Telecommunications Policy 48 (2024) 102676

Contents lists available at ScienceDirect

Telecommunications Policy

journal homepage: www.elsevier.com/locate/telpol

Blockchain for sustainability: A systematic literature review for policy impact☆

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ARTICLE INFO

Keywords:
Blockchain
Sustainability
Social good
Policy
ESG
Energy

ABSTRACT

Blockchain technology has been proposed to achieve sustainable development through various solutions, such as carbon credit trading, energy systems and supply chain management. While existing literature has not covered this topic in a structured fashion, this paper provides insights to policymakers on how blockchain can deliver sustainable development. This study conducted a systematic literature review on the role of blockchain technologies in assisting policymakers in achieving ESG and environmental sustainability goals. The paper performs a detailed PRISMA SLR analysis of 10,188 technical and policy papers sourced from Scopus and IEEE databases to ensure high-quality inputs and breadth of coverage across relevant sources. In addition, the study reviews the relevant regulatory environment related to ESG, including SDGs, IPCC, COP 27, ESMA, ISSB, SEC, GRI, TCFD, ESRS, IFRS S1 and S2 and CRSD. Most papers do not outline a structured approach to applying blockchain in the emerging regulatory environment. Our paper outlines recommendations to policymakers wishing to ensure that the blockchain research community and solutions proposed are usefully directed to enable the world to achieve its net zero goals.

1. Introduction

A significant amount of focus has been placed on the role of blockchain in achieving sustainable development. A plethora of new solutions that use cryptocurrencies have been proposed, from enabling carbon credit trading (Brown et al., 2022), raising funds for environmental projects (Ngyuen et al., 2021) or the Ukraine war effort (Davis, 2022) to better-managing donations to museums to name just a few examples. Within the enterprise blockchain space, there have been several efforts to improve the efficiency of supply chain management for food and agriculture (Feng et al., 2020), enabling peer-to-peer energy systems (Afzal et al., 2022) and healthcare (Zhao et al., 2023). This paper provides a systematic literature review (SLR) of 10,188 papers to illustrate the policy implications of this application of the technology. Literature has not covered the policy implications of using blockchain to deliver sustainability in a structured fashion. This paper aims to redress this imbalance and provide insights to policymakers on the capabilities of blockchain to achieve this critical policy requirement for sustainable development.

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https://doi.org/10.1016/j.telpol.2023.102676
Received 1 May 2023; Received in revised form 14 September 2023; Accepted 9 October 2023
Available online 17 October 2023
0308-5961/

1.1. Structure of this paper

The role of blockchain in sustainability and the associated policy implications are complex, so we have structured the paper as illustrated in Fig. 1. Firstly, we provide an overview of Blockchain to delineate the framework we have approached the sustainability aspects. Secondly, we provide an overview of technology drivers for sustainability itself. Finally, we outline the emerging regulatory environment for sustainability. We then combine these themes through a systematic literature review (SLR) of 10,188 articles addressing blockchain and sustainability. We close the paper with the policy implications of the SLR and a brief overview of future work.

1.2. Research questions

Table 1 outlines the overall research questions. RQ1 focuses on the state of the art in applying blockchain to environmental sustainability. This includes assessing the main areas of research currently, what countries and regions are involved, and the main research topics outlined in the study. RQ2 aims to understand how well research aligns with the regulatory environment, focusing on how the research is helping to meet those goals.

1.3. Blockchain as GPT

To effectively create or update policy for new technologies, it is essential to understand where and how they play a role in the economy and society. Much focus has been placed on cryptocurrencies' financial services aspect. With several high-profile collapses during 2022 (Akanksha & Matkovskyy, 2023), the policy focus has been on protecting consumers from cryptocurrency risks (ibid) and ensuring that cryptocurrency does not pose a significant contagion risk to the rest of the economy. Many of those in the crypto industry are unaware of the complexity of technology policy in their own countries. This issue is compounded when blockchain's global scope is considered as blockchain knows no country boundaries.

An added complexity is that blockchain is more than just a financial technology; it is also often used as a form of General-Purpose Technology (GPT). Some initial solutions proposed for blockchain range from financial services, carbon credits, and supply chain management to supporting 5G service slicing - (Sun et al., 2022) cover many other use cases. "GPTs are characterized by pervasiveness (they are used as inputs by many downstream sectors), inherent potential for technical improvements, and innovational complementarities', meaning that the productivity of R&D in downstream sectors increases because of innovation in the GPT. Thus, as GPTs improve, they spread throughout the economy, bringing about generalized productivity gains." (Bresnahan & Trajtenberg, 1995).

There is significant literature on GPTs (see e.g. Brynjolfsson et al., 2021; Liao et al., 2016; Vu et al., 2020), it is beyond this paper's scope to go into depth on GPT itself. However, it is helpful to delineate the issue of blockchain as a GPT and illustrate the different typologies of blockchain. Within computer science, blockchain is housed within concepts of distributed systems; what is commonly referred to as blockchain is a subset of a broader set of technologies called "Distributed Ledger Technologies" (DLT). Three main archetypes of DLTs – Public, Private, and Hybrid-can be delineated using the attributes listed in Table 2. It should be noted that some are mutually exclusive – for example, it is impossible to be permissioned and permissionless within the same blockchain.

1.4. Types of DLT

The three main archetypes of DLT are illustrated below in Fig. 2.

On the right side of the diagram, databases serve as a historical reference for technologies closely linked to DLT. Introduced in the 1970s, databases have been the traditional tool for initially implementing ledgers in accounting practices and eventually in other business domains.

1.4.1. Public, permissionless, Shared Systems

Public, Permissionless and Shared Systems are on the diagram's far left. This is what many people refer to when they say

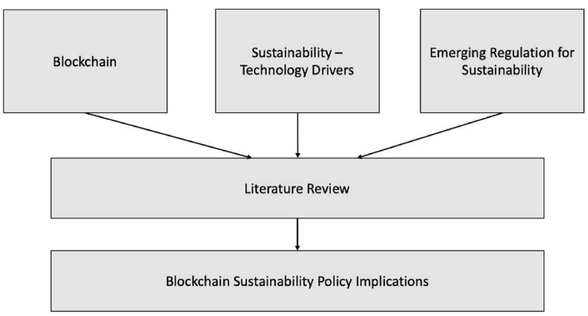

Fig. 1. Structure of this Paper.

Table 1
Research questions.

Main Research Question	Sub Question
Q1: What is the state of the art in applying blockchain technologies to achieve sustainability?	1.1 What are the main areas of research? 1.2 What countries/regions are involved? 1.3 What are the main research topics?
Q2: How is the research community aligning to the emerging regulatory environment?	2.1 What are the main regulations? 2.2 How is the research addressing the regulations? 2.2 Are there any gaps?

Table 2
Attributes of DLT.

Distributed Ledger Attribute	Description
Permissionless	Anyone can join the network; you do not need someone to give you access to join. It is not possible to be permissioned and permissionless within the same blockchain.
Public	Anyone can read the transactions on the network – these are publicly available for everyone to read. It is not possible for a blockchain to be public and private at the same time.
Shared	The ledger is shared across several nodes normally connected via the internet. This contrasts with a traditional database which is houses a ledger, which is normally internal to a corporation (i.e., inside the boundaries of the firm)
Private	To access the ledger in question, you must be white-listed – namely you must be given access to join the network. It is not possible for a blockchain to be public and private at the same time.
Permissioned	To write transactions to the network, you must be whitelisted – i.e., given access to write transactions. It is not possible to be permissioned and permissionless within the same blockchain.

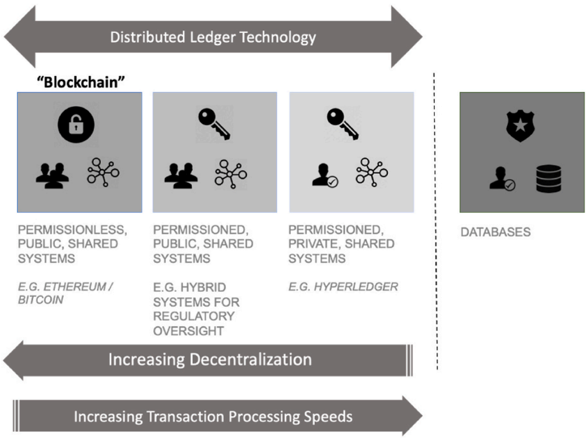

Fig. 2. Typologies of distributed ledger technologies.

"Blockchain". This paper refers to these types of DLT as Public DLT (PubDLT). Nearly all so-called Cryptocurrencies fall within this realm of DLTs. Examples include Bitcoin and Ethereum and the large number of newer cryptocurrencies that have emerged during the recent Decentralized Finance (DeFI) cycle. As described in Table 1, DLT, anyone with a computer can participate in these networks. They achieve trust through radical transparency –making all the transactions publicly available for everyone to verify that a specific exchange has occurred independently rather than rely on an intermediary. To achieve this, it is necessary to implement a mechanism to ensure that the network does not become flooded with nefarious transactions and to overcome the 'double-spend' problem, where cryptocurrency users can spend their funds more than once.

To overcome this, PubDLTs create an agreement that a transaction has occurred and is valid through a consensus protocol. These protocols are often the key differentiator between PubDLTs. This security mechanism is mostly provided by miners who perform mathematically complex calculations to create the foundations of the consensus protocol. This protocol ensures that all nodes on a network have the same version of the ledger and that no transactions have been tampered with. Within Bitcoin, this consensus protocol is called "Proof of Work", while Ethereum has recently moved to "Proof of Stake" due to the environmental impact of the heavy computation requirements for Proof of Work algorithms (ETH, 2021); there are, however, many other types of consensus protocol.

1.4.2. Private, permissioned, Shared Systems

The second most common type of distributed ledger technology is Private, Permissioned, Shared Systems. For this paper, we refer to these types of DLT as Permissioned DLT (PerDLT). Examples include Hyperledger and R3. These solutions are generally consortia-based systems – customarily created when a group of companies or entities/organizations form a consortium and develop a distributed ledger solution together. Such solutions share many attributes with PubDLT – those within the consortia can access all the transactions but with two main differences: 1) users must be given permission to access the network, and 2) transactions are not publicly shared on the open internet. PerDLTs are, therefore, often used when there are clear benefits to sharing data, but sharing in the public domain as done on PubDLT would cause legal or other problems to the organizations involved. It enables participants to have the benefits of a blockchain while ensuring their data is kept secure from others on the internet. Examples include food supply chains (Adams et al., 2021).

1.4.3. Hybrid systems

Private, permissioned systems may be necessary for commercial reasons but can conflict with regulatory requirements. For instance, in the insurance industry, insurers may benefit from sharing information to reduce insurance fraud but may opt for a private permissioned system to keep transactions private. While this may protect claims data, there is also a potential risk for the exchange of information between insurers, leading to an adverse effect for consumers. As a result, such an approach may raise concerns about consumer protection from regulators. In such cases, a hybrid DLT can be implemented, where the system runs similarly to a PerDLT, but the regulator has complete access to all transactions to ensure compliance with all regulations.

1.5. The blockchain technology stack – foundations to understanding sustainability

One area of confusion when discussing the use of blockchain to achieve sustainability outcomes is how the technology is constructed across the three different archetypes of DLT. This paper divides the blockchain technology stack into three components: Layer 1, Layer 2, and Intermediary Services, illustrated in Fig. 3.

Layer 1 is the base layer of the blockchain network and provides the peer-to-peer network of nodes that house the ledger itself. Layer 1 also includes the consensus protocols that implement the rules of how new transactions are accepted and wrapped up into new blocks and is, therefore, where the *miners* are. Layer 1 also houses the cryptographic algorithms used to secure the network. Within PubDLT, this is the most environmentally challenging aspect, as the mathematical solutions the miners are required to solve require large amounts of computational power. This has led to many different estimations of how much energy these blockchains consume. For PerDLT, it is still relevant to measure these impacts, but the energy consumption is generally a lot less due to the reduced requirements for excess computational capacity.

Layer 2 consists of the applications and solutions built on the blockchain. For PubDLT, this can include the dAPPs or DeFi, while for PerDLT, this will include the software that implements the business logic of the consortium.

Intermediary Providers Intermediary providers have recently received much attention due to FTX and Luna's collapse. In contrast, these types of providers are the ethos of decentralization promised by PubDLT - centralised services that sit on top of the decentralized CB and provide wallet management and custody services. For some PubDLT, measuring these providers' impact will also be necessary.

For the PerDLT, Layers 1 and 2 are relevant to measuring environmental impact. At the same time, for PubDLT, measuring Layer 1, Layer 2 and, in many instances, the intermediary services is necessary.

1.6. Blockchain and three waves of GPT

Significant literature exists on GPTs and their economic impact (Brynjolfsson et al., 2021). However, it is helpful to consider three waves of GPTs within the scope of blockchain and sustainability, illustrated in Fig. 4. The first wave came between the 1980s and 1990s as digitalization spread through enterprises, with the first PCs and larger-scale IT platforms housed internally in a company. The second wave came with the internet and web platforms, enabling extremely large companies such as Meta, Twitter, and Google. At the same time, the Mobile Broadband (MBB) platform emerged with the advent of 3G and 4G communications technologies driven by smartphones and apps on mobile devices (Schneir et al., 2019). A vital aspect of the second wave of GPTs was the rise of the data society – where digital data capture expanded far beyond the boundaries of the firm and started to include data capture from end-users. Through this data-driven society, a third wave of GPTs is emerging. In contrast to previous waves of GPT, however, several disparate technologies are forming the base of a new 'infostructure' GPT. Advanced communications allow for increased data collection, which

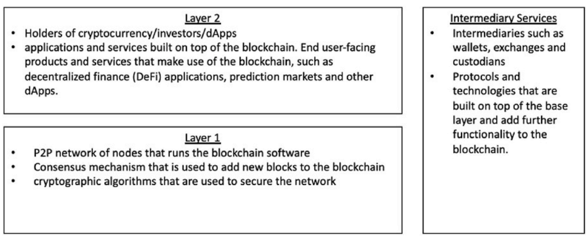

Fig. 3. Technology stack of the blockchain space.

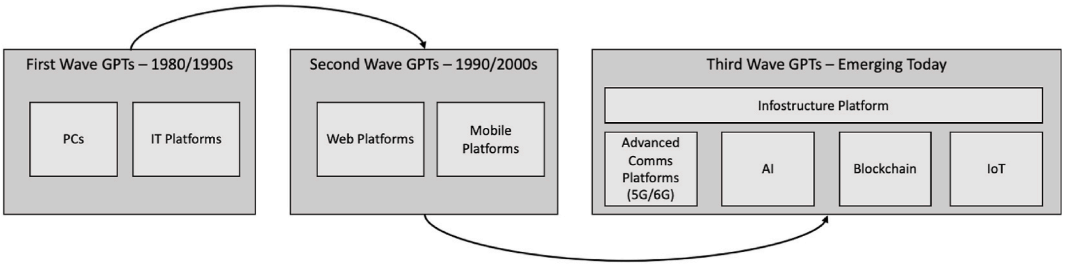

Fig. 4. Three waves of GPTs within the economy and society.

enables new AI solutions and systems to be developed. However, this has raised numerous issues about the ethics, privacy, and security of such Data Supply Chains (DSC) (Spanaki et al., 2018). Technologies such as blockchain are viewed as support technologies to enable this new infostructure to be more fully realised as privacy-preserving, enabling transparency at the right level for end-users to see how their data has been used. Therefore, in the new wave of GPT, several technologies deliver these services to end-users. As seen in many of the articles we assessed, blockchain is considered a support mechanism for several other technologies – enabling trust in AI data collection and models, ensures the security of IoT systems (Kshetri, 2017), and assisting certain parts of 5G and 6G. Within the infostructure GPT, blockchain enables complex data exchanges that would otherwise not be possible for IoT, AI and advanced communication platforms.

Such data exchanges in the infostructure platform have gained significant attention in the literature. Cross-border data flows are critical for the global economy and for achieving the United Nations Sustainable Development Goals (OECD, 2023).

Blockchain is often touted for its ability to provide data integrity, which is crucial from a sustainability perspective. Data Supply Chains (DSC) are becoming increasingly important with the advent of digital Measurement Reporting and Verification (dMRV), particularly in the Voluntary Carbon Markets (VCM), where reliable monitoring is necessary to ensure real carbon reductions. The need for ex-post proof of offsets is growing, and blockchain-enabled DSC can provide data assurance, integrity, and audibility. This is illustrated in Fig. 5.

Blockchain also consumes energy and has an environmental impact. The debate about blockchain's energy consumption has led to some detailed discussions about how it can be effectively applied to solve the climate crisis.

1.7. Blockchain's own energy consumption

There is significant variability between blockchains in carbon footprint and energy intensity. Moreover, there is currently no single methodology for quantifying the carbon footprint of a blockchain due to the variation in algorithms, consensus protocols, types of hardware used, etc … It is also often difficult to extract the energy impact of blockchain versus the energy impact of the underlying networks.

Multiple attempts have been made by the cryptocurrency community to measure the environmental impact of blockchains, often with a focus on Bitcoin and Ethereum, due to their significant uptake and the use of the Proof of Work algorithm. Some of the most used

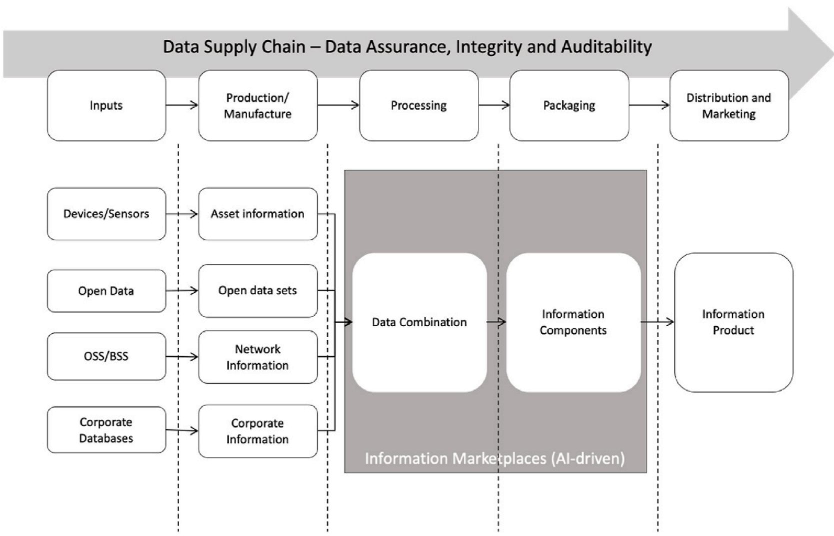

Fig. 5. Data Supply Chain for dMRV for Carbon Offsets.

methods are illustrated in Table 3.

One of the significant issues with the attempts to measure the environmental impact of blockchain is the lack of comparable, peer-reviewed methods and disparity in the estimates produced, which vary widely. This is primarily due to the problems of assessing the energy consumption of a blockchain in the first place but also due to a level of inexperience in the PubDLT industry, which only just started to come to terms with the measurement of climate impact. For example, many of the papers in Table 3 do not refer to pre-existing work in climate impact from, e.g., the ICT industry (ITU, 2023), nor do they reference the existing standards for measuring environmental impact (ISO, n. d).

2. The sustainability imperative

The need to respond effectively to climate change has increased over the last years, and many blockchain solutions have been devised to respond to the drive towards sustainability. This section briefly covers these initial drivers and some of the activities developed in the policy space to drive society towards sustainability. In Section 3, we conduct an SLR to assess the existing literature base.

Table 3
Summary of measurement for energy footprint of blockchains.

Author	Peer Reviewed Methodology	Date of Publication	Title	Stack Layer	Consensus Mechanisms	Protocol	Estimate in GWh
CCAF	No	N/A	Cambridge Bitcoin Electricity Consumption Index	1	PoW	Bitcoin	86,580.0 and
CCRI	No	N/A	CCRI Crypto Sustainability Indices	1	PoW and PoS	Bitcoin/ Ethereum	86,580.0 and 2.7
Digiconomist	No	N/A	Bitcoin Energy Consumption Index	1	PoW and PoS	Bitcoin/ Ethereum	113,420.0 and 10.0
Alex de Vries, Ulrich Gallersdörfe, Lena Klaaβen Christian Stoll	Yes	February 2022	Revisiting Bitcoin's Carbon Footprint	1	PoW	Bitcoin	117,296.4
CoinShares	No	Jan 2022	The Bitcoin Mining Network: Energy and Carbon Impact	1	PoW	Bitcoin	89,000.0
Xiaoyang Shi, Hang Xiao, Weifeng Liu, Xi Chen, Klaus S. Lackner, Vitalik Buterin and Thomas F. Stocker	No	Dec 2021	Confronting the Carbon-Footprint Challenge of Blockchain	1	PoW	Ethereum	311.9
Moritz Platt, Johannes Sedlmeir, Daniel Platt, Jiahua Xu, Paolo Tasca, Nikhil Vadgama and Juan Ignacio Ibañez	No	Sept 2021	Energy Footprint of Blockchain Consensus Mechanisms Beyond Proof-of-Work	1	PoW	Ethereum	974.7
Philipp Sandner, Constantin Lichti, Cedric Heidt, Robert Richter and Benjamin Schaub	No	N/A	The Carbon Emissions of Bitcoin from an Investor Perspective	1	PoW	Bitcoin	90,860.0
Susanne Köhler and Massimo Pizzol	Yes	Nov 2019	Life Cycle Assessment of Bitcoin Mining	1	PoW	Bitcoin	31,290
Christian Stoll, Lena Klaaβen and Ulrich Gallersdorfer	Yes	Jun 2019	The Carbon Footprint of Bitcoin	1	PoW	Bitcoin	48,500.0
Michel Zade, Jonas Myklebost, Peter Tzscheutschler and Ulrich Wagner	Yes	Mar 2019	Is Bitcoin the Only Problem? A Scenario Model for the Power Demand of Blockchains	1	PoW	Bitcoin	33,743.5
Max J. Krause and Thabet Tolaymat	Yes	Nov 2018	Quantification of Energy and Carbon Costs for Mining Cryptocurrencies	1	PoW	Bitcoin	30,143.2
Hass McCook	No	Aug 2018	The Cost and Sustainability of Bitcoin	1	PoW	Bitcoin	105,000
Alex de Vries	Yes	May 2018	Bitcoin's Growing Energy Problem	1	PoW	Bitcoin	from 22,338.0 to 67,189.2
Harald Vranken	Yes	Oct 2017	Sustainability of Bitcoin and Blockchains	1	PoW	Bitcoin	from 876.0 to 4380.0
Marc Bevand	No	Feb 2017	Electricity Consumption of Bitcoin: A Market-Based and Technical Analysis	1	PoW	Bitcoin	from 4120.0 to 4730.0
Karl J. O'Dwyer and David Malone	No	Sep 2014	Bitcoin Mining and its Energy Footprint	1	PoW	Bitcoin	from 876.0 to 87,600.0

2.1. Sustainable Development Goals

Many blockchain solutions use the UN SDGs to assist them in defining their sustainability goals and approaches. Released in January 2016, the Sustainable Development Goals (SDGs) comprise 17 high-level goals, 169 targets and 231 indicators designed to help the world achieve sustainability (UNSD, n.d.). The goals are broad in scope and highly ambitious; Table 4 below illustrates the high-level goals.

Several issues arise with using the SDGs as the only tool for blockchain solutions to align to sustainability. Firstly, because of the nature of Blockchain as a GPT, often supporting other technologies such as AI, IoT, or 5G, etc., it isn't easy to measure the direct impact of blockchain on the different areas of an SDG. Secondly, because of the way that the 231 SDG indicators are developed and implemented, it is difficult to measure them at all (Kim, 2023): "Many scholars have critiqued the SDG indicators from this perspective, often concluding that the indicator framework should be streamlined with fewer but more relevant indicators" - Kubiszewski et al. (2021) argue that 'most of the current indicators are not necessary' because they are 'unable to measure sustainable development holistically'. This makes it difficult for blockchain solutions to correctly align themselves to solve the challenges they wish to address. According to Kim (2023), the indicators 1) have a distorting effect on SDGs and targets, and 2) the overreliance on limited, primarily quantitative indicators exacerbates adverse outcomes.

In addition, due to the focus on developing nations within the SDGs, there is also a risk that the work that needs to be done to reduce the *sources* of climate change in the developed world is missed. Since most of the negative environmental impact originates in the developed world, the SDGs risk placing the focus on the incorrect places to solve these problems. As a result, many blockchain solutions that claim to address the SDGs are not directly addressing them but are using them as advertising.

2.2. Technology in the transition towards net zero

Alongside the SDGs, extra pressure to solve environmental issues has been driven by IPCC, established by the UN Environment Programme and the World Meteorological Organization, and 27th Conference of Parties to the United Nations Framework Convention on Climate Change (UNFCCC) (COP 27) (IPCC, 2023). Both have reinforced the urgency to achieve the Paris Agreement COP21 in 2015, aims to limit global warming below 2 °C while focusing on achieving 1.5 °C. The Emissions Gap Report (UNEP, 2022) emphasised the need for system-wide transformation to reach 1.5 °C to reduce the global consequences of increased deaths, droughts, floods and ecosystem loss (Mooney et al., 2021).

Tracking emissions related to IPCC and COP27 is complex due to various data sources and regulations, hindering net-zero goals (UN, 2021). Multiple solutions using sensors and blockchain technology have been proposed to offer secure, verifiable emissions data, aiding accountability, and equitable access to innovation for emissions reduction and net-zero targets as well as enhancing efficiency and promotive environmentally friendly actions (Watts, 2023). Table 5 provides examples of different blockchain solutions across the four main areas of concern discussed at COP 27 (see Table 6).

However, despite these efforts, there are also regulatory efforts toward a low-carbon economy, and there's growing pressure to incorporate environmental and social data into corporate decision-making. The fundamental framework for sustainable enterprise development is ESG, stemming from ethical and responsible investment (Wan et al., 2023). Unlike the current ad-hoc efforts to define sustainability solutions in the blockchain community, these evolving standards provide a strong foundation for advancing low-carbon solutions.

Table 4
High-level SDG goals.

Sustainable Development Goals	
Number	Title
SDG 1	No poverty
SDG 2	Zero Hunger
SDG 3	Good Health and well-being
SDG 4	Quality Education
SDG 5	Gender Equality
SDG 6	Clean Water and Sanitation
SDG 7	Affordable and clean energy
SDG 8	Decent work and economic growth
SDG 9	Industry, Innovation and infrast
SDG 10	Reduced Inequalities
SDG 11	Sustainable Cities and Communities
SDG 12	Responsible consumption and production
SDG 13	Climate Action
SDG 14	Life below water
SDG 15	Life on land
SDG 16	Peace, Justice, and strong institutions
SDG 17	Partnership for the goals

Table 5
Example case studies of blockchain for COP 27.

Area	Description	Blockchain solution
Decarbonisation of Industry and Transport	To achieve the Paris Agreement's 1.5 °C goal requires addressing carbon-intensive activities, materials, and fuels. Replacing these materials and fuels with cleaner and greener options requires substantial investment and careful planning.	Zumo uses open-source industry data to forecast and calculate crypto electricity consumption. They then use renewable energy certificates (RECs) to ensure that blockchain and crypto activities are powered by renewables. Zumo completed the Zero Hero pilot project in 2022, which involved purchasing RECs to offset the electricity consumption of bitcoin acquired via the Zumo app. The pilot covered bitcoin worth £1.5 million and compensated a total of 850 MW-hours (MWh) of electricity (Zumo, 2022).
Climate Adaptation	Climate adaptation funding is crucial for providing support to the most vulnerable communities. In addition to the humanitarian, environmental, and ethical justifications, there is an increasing business case for investing in climate adaptation to ensure business longevity	Positive Energy is an example of a blockchain-based digital platform for small- to mid-sized renewable energy projects that connects developers with a global investor community to finance or refinance projects and increase liquidity. The platform has been able to reduce the time to finance by 50 per cent through blockchain-based asset financing, trading and management (SAF, 2022)
Nature & Food Supply	Limiting global warming to 1.5 °C will heavily depend on nature and land use. The future of land use, food production, and preservation of natural environments such as forests and oceans, is a crucial area of concern.	Gainforest is an AI-based decentralized fund that rewards sustainable nature stewardship, helping to accelerate conservation efforts. They are among the top 15 semi-finalists competing for the $10 M XPRIZE Rainforest (to develop innovative monitoring technology. Impact NFTs are also utilized by Gainforest, which turns conservation project donations into a dynamic NFTreesTM certificate that captures live data from the conservation area and tracks donors' impact over time (Gainforest, 2023).
Agriculture and Water Systems	Food systems, water supply, and the impact of floods and droughts caused by climate change require increased prioritization as increasing numbers are affected.	AgriLedger, SourceTrace, and ESIH are collaborating to establish blockchain-based business platforms. In Haiti, a bespoke platform for fresh produce chains enables buyers to scan a QR code on a mango and view information about the mango's source tree, packaging, transportation, and associated costs. The cold-chain logistics data, including registration, certification, transport, and sales documents, is stored immutably and made available on the web and via smartphones in user-friendly formats (Maestracci, 2019)

Table 6
Source: GRI, 2016.

What is the total amount of fuel consumption from non-renewable sources (in gigajoules) that the organization is responsible for?
What isthe company'stotal energy consumption (in gigajoules)?
What is the total amount of fuel consumption from renewable sources (in gigajoules) that the organization is responsible for?
What isthe total amount of energy consumption outside of the organization in gigajoules?
What isthe energy intensity ratio for the organization?
In relation to the previous year, how much has the company reduced its energy consumption as a direct result of conservation and efficiency initiatives?
In relation to the previous year, how much hasthe company reduced the energy requirements of its products and/or services?

2.3. Emerging regulation for sustainability

2.3.1. ESG – current and developing financial reporting requirements

Governments and regulators are introducing mandatory ESG-related disclosure requirements in regulated reports like annual reports. This aims to inform investors about ESG risks and opportunities and to compel entities to report on ESG matters that impact their financial performance, including the financial effects of specific ESG-related risks and opportunities. Previously, ESG reporting was voluntary and lacked standardisation, leading to incomplete information and investor dissatisfaction. To address this, ESG reporting is now required in many capital markets through regulatory filings. However, global regulators are taking diverse approaches to mandating ESG-specific financial reporting. This section briefly outlines the history and current status of these efforts. Notably, while some regulators or standard setters may offer industry-specific guidance, none have specifically evaluated metrics directly relevant to blockchain and other emerging technologies.

Krueger et al. (2023), documented by country the first time the government mandated environmental disclosures or the appropriate securities regulator. These mandatory disclosures were typically not required to be presented within the regulatory filings. Recent attention has been drawn to the development of financial statement filings' regulations and standards within the European Union (EU), the International Sustainability Standards Board (ISSB)'s jurisdictions, and the United States (US). These regions' activities are in the spotlight globally due to the nature of their expected requirements and the size of each capital market(s).

2.3.2. European securities and markets authority (ESMA)

ESMA sets sustainability reporting requirements in the EU under the Non-Financial Reporting Directive (NFRD). The Corporate Sustainability Reporting Directive (CSRD) and Taxonomy Regulation Article 8 will require detailed information using XBRL tagging. EFRAG was tasked with creating European Sustainability Reporting Standards (ESRS), adopted by the European Commission in July 2023 (EFRAG, 2023).

In July 2023, ISSB, EC, and EFRAG committed to enhancing interoperability despite differences in impact materiality approaches. To aid reporting entities, EFRAG has published an assessment of the interoperability, along with a mapping table as of August 2023 to identify ESRS information that corresponds to IFRS S1 and S2 requirements that relate to climate. In September 2023, EFRAG and GRI also published a joint statement on interoperability, focusing on double materiality reporting, which is not a focus as yet of ISSB standards. This compatibility ensures that entities reporting under GRI standards can transition smoothly to EFRS, reducing the common issue of double reporting in the ESG field.

2.3.3. International Sustainability Standards Board (ISSB)

The IFRS Foundation established the International Sustainability Standards Board (ISSB) to provide global financial reporting regulators and stakeholders with guidance on sustainability reporting (IFRS, 2021). The ISSB consolidates or collaborates with other pre-existing ESG-reporting organizations, such as the Carbon Disclosure Project (CDP), Climate Disclosure Standards Board (CDSB), Sustainability Accounting Standards Board (SASB), Task Force on Climate-Related Financial Disclosures (TCFD), Value Reporting Foundation (VRF), among others. Other organizations, such as the Global Reporting Initiative (GRI) cooperate with but are not a direct part of the ISSB.

2.3.4. Securities and exchange commission (SEC)

In March 2022, the SEC announced significant proposed rule changes for its registrants, requiring new disclosures along three ESG-related dimensions: material climate impacts, greenhouse gas emissions, and any targets or transition plans. The proposed rule was released for public comment at the time of the announcement, and the final version was not released at publication.

2.4. Current or developing energy-specific reporting standards

This section outlines energy-specific reporting standards, starting with their development timeline. We then address the gap in standards for crypto or blockchain activities, as no standard-setting body has ventured into this industry.

2.4.1. GRI 302: energy

Established in 1997 after the Exxon Valdez oil spill, GRI is the oldest ESG standard-setter. Initially, it focused on developing environmental accountability standards. Its standards now cover all aspects of ESG reporting, categorized into Universal, Sector, and Topic. While cooperating with the ISSB, GRI remains independent, see Table 6.

The stated goal of the GRI 302: Energy (GRI, 2016) standard is to allow management to explain its approach to energy consumption and management. The required energy-specific measurements and disclosures are:

2.4.2. Task Force on Climate-Related Financial Disclosures

The Task Force on Climate-related Financial Disclosures (TCFD) issued its initial guidance in 2017 for disclosing climate-related financial information. In 2021, they released "2021 TCFD Implementing Guidance," which provides further insights on climate scenario analysis and financial services providers' involvement in disclosing climate-related aspects and using metrics and targets to monitor climate risk and opportunity management. These updates aim to enhance climate-related financial disclosure and promote consistent reporting globally.

2.4.3. European Sustainability Reporting Standards

The ESRS comprises two general standards (ESRS 1 and ESRS 2): (1) general principles and (2) information to provide. In addition, there are specific topical standards, including:

- E1–E5 – to establish requirements specific to environmental reporting objectives;
- S1–S4 – to establish requirements specific to social reporting objectives;
- G1 – to establish requirements specific to governance reporting objectives.

Each standard defines specific ESG metrics that must be measured and disclosed and includes a related link to specific financial reporting metrics deemed relevant.

The ESRS E1 standard defines the requirements for climate change. The specific disclosures for energy usage are as follows:

- Energy consumption and mix
- Energy intensity per net turnover (revenue)
- Scope 1 GHG emissions
- Scope 2 GHG emissions
- Scope 3 GHG emissions

- Total GHG Emissions
- GHG intensity per net turnover
- GHG removals in own operations and the value chain
- GHG mitigation projects financed through carbon credits
- Potential financial effects from material physical risks
- Potential financial effects from material transition risks
- Potential financial effects from climate-related opportunities.

2.4.4. IFRS S1 and S2

IFRS sustainability standards comprise two key standards issued in June 2023: IFRS S1 and IFRS S2. IFRS S1, titled "General Requirements for Disclosure of Sustainability-related Financial Information", covers scope, conceptual foundations, core content (including metrics and targets), and offers general guidance (IFRS, 2022). This guidance addresses sources, information disclosure methods, and considerations regarding judgments, measurement uncertainty, and errors, see Table 7.

The TCFD's 2021 background notes that the "Exposure Draft IFRS S2 – Climate-related disclosures" builds upon TCFD recommendations and incorporates industry-specific requirements from SASB Standards. The IFRS S2 Exposure Draft (ED) also includes Appendix B outlining industry-specific requirements for identifying, measuring, and disclosing climate-related risks and opportunities across 68 subsectors, categorized within 11 sectors.

- Consumer goods
- Extractives and minerals processing
- Financials
- Food and beverage
- Healthcare
- Infrastructure
- Renewable resources and alternative energy
- Resource transformation
- Services
- Technology and communications
- Transportation

The final IFRS S2 standard does not include the Appendix or comprehensive industry-specific guidance. Nonetheless, we provide examples of energy consumption metrics required by select sectors to illustrate potential approaches the ISSB could adopt if it develops more industry-specific metrics and guidance. The ED highlighted that these requirements closely align with those developed by the SASB, and the final IFRS S1 and S2 standards recommend consulting SASB guidance, which is industry-specific. The chosen example

Table 7
Summary of IT and investment metrics in IFRS 2 exposure draft (adapted from IFRS, 2022).

	Topic	Accounting Metric	Category	Unit of Measure	Code
IT	Environmental Footprint of Hardware and Infrastructure	Total Energy Consumed, Percentage grid electricity, percentage renewable	Quantitative	various	TC–SI–130a.1
		Total water withdrawn, total water consumed, percentage of each in regions of High or Extremely High Baseline Water Stress	Quantitative	various	TC–SI–130a.2
		Discussion on the integration of environmental considerations into strategic planning for data center needs	Discussion and Analysis	various	TC–SI–130a.3
financial services – Asset Management and Custody	Incorporation of ESG in Investment Management and Advisory	Amount of assets under management by asset class that employ 1) integration of ESG issues 2) sustainability themed investing and 3) screening	Quantitative	reorting currency	FN-AC-410a.1
		Description of approach to incorporation of ESG factors in investment and/or wealth management processes and strategies	Discussion and Analysis	n/a	FN-AC-410a.2
	Transition Risk Exposure	Description of proxy voting and investee engagement policies and procedures	Discussion and Analysis	n/a	FN-AC-410a.3
		Percentage of total assets under management included in financed emissions calculation	Quantitative	percentage	FN-AC-1
		Absolute gross Scope 1, 2 and 3 emissions and associated amount of total AUM	Quantitative	metric tons	FN-AC-2
		Gross emissions intensity by Scope 1, 2 and 3 emissions and total AUM	Quantitative	metric tons	FN-AC-3
		Description of the methodology used to calculate financed emissions	Discussion and Analysis	n/a	FN-AC-4

sectors below are relevant to activities associated with the crypto industry since neither the ISSB nor the SASB has issued guidance for the crypto or blockchain sectors.

2.4.5. SEC rule 33-11042

The SEC's proposed rule necessitates additional information in registrants' filings, including the annual 10-K report (SEC, 2021). Some of this new information requires formal attestation and a stricter level of financial reporting materiality. Many of the specific SEC requirements draw from the 2021 TCFD Implementing Guidance (TCFD, 2021), which offers examples of necessary energy-related disclosures. The TCFD guidance aids in identifying potential impacts on financial statements, a key aspect of the proposed rule. It's important to note that this rule has faced multiple delays, and as of this paper's publication, it remains a proposal.

2.4.6. CRSD

The Non-Financial Reporting Directive (NFRD, 2014) mandates approximately 12,000 EU organizations to disclose non-financial and diversity information, including sustainability reports. The Corporate Sustainability Reporting Directive (CSRD) enhances and extends this requirement to many more companies, including SMEs, across all sectors (an additional 50,000 compared to the NFRD) (EC, 2021). Effective from 2024, with the first reports due in 2025, the CSRD compels companies to offer comprehensive insights into how sustainability issues affect their operations, society, and the environment. This empowers stakeholders like investors, consumers, policymakers, and civil society groups to evaluate companies based on financial and non-financial data. The CSRD adopts a double materiality approach, necessitating financial and impact materiality measurement. This directive seeks to provide investors with more accessible, reliable, and verifiable non-financial data while encouraging companies to meet enhanced disclosure requirements and engage more effectively with stakeholders.

Financial materiality concerns disclosing transactions or events that meet specific regulatory definitions, which can vary by jurisdiction (e.g., differences between US GAAP and IFRS financials). It involves qualitative and quantitative assessments to determine whether a disclosure affects investor or creditor decisions, focusing solely on financial reports. Impact materiality, the second aspect of double materiality, looks at the broader societal effects of a company's decisions.

There is a debate over double versus single materiality in ESG reporting. GRI and EFRAG endorse double materiality, while the ISSB initially leaned toward single materiality but expanded its perspective due to stakeholder input (Kirkland and Ellis, 2022). Some believe double materiality is more meaningful for investors, even within the financial services industry (Ritchie & Schwartzkopff, 2022).

3. Systematic literature review

We have followed the Kitchenham and Charters (2007) guide for systematic reviews and used the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) approach for a detailed structured literature analysis (Page et al., 2021). The Kitchenham report outlines three stages for an SLR – Plan, Conduct and Report, illustrated in Fig. 6.

3.1. Method

In the Plan stage, we analysed existing review articles (see Fig. 7). We decided to perform an SLR on the role of blockchain in achieving sustainability, focusing on how the literature was helping guide policymakers to enable blockchain to achieve environmental goals and vice versa.

During the Conduct stage, due to the large number of papers and the broad nature of the topic in question, a rigorous approach to conducting the SLR was selected to ensure that the review was robust, transparent, and replicable. PRISMA is an evidence-based minimum set of items aimed at helping scientific authors report a wide array of systematic reviews and meta-analyses. PRISMA was initially developed within medical research, explicitly aiming to understand the benefits/harms of a healthcare intervention (PRISMA, 2020). However, this approach is increasingly used within technical research as a robust and repeatable method of approaching SLRs (Javed et al., 2019; Madurapperumage et al., 2021; Pattnaik et al., 2023).

3.2. Data

Comprehensive data retrieval (Bar-Ilan, 2018) is critical for research assessment. Three databases were selected to provide good

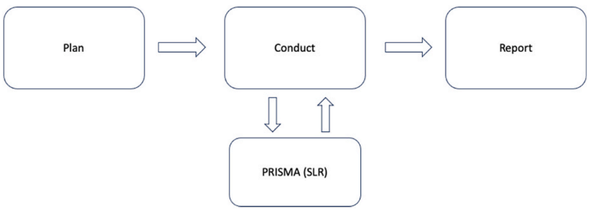

Fig. 6. PRISMA within the Kitchenham guide.

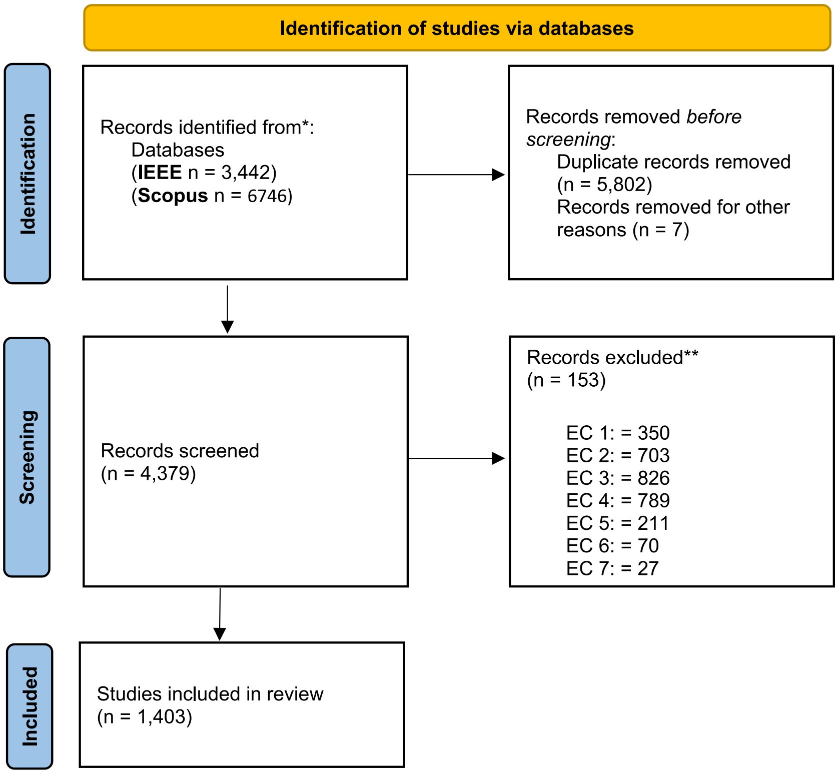

Fig. 7. Identification, screening, and inclusion procedure following the PRISMA framework.

coverage within our SLR: Scopus and IEEE Xplore. So far, most of the existing academic work on blockchain applied to sustainability has been published in technical journals. The IEEE is one of the most comprehensive and high-quality publishers within the blockchain and DLT technology domains and was selected for inclusion. Scopus is a comprehensive interdisciplinary database. In addition to covering Elsevier journals, other well-known academic publishers are also indexed in Scopus, including Springer, John Wiley & Sons. Scopus was deemed the most appropriate database due to its focus on global content, ensuring better coverage of emerging markets. Due to the nature of the research question focusing on sustainable development and the focal point of many of the blockchain solutions impacting emerging markets, ensuring the SLR included them as much as possible was deemed appropriate. These databases provide a relatively complete overview of high-quality literature in this space, which makes them suitable for literature analysis.

3.3. Search criteria

"Blockchain" and "Sustainability" were selected as the main keywords for this SLR. However, these terms can be used by authors in different ways. We, therefore, defined the following search criteria outlined in Table 8:

The same query was used for all three databases within the metadata – paper title, abstract and keywords. The search period was from January 1, 1960, to September 2023. However, the first article on blockchain and sustainability was published in 2016, so the effective search period is from 2016 to 2023. Only journal articles, conference papers and early-access articles were included in the search. 10,188 articles were obtained. Data downloaded included titles, authors, journal sources, abstracts, and references. 5802 were duplicates, and 7 papers were listed as retracted due to problems with peer review, leaving 4379 for initial review.

Table 8
Search criteria.

Blockchain	Distributed Ledger Technologies
Blockchain AND Sustainability	Distributed Ledger Technologies AND Sustainability
Blockchain AND Sustainable Development	Distributed Ledger Technologies AND Sustainable Development
Blockchain AND Environment	Distributed Ledger Technologies AND Environment
Blockchain AND Environmental	Distributed Ledger Technologies AND Environmental
Blockchain AND SDG	Distributed Ledger Technologies AND SDG

3.4. Evaluation criteria

Eligibility assessment was conducted considering the following exclusion criteria:

EC 1: The article is not publicly available online (350 articles).
EC 2: The abbreviation "SDG" or "DLT" has a different meaning (703 articles).
EC 3: The work presented in the article does not qualify as research about sustainability (826 articles) - for example, the key term "sustainability" is used to clarify that the article is about sustainable blockchain business models rather than achieving environmental sustainability.
EC 4: Sustainability is not the main topic. Instead, it is used as an argument for discussing something else (789 articles).
EC 5: Blockchain is mentioned only peripherally rather than as a driving solution in the paper. For example, the key term "blockchain" is mentioned as a supporting technology for AI and 6G or similar (211 articles).
EC 6: The article has the same author(s), results, and methodological approach as another paper already included (70 articles).
EC 7: Paper not in English: 27.

1403 papers remained relevant to this paper's concepts used for the in-depth analysis. Literature was filtered according to the PRISMA approach. Data visualisation was also applied to understand the overall research literature better. The open-source VOS-Viewer software was used for the analysis. Descriptive analysis focused on the spread of literature and which countries were involved. Languages were also assessed. We then investigate the trends within the papers, identifying foci of the research and trends through clustering analysis of co-authors, co-keywords, and timelines of the papers.

The first paper related to blockchain in sustainability appeared in 2016. Before this, the discussions on cryptocurrency and blockchain focus mainly on cryptocurrencies and the development of appropriate business models (Sun et al., 2022). There has been an increasing trend around the application of blockchain to sustainability. This may be related to the increased focus on sustainability and the SDGs as the world faces the climate crisis. Governments' more vigorous focus on net zero and the shifting regulatory environment have likely caused this increase in attention to how blockchain can help achieve the SDGs and sustainability more generally.

The top contributors in the space come from the EU, with 468, China, followed with 280, USA, with 145. The UK had 117. This intense focus from the EU correlates well with the investment during the Horizon 2020 Programme on the environment and the role of technology in assisting the region to transform. The top European contributor was Italy, whose contributions strongly focused on food supply chains. Europe also has a strong research focus on energy and digital technologies, reflected in our keyword mapping in the next section (see Figs. 8–12).

Other nations that focus on publication within the blockchain and sustainability space are Australia (59), Korea (41), Pakistan (38), Saudi Arabia (37) and Malaysia (36).

To investigate the literature, data visualisation was applied. Three main research themes become clear can be seen through different aspects of visualisation –

1) Supply Chains, mainly agricultural and food supply chains,
2) Energy, specifically smart grid; and finally,
3) The combination of blockchain with the Internet of Things (IoT) to enable sustainability outcomes within Smart Cities:

Over the timeline, the focus on supply chains has persisted, but it has evolved toward more direct applications of blockchain technology. Concurrently, the research landscape has shifted towards more intricate technological solutions, which blend IoT and Artificial Intelligence or Machine Learning, and apply them to various aspects of sustainability, particularly in energy networks. This shift could be attributed to the EU Horizon program's significant emphasis on technological applications within the energy system.

A summary of the occurrence of keywords was used to push the classifications further. Table 9 below outlines the top 40 keywords; this re-enforces the findings of the three main clusters.

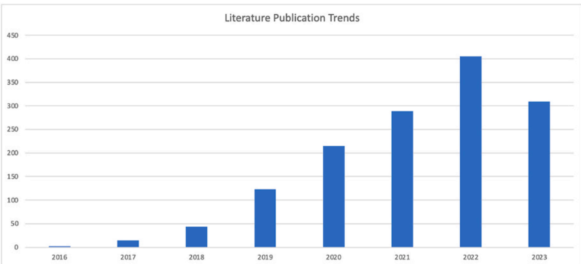

Fig. 8. Literature publication trends.

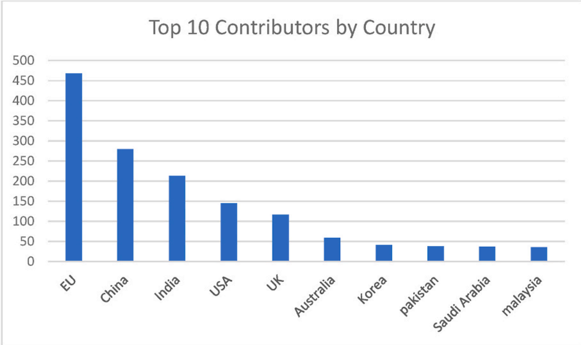

Fig. 9. Top 10 contributors.

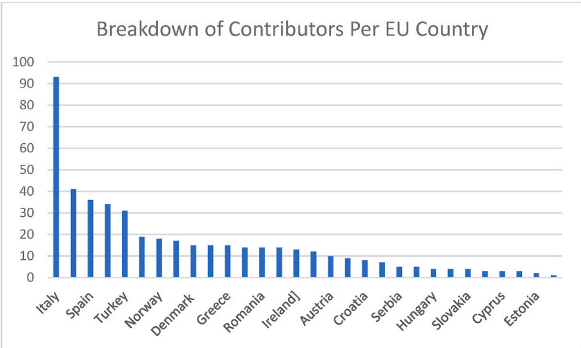

Fig. 10. EU contributors by country.

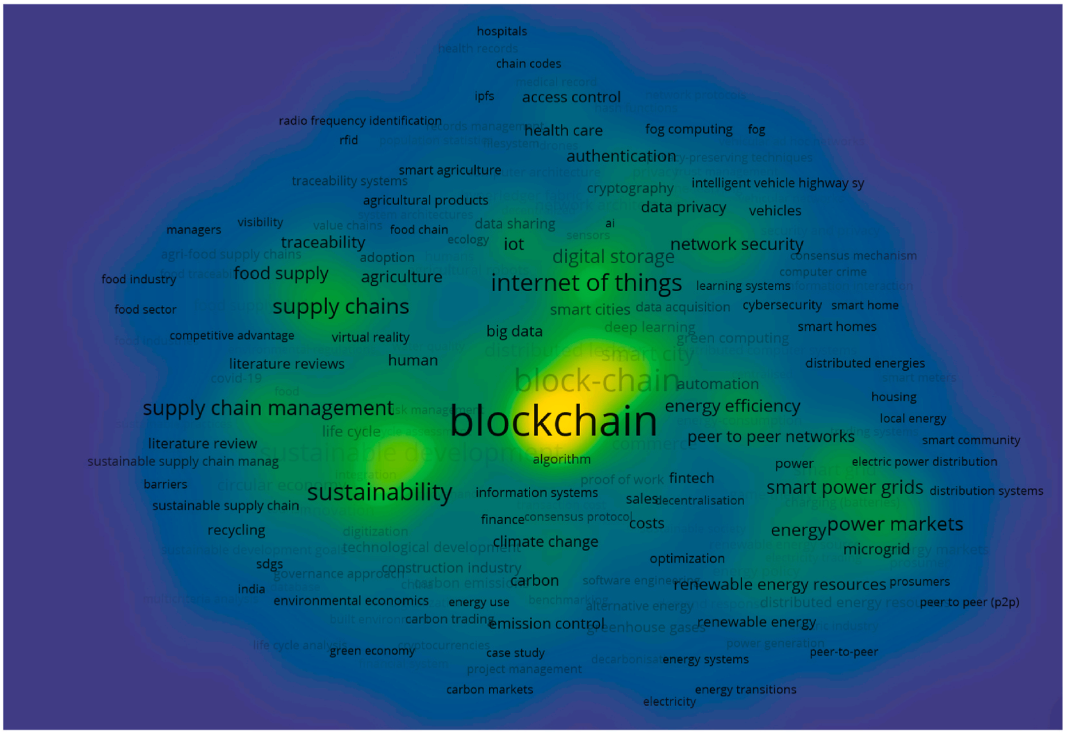

Fig. 11. Heat map of keywords.

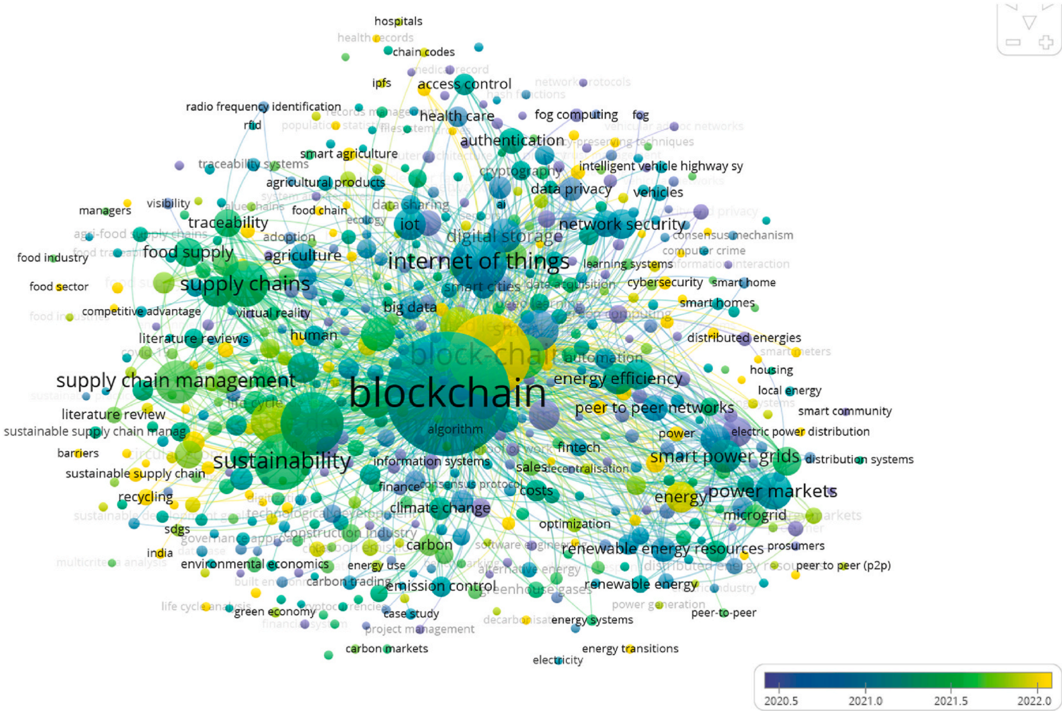

Fig. 12. Keyword cluster map.

Table 9
Top 40 keywords.

Keyword	Occurrence	Keyword	Occurrence
Blockchain	1504	Energy utilisation	60
Supply chain	446	Energy trading	59
Internet of things	336	Food supply	57
Sustainable development	267	Circular economy	53
Smart contract	207	Traceability	52
Smart cities	152	Decentralized	51
Smart grid	138	Security	51
Energy	128	Authentication	47
Power markets	94	Transparency	46
Distributed ledger	93	Agriculture	45
Artificial intelligence	80	Industry 4.0	41
Information management	80	Life cycle	40
Peer to peer networks	79	Data privacy	39
Decision-making	74	Big data	38
Renewable energies	71	Network architecture	37
Environmental technology	67	Climate change	36
Commerce	65	Innovation	36
Energy efficiency	65	Machine learning	36
Technology	63	Microgrid	36
Network security	62	Bitcoin	33

4. Results and conclusions

Our SLR illustrates that the role of blockchain in sustainability has mainly focused on three areas of sustainability – energy systems, supply chains and enabling IoT solutions such as smart cities, for example, to create peer-to-peer energy trading systems (Diego et al., 2021) and improve grid efficiency (Hongliang et al., 2022). Another key focus area within the literature is agricultural traceability and assurance, enabling improved crop maintenance through blockchain to ensure IoT devices in fields (Corte et al., 2021). Construction and Smart Cities have a similar focus within the literature, with several solutions put forward to help solve data integrity in various smart cities (Qian et al., 2018), smart buildings (Bindra et al., 2019) and smart construction solutions (Kong, 2022). In addition, healthcare has multiple solutions proposed, most focusing on electronic health records (Gowda, 2022). Another area of focus was the role of blockchain in enabling sustainable supply chains (Kleinknecht, 2021; Kshetri, 2018; Nguyen et al., 2021).

4.1. Gaps in literature

Regarding the literature, several gaps could be usefully filled to help companies, people, and organizations achieve the needs outlined in the Regulations of Section 2. Arshad et al. (2023) conducted an SLR on the role of blockchain in achieving sustainable finance. However, they did not use any technical databases. As a result, their results focus solely on the economic policy aspects rather than the broader aspects of ESG itself. Other papers.

While much of the literature claims to focus on blockchain application to sustainability solutions, the approaches taken do not align particularly well with COP 27, IPCC needs, or the emerging regulations in the ESG space. Even within the literature, the application of the SDGs appears arbitrarily selected and not linked to the SDG indicators used to measure their impact.

The new era of climate change and the increasing reliance on these technologies to help achieve sustainability means that the research could more usefully be directed if research is linked to regulatory outcomes. Where blockchain solutions state they are solving SDGs, it is essential that policymakers assess how that can be aligned to the SDG indicators.

4.1.1. Measuring the impact of blockchain solutions

To ensure blockchain solutions comply with the emerging ESG standards and regulations, the research community should develop robust and peer-reviewed methods and contribute to the ongoing standards discussions, e.g., ISSB. Currently, few regulators can offer practical guidance on ensuring that blockchain solutions are compliant; this is an open area of research that can usefully be filled. Within the SLR, there are only 27 papers related to blockchain protocols, and only a handful are related to energy consumption issues. As discussed in Section 1 of this paper, the PubDLT industry requires these methods to be developed to comply with EU regulations. Failure to establish these methods could severely stifle the role of blockchain in achieving sustainability.

One of the key recommendations is that the solution-ism approach currently taken within blockchain may be better used with a focus on blockchain as part of the emerging infostructure rather than as a solution in and of itself. To fully address sustainability issues, policymakers should focus on blockchain as a subset of a broader system rather than a GPT. This means that policy assessment related to blockchain for sustainability should assess it within the context of the industry it is used, e.g., financial services, water systems or construction, as this will enable a whole-systems approach.

4.1.2. Carbon trading

The SLR is also sparse, relating to blockchain's role in carbon trading and data protection from a sustainability perspective. Due to the increasing role that data integrity will need to play to ensure that ESG reporting and carbon trading are done correctly and genuinely contribute to the transition towards a carbon-neutral or net zero future (Truby et al., 2022), the research community could work to deliver this much-needed interdisciplinary work. Moreover, this would enable the community to assist in measuring IPCC and COP outcomes, as discussed in Section 2.

4.1.3. Linking to ESG regulation

Globally, there is a significant focus on ensuring the world achieves net zero, the regulations discussed in Section 2. However, most papers mention policy only peripherally and do not focus their attention on it. Only eight papers in total in the SLR covered ESG. Asif et al. (2023) and Saxena et al. (2023) mention blockchain only in passing within the broader notion of Industry 5.0. Other papers propose solutions using blockchain for ESG from the perspective of capturing data (Liu et al., 2021, 2023), the creation of a new digital asset designed to create an ESG reputation score and incentivise sustainable behaviour (Golding et al., 2022; Wu et al., 2022) or a more traditional blockchain approach of using it for traceability of the carbon emissions along a supply chain (Qian et al., 2023). A key issue, however, is that many of these papers do not consider the regulation. As a result, they propose technical solutions that may or may not assist companies in complying with the emerging regulation.

4.1.4. Collaboration and measuring systems

Additionally, many solutions proposed are close copies of one another, and several journals publish similar conceptual ideas by different authors; for example, within the SLR there are 44 articles alone that are about creating peer-to-peer energy exchange using blockchain for microgrids. This competitive approach to science may reduce the world's ability to meet its net zero/ESG goals. Policymakers should investigate mechanisms that incentivise greater collaboration between research areas and across international boundaries for technologies such as blockchain that are GPTs.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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