchange," *Sustainability*, vol. 12, no. 21, pp. 1–19, 2020, doi: 10.3390/su12218866.

[15] P. D. R. Griffiths and P. Baudier, "Enabling responsible banking through the application of blockchain," *J. Innov. Econ. Manag.*, vol. 2022, p. I126, Jan. 2022.

[16] V. Paliwal, S. Chandra, and S. Sharma, "Blockchain technology for sustainable supply chain management: A systematic literature review and a classification framework," *Sustainability*, vol. 12, no. 18, p. 7638, Sep. 2020, doi: 10.3390/su12187638.

[17] J. Leng, G. Ruan, P. Jiang, K. Xu, Q. Liu, X. Zhou, and C. Liu, "Blockchain-empowered sustainable manufacturing and product lifecycle management in industry 4.0: A survey," *Renew. Sustain. Energy Rev.*, vol. 132, Oct. 2020, Art. no. 110112, doi: 10.1016/j.rser.2020.110112.

[18] P. Fraga-Lamas and T. M. T. M. Fernández-Caramés, "A review on blockchain technologies for an advanced and cyber-resilient automotive industry," *IEEE Access*, vol. 7, pp. 17578–17598, 2019, doi: 10.1109/ACCESS.2019.2895302.

[19] A. A. A. Khanfar, M. Iranmanesh, M. Ghobakhloo, M. G. Senali, and M. Fathi, "Applications of blockchain technology in sustainable manufacturing and supply chain management: A systematic review," *Sustainability*, vol. 13, no. 14, p. 7870, Jul. 2021, doi: 10.3390/su13147870.

[20] S. Jiang, K. Jakobsen, L. Jaccheri, and J. Li, "Blockchain and sustainability: A tertiary study," in *Proc. IEEE/ACM Int. Workshop Body Knowl. Softw. Sustainability (BoKSS)*, Los Alamitos, CA, USA, Jun. 2021, pp. 7–8, doi: 10.1109/BoKSS52540.2021.00011.

[21] B. A. Kitchenham and S. Charters, "Guidelines for performing systematic literature reviews in software engineering," Keele Univ., Keele, U.K., Tech. Rep., EBSE 2007-001, 2007. [Online]. Available: https://www.elsevier.com/_data/promis_misc/525444systematic reviewsguide.pdf

[22] V. Braun and V. Clarke, "Using thematic analysis in psychology," *Qualitative Res. Psychol.*, vol. 3, no. 2, pp. 77–101, Jan. 2006, doi: 10.1191/1478088706qp063oa.

[23] M. Nilsson, D. Griggs, and M. Visbeck, "Policy: Map the interactions between sustainable development goals," *Nature*, vol. 534, no. 7607, pp. 320–322, Jun. 2016, doi: 10.1038/534320a.

[24] J. Astill, R. A. Dara, M. Campbell, J. M. Farber, E. D. G. Fraser, S. Sharif, and R. Y. Yada, "Transparency in food supply chains: A review of enabling technology solutions," *Trends Food Sci. Technol.*, vol. 91, pp. 240–247, Sep. 2019, doi: 10.1016/j.tifs.2019.07.024.

[25] M. S. Ferdous, M. J. M. Chowdhury, and M. A. Hoque, "A survey of consensus algorithms in public blockchain systems for crypto-currencies," *J. Netw. Comput. Appl.*, vol. 182, May 2021, Art. no. 103035, doi: 10.1016/j.jnca.2021.103035.

[26] B. Cao, Y. Li, L. Zhang, S. Mumtaz, Z. Zhou, and M. Peng, "When Internet of Things meets blockchain: Challenges in distributed consensus," *IEEE Netw.*, vol. 33, no. 6, pp. 133–139, Nov./Dec. 2019.

[27] P. F. Wong, F. C. Chia, M. S. Kiu, and E. C. W. Lou, "The potential of integrating blockchain technology into smart sustainable city development," *IOP Conf. Ser., Earth Environ. Sci.*, vol. 463, Apr. 2020, Art. no. 012020, doi: 10.1088/1755-1315/463/1/012020.

[28] J. Thomason, "Blockchain: An accelerator for women and children's health?" *Global Health J.*, vol. 1, no. 1, pp. 3–10, Jun. 2017.

[29] V. Astarita, V. P. Giofrè, G. Mirabelli, and V. Solina, "A review of blockchain-based systems in transportation," *Information*, vol. 11, no. 1, p. 21, Dec. 2019, doi: 10.3390/info11010021.

[30] L. P. Mahyuni, R. Adrian, G. S. Darma, N. N. K. Krisnawijaya, I. G. A. A. P. Dewi, and G. P. L. Permana, "Mapping the potentials of blockchain in improving supply chain performance," *Cogent Bus. Manage.*, vol. 7, no. 1, Jan. 2020, Art. no. 1788329, doi: 10.1080/23311975.2020.1788329.

[31] M. Xu, X. Chen, and G. Kou, "A systematic review of blockchain," *Financial Innov.*, vol. 5, no. 1, pp. 1–14, 2019.

[32] Z. Zheng, S. Xie, H. Dai, X. Chen, and H. Wang, "An overview of blockchain technology: Architecture, consensus, and future trends," in *Proc. IEEE Int. Congr. Big Data (BigData Congr.)*, Jun. 2017, pp. 557–564, doi: 10.1109/BigDataCongress.2017.85.

[33] D. Puthal, N. Malik, S. P. Mohanty, E. Kougianos, and G. Das, "Everything you wanted to know about the blockchain: Its promise, components, processes, and problems," *IEEE Consum. Electron. Mag.*, vol. 7, no. 4, pp. 6–14, Jul. 2018, doi: 10.1109/MCE.2018.2816299.

[34] T. Ahram, A. Sargolzaei, S. Sargolzaei, J. Daniels, and B. Amaba, "Blockchain technology innovations," in *Proc. IEEE Technol. Eng. Manage. Conf. (TEMSCON)*, Jun. 2017, pp. 137–141, doi: 10.1109/TEMSCON.2017.7998367.

[35] R. Vinuesa, H. Azizpour, I. Leite, M. Balaam, V. Dignum, S. Domisch, A. Felländer, S. D. Langhans, M. Tegmark, and F. Fuso Nerini, "The role of artificial intelligence in achieving the sustainable development goals," *Nature Commun.*, vol. 11, no. 1, p. 233, Jan. 2020, doi: 10.1038/s41467-019-14108-y.

[36] F. Fuso Nerini, B. Sovacool, N. Hughes, L. Cozzi, E. Cosgrave, M. Howells, M. Tavoni, J. Tomei, H. Zerriffi, and B. Milligan, "Connecting climate action with other sustainable development goals," *Nature Sustainability*, vol. 2, no. 8, pp. 674–680, Aug. 2019, doi: 10.1038/s41893-019-0334-y.

[37] F. F. Nerini, J. Tomei, L. S. To, I. Bisaga, P. Parikh, M. Black, A. Borrion, C. Spataru, V. Castán Broto, G. Anandarajah, B. Milligan, and Y. Mulugetta, "Mapping synergies and trade-offs between energy and the sustainable development goals," *Nature Energy*, vol. 3, no. 1, pp. 10–15, Jan. 2018, doi: 10.1038/s41560-017-0036-5.

[38] N. Kshetri, "1 Blockchain's roles in meeting key supply chain management objectives," *Int. J. Inf. Manage.*, vol. 39, pp. 80–89, Apr. 2018, doi: 10.1016/j.ijinfomgt.2017.12.005.

[39] J. Hou, H. Wang, and P. Liu, "Applying the blockchain technology to promote the development of distributed photovoltaic in China," *Int. J. Energy Res.*, vol. 42, no. 6, pp. 2050–2069, May 2018, doi: 10.1002/er.3984.

[40] Y. Wang, J. H. Han, and P. Beynon-Davies, "Understanding blockchain technology for future supply chains: A systematic literature review and research agenda," *Supply Chain Manage.*, vol. 24, no. 1, pp. 62–84, Jan. 2019, doi: 10.1108/SCM-03-2018-0148.

[41] H. Feng, X. Wang, Y. Duan, J. Zhang, and X. Zhang, "Applying blockchain technology to improve agri-food traceability: A review of development methods, benefits and challenges," *J. Cleaner Prod.*, vol. 260, Jul. 2020, Art. no. 121031, doi: 10.1016/j.jclepro.2020.121031.

[42] J. Duan, C. Zhang, Y. Gong, S. Brown, and Z. Li, "A content-analysis based literature review in blockchain adoption within food supply chain," *Int. J. Environ. Res. Public Health*, vol. 17, no. 5, p. 1784, Mar. 2020, doi: 10.3390/ijerph17051784.

[43] S. S. Kamble, A. Gunasekaran, and S. A. Gawankar, "Achieving sustainable performance in a data-driven agriculture supply chain: A review for research and applications," *Int. J. Prod. Econ.*, vol. 219, pp. 179–194, Jan. 2020, doi: 10.1016/j.ijpe.2019.05.022.

[44] E. Tijan, S. Aksentijević, K. Ivanić, and M. Jardas, "Blockchain technology implementation in logistics," *Sustainability*, vol. 11, no. 4, p. 1185, Feb. 2019, doi: 10.3390/su11041185.

[45] M. Pankowska, "Information technology outsourcing chain: Literature review and implications for development of distributed coordination," *Sustainability*, vol. 11, no. 5, p. 1460, Mar. 2019, doi: 10.3390/su11051460.

[46] J. Nurgazina, U. Pakdeetrakulwong, T. Moser, and G. Reiner, "Distributed ledger technology applications in food supply chains: A review of challenges and future research directions," *Sustainability*, vol. 13, no. 8, p. 4206, Apr. 2021, doi: 10.3390/su13084206.

[47] N. Ada, Y. Kazancoglu, M. D. Sezer, C. Ede-Senturk, I. Ozer, and M. Ram, "Analyzing barriers of circular food supply chains and proposing industry 4.0 solutions," *Sustainability*, vol. 13, no. 12, p. 6812, Jun. 2021, doi: 10.3390/su13126812.

[48] T. K. Dasaklis, T. G. Voutsinas, G. T. Tsoulfas, and F. Casino, "A systematic literature review of blockchain-enabled supply chain traceability implementations," *Sustainability*, vol. 14, no. 4, p. 2439, Feb. 2022, doi: 10.3390/su14042439.

[49] C. Bux, E. Varese, V. Amicarelli, and M. Lombardi, "Halal food sustainability between certification and blockchain: A review," *Sustainability*, vol. 14, no. 4, p. 2152, Feb. 2022, doi: 10.3390/su14042152.

[50] P. Dutta, R. Chavhan, P. Gowtham, and A. Singh, "The individual and integrated impact of blockchain and IoT on sustainable supply chains: A systematic review," *Supply Chain Forum, Int. J.*, vol. 2022, pp. 1–24, Jun. 2022, doi: 10.1080/16258312.2022.2082851.

[51] D. L. Cortes-Murcia, W. J. Guerrero, and J. R. Montoya-Torres, "Supply chain management, game-changing technologies, and physical internet: A systematic meta-review of literature," *IEEE Access*, vol. 10, pp. 61721–61743, 2022, doi: 10.1109/ACCESS.2022.3181154.

[52] Z. Liu, Z. Chi, M. Osmani, and P. Demian, "Blockchain and building information management (BIM) for sustainable building development within the context of smart cities," *Sustainability*, vol. 13, no. 4, p. 2090, Feb. 2021, doi: 10.3390/su13042090.

[53] K. Figueiredo, A. W. A. Hammad, A. Haddad, and V. W. Y. Tam, "Assessing the usability of blockchain for sustainability: Extending key themes to the construction industry," *J. Cleaner Prod.*, vol. 343, Apr. 2022, Art. no. 131047, doi: 10.1016/j.jclepro.2022.131047.

[54] C. H. Lim, S. Lim, B. S. How, W. P. Q. Ng, S. L. Ngan, W. D. Leong, and H. L. Lam, "A review of industry 4.0 revolution potential in a sustainable and renewable palm oil industry: HAZOP approach," *Renew. Sustain. Energy Rev.*, vol. 135, Jan. 2021, Art. no. 110223, doi: 10.1016/j.rser.2020.110223.

[55] P. Giungato, R. Rana, A. Tarabella, and C. Tricase, "Current trends in sustainability of bitcoins and related blockchain technology," *Sustainability*, vol. 9, no. 12, p. 2214, Nov. 2017, doi: 10.3390/su9122214.

[56] P. Kaur and A. Parashar, "A systematic literature review of blockchain technology for smart villages," *Arch. Comput. Methods Eng.*, vol. 29, no. 4, pp. 2417–2468, Jun. 2022, doi: 10.1007/s11831-021-09659-7.

[57] Z. He and P. Turner, "Blockchain applications in forestry: A systematic literature review," *Appl. Sci.*, vol. 12, no. 8, p. 3723, Apr. 2022, doi: 10.3390/app12083723.

[58] J. Qian, L. Ruiz-Garcia, B. Fan, J. I. R. Villalba, U. McCarthy, B. Zhang, Q. Yu, and W. Wu, "Food traceability system from governmental, corporate, and consumer perspectives in the European union and China: A comparative review," *Trends Food Sci. Technol.*, vol. 99, pp. 402–412, May 2020, doi: 10.1016/j.tifs.2020.03.025.

[59] L. Alves, E. F. Cruz, S. I. Lopes, P. M. Faria, and A. M. R. da Cruz, "Towards circular economy in the textiles and clothing value chain through blockchain technology and IoT: A review," *Waste Manage. Res., J. Sustain. Circular Economy*, vol. 40, no. 1, pp. 3–23, Jan. 2022, doi: 10.1177/0734242X211052858.

[60] A. Böckel, A.-K. Nuzum, and I. Weissbrod, "Blockchain for the circular economy: Analysis of the research-practice gap," *Sustain. Prod. Consumption*, vol. 25, pp. 525–539, Jan. 2021, doi: 10.1016/j.spc.2020.12.006.

[61] J. Horner and P. Ryan, "Blockchain standards for sustainable development," *J. ICT Stand.*, vol. 7, no. 3, pp. 225–247, 2019, doi: 10.13052/jicts2245-800X.733.

[62] J. Truby, "Decarbonizing bitcoin: Law and policy choices for reducing the energy consumption of blockchain technologies and digital currencies," *Energy Res. Social Sci.*, vol. 44, pp. 399–410, Oct. 2018, doi: 10.1016/j.erss.2018.06.009.

[63] A. Samoggia and Z. Beyhan, "Fairness-enabling practices in agro-food chain," *Sustainability*, vol. 14, no. 11, p. 6391, May 2022, doi: 10.3390/su14116391.

[64] The Explorer. *The Online SDG Explorer*. Accessed: Oct. 7, 2021. [Online]. Available: https://www.theexplorer.no/goals

[65] A. S. L. França, J. A. Neto, R. F. Gonçalves, and C. M. V. B. Almeida, "Proposing the use of blockchain to improve the solid waste management in small municipalities," *J. Cleaner Prod.*, vol. 244, Jan. 2020, Art. no. 118529, doi: 10.1016/j.jclepro.2019.118529.

[66] G. Zhao, S. Liu, C. Lopez, H. Lu, S. Elgueta, H. Chen, and B. M. Boshkoska, "Blockchain technology in agri-food value chain management: A synthesis of applications, challenges and future research directions," *Comput. Ind.*, vol. 109, pp. 83–99, Aug. 2019, doi: 10.1016/j.compind.2019.04.002.

[67] M. O. AlMuhairi. (May 8, 2020). *Why COVID-19 Makes a Compelling Case for the Wider Integration of Blockchain*. Accessed: Aug. 9, 2021. [Online]. Available: https://www.weforum.org/agenda/2020/05/why-covid-19-makes-a-compelling-case-for-wider-integration-of-blockchain/

[68] S. Sinclair. (Apr. 17, 2020). *Spanish Researchers Working to Curb Coronavirus Spread With Blockchain App*. Accessed: Aug. 9, 2021. [Online]. Available: https://finance.yahoo.com/news/spanish-researchers-working-curb-coronavirus-140007260.html

[69] E. M. Dogo, A. F. Salami, N. I. Nwulu, and C. O. Aigbavboa, "Blockchain and Internet of Things-based technologies for intelligent water management system," in *Artificial Intelligence in IoT*. Cham, Switzerland: Springer, 2019, pp. 129–150, doi: 10.1007/978-3-030-04110-6_7.

[70] N. Kshetri, "Blockchain and sustainable supply chain management in developing countries," *Int. J. Inf. Manage.*, vol. 60, Oct. 2021, Art. no. 102376, doi: 10.1016/j.ijinfomgt.2021.102376.

[71] L. Recuero Virto, "A preliminary assessment of the indicators for sustainable development goal (SDG) 14 'conserve and sustainably use the oceans, seas and marine resources for sustainable development,'" *Mar. Policy*, vol. 98, pp. 47–57, Dec. 2018, doi: 10.1016/j.marpol.2018.08.036.

[72] P. Baudier, G. Kondrateva, C. Ammi, and E. Seulliet, "Peace engineering: The contribution of blockchain systems to the e-voting process," *Technol. Forecasting Social Change*, vol. 162, Jan. 2021, Art. no. 120397, doi: 10.1016/j.techfore.2020.120397.

[73] R. Adams, B. Kewell, and G. Parry, "Blockchain for good? Digital ledger technology and sustainable development goals," in *Handbook of Sustainability and Social Science Research*. Cham, Switzerland: Springer, 2018, pp. 127–140, doi: 10.1007/978-3-319-67122-2_7.

[74] E. H. Lund, L. Jaccheri, J. Li, O. Cico, and X. Bai, "Blockchain and sustainability: A systematic mapping study," in *Proc. IEEE/ACM 2nd Int. Workshop Emerg. Trends Softw. Eng. Blockchain (WETSEB)*, May 2019, pp. 16–23, doi: 10.1109/WETSEB.2019.00009.

[75] R. Chitchyan and C. Bird, "Theory as a source of software requirements," in *Proc. IEEE 28th Int. Requirements Eng. Conf. (RE)*, Aug. 2020, pp. 227–237, doi: 10.1109/RE48521.2020.00033.

[76] D. J. Wilkins, R. Chitchyan, and M. Levine, "Peer-to-peer energy markets: Understanding the values of collective and community trading," in *Proc. CHI Conf. Hum. Factors Comput. Syst.*, New York, NY, USA, Apr. 2020, pp. 1–14, doi: 10.1145/3313831.3376135.

[77] L. Hughes, Y. K. Dwivedi, S. K. Misra, N. P. Rana, V. Raghavan, and V. Akella, "Blockchain research, practice and policy: Applications, benefits, limitations, emerging research themes and research agenda," *Int. J. Inf. Manage.*, vol. 49, pp. 114–129, Dec. 2019, doi: 10.1016/j.ijinfomgt.2019.02.005.

[78] R. Medaglia and J. Damsgaard, "Blockchain and the United Nations sustainable development goals: Towards an agenda for IS research," in *Proc. PACIS*, Dubai, UAE, 2020, p. 11. [Online]. Available: https://aisel.aisnet.org/pacis2020/36

[79] Y. Tang, J. Xiong, R. Becerril-Arreola, and L. Iyer, "Ethics of blockchain," *Inf. Technol. People*, vol. 33, no. 2, pp. 602–632, Aug. 2019, doi: 10.1108/ITP-10-2018-0491.

[80] A. Zwitter and J. Herman. (2018). *Blockchain for Sustainable Development Goals: #Blockchain4SDGs*. Rijksuniversiteit Groningen. [Online]. Available: https://www.rug.nl/cf/events/events-items/blockchain4sdgs-workshop

[81] B. Rodrigues, T. Bocek, and B. Stiller, "Chapter six—The use of blockchains: Application-driven analysis of applicability," in *Advances in Computers*, vol. 111, P. Raj and G. C. Deka, Eds. Amsterdam, The Netherlands: Elsevier, 2018, pp. 163–198, doi: 10.1016/bs.adcom.2018.03.011.

[82] M. E. Peck, "Blockchain world—Do you need a blockchain? This chart will tell you if the technology can solve your problem," *IEEE Spectr.*, vol. 54, no. 10, pp. 38–60, Oct. 2017, doi: 10.1109/MSPEC.2017.8048838.

[83] S. K. Lo, X. Xu, Y. K. Chiam, and Q. Lu, "Evaluating suitability of applying blockchain," in *Proc. 22nd Int. Conf. Eng. Complex Comput. Syst. (ICECCS)*, Nov. 2017, pp. 158–161, doi: 10.1109/ICECCS.2017.26.

[84] C. Mulligan, J. Z. Scott, S. Warren, and J. Rangaswami, "Blockchain beyond the hype: A practical framework for business leaders," World Economic Forum, Cologny, Switzerland, 2018. [Online]. Available: http://www3.weforum.org/docs/48423_Whether_Blockchain_WP.pdf

[85] M. G. Jaatun, P. H. Haro, and C. Froystad, "Five things you should not use blockchain for," in *Proc. IEEE Cloud Summit*, Los Alamitos, CA, USA, Oct. 2020, pp. 167–169, doi: 10.1109/IEEECLOUDSUM-MIT48914.2020.00032.

[86] A. Di Vaio, R. Palladino, R. Hassan, and O. Escobar, "Artificial intelligence and business models in the sustainable development goals perspective: A systematic literature review," *J. Bus. Res.*, vol. 121, pp. 283–314, Dec. 2020, doi: 10.1016/j.jbusres.2020.08.019.

[87] F. Alvino, A. Di Vaio, R. Hassan, and R. Palladino, "Intellectual capital and sustainable development: A systematic literature review," *J. Intellectual Capital*, vol. 22, no. 1, pp. 76–94, Apr. 2020.

[88] A. Di Vaio, S. Hasan, R. Palladino, and R. Hassan, "The transition towards circular economy and waste within accounting and accountability models: A systematic literature review and conceptual framework," *Environ., Develop. Sustainability*, vol. 2022, pp. 1–77, Jan. 2022, doi: 10.1007/s10668-021-02078-5.

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