Journal of Environmental Management 354 (2024) 120273

Contents lists available at ScienceDirect

Journal of Environmental Management

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

Review

Toward a greener future: A survey on sustainable blockchain applications and impact

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ARTICLE INFO

Keywords:
Sustainable
Blockchain
Conservations
Applications
Environmental sustainability
Energy-efficient

ABSTRACT

Blockchain Technology has garnered significant attention due to its immense potential to transform the way transactions are conducted and information is managed. Blockchain is a decentralized digital ledger that is spread across a network of computers, ensuring the secure, transparent, and unchangeable recording of transactions. However, the energy consumption of certain blockchain networks like Bitcoin, Litecoin, Monero, Zcash, and others has generated apprehensions regarding the sustainability of this technology. Bitcoin alone consumes approximately 100 terawatt-hours annually, contributing significantly to global carbon emissions. The substantial energy requirements not only contribute to carbon emissions but also pose a risk to the long-term viability of the blockchain industry. This study reviews articles from eight reputable databases between 2017 to August 2023, employing the systematic review and preferred reporting items for systematic reviews and meta-analyses approach for screening. Therefore, explore the applications of sustainable blockchain networks aimed at reducing environmental impact while ensuring efficiency and security. This survey also assesses the challenges and limitations posed by diverse blockchain applications regarding sustainability and provides valuable foresight into potential future advancements. Through this survey, the aim is to track and verify sustainable practices, facilitating the transition to a low-carbon economy, and promoting environmental stewardship, with a specific focus on highlighting the potential of sustainable blockchain networks in enabling secure and transparent tracking of these practices. Finally, the paper sheds light on pertinent research challenges and provides a roadmap of future directions, stimulating further research in this promising field.

1. Introduction

Ralph C. Merkle's proposal in 1979 introduced the concept of a "hash tree", which is now commonly referred to as a "Merkle tree" (Merkle, 1979). The inclusion of a hash tree in data structures facilitates efficient and secure validation of the contents within significant datasets.

This structure is created by hashing smaller subsets of data and then aggregating those hashes together in a hierarchical structure, with the final hash representing the entire data set (Merkle, 1979; Nakamoto, 2008).

The concept of a hash tree was later implemented to establish a distributed database system facilitating secure and decentralized transactions, eliminating the necessity of a central authority. This is what we now know as Blockchain Technology(BT).

Satoshi Nakamoto's white paper on Bitcoin in 2008 built upon Merkle's concept of a distributed database and introduced the idea of a decentralized ledger for recording transactions (Nakamoto, 2008). Since then, BT has been applied in various industries and has evolved into a complex and diverse ecosystem (Nguyen et al., 2020; Abou Jaoude and Saade, 2019).

BT is revolutionizing the finance and banking industry, as well as making a significant impact on healthcare and Supply Chain Management (SCM), among other sectors. This technology has gained a lot of attention due to its decentralized and transparent nature, which provides security and transparency while reducing the need for intermediaries (Abou Jaoude and Saade, 2019; Sharma et al., 2020).

Although BT has numerous benefits, including transparency, security, and efficiency (Rani et al., 2023a; Shin et al., 2020), it has been criticized for its negative environmental impact (Yli-Huumo et al., 2016) due to its high energy consumption (Jiang et al., 2021), greenhouse gas emissions (Jiang et al., 2021), and carbon footprint (Jiang et al., 2021; Tang et al., 2015), wasted resources, 51% attack (Yli-Huumo et al., 2016), etc. In recent years, sustainability and BT have gained considerable prominence, becoming primary areas of focus and scrutiny (Giungato et al., 2017).

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https://doi.org/10.1016/j.jenvman.2024.120273
Received 30 September 2023; Received in revised form 10 January 2024; Accepted 1 February 2024
Available online 13 February 2024

Consequently, there is an increasing interest in developing sustainable blockchain solutions that can reduce these negative effects while still providing the benefits of BT. Sustainable blockchain refers to the responsible use of BT that is environmentally and socially conscious (Rana et al., 2019).

This includes reducing energy consumption, minimizing carbon footprint, and ensuring that the technology is used to benefit society as a whole (Rana et al., 2019).

One of the key challenges facing blockchain is the high energy consumption (De Vries, 2018) required for mining and verifying transactions. This is because the blockchain operates using a Proof-of-Work (PoW) consensus mechanism, which requires nodes to solve complex mathematical problems to verify transactions and add them to the blockchain (Zheng et al., 2018; Yli-Huumo et al., 2016).

This process is computationally intensive and requires a significant amount of energy (De Vries, 2018; Daian et al., 2019). One approach to mitigating the energy consumption of BT is to shift from the PoW consensus mechanism to a Proof-of-Stake (PoS) mechanism (Daian et al., 2019).

The selection of validators in PoS consensus depends on the stake they hold in the network, determining their role in validating transactions. This approach eliminates the need for miners to perform complex calculations, reducing the energy consumption required for network validation.

In addition, PoS can also enable greater scalability, as the number of transactions that can be processed is not limited by the speed of the validation process (Daian et al., 2019; Saleh, 2021).

Another approach to sustainable BT is to use renewable energy sources to power the network (Liu et al., 2021). Many blockchain networks rely on traditional energy sources, such as coal (Liu et al., 2022) or natural gas (Lakhanpal and Samuel, 2018), which contribute significantly to greenhouse gas emissions (Jiang et al., 2021).

Leveraging renewable energy sources like solar or wind power not only allows sustainable blockchain networks to diminish their carbon footprint (Liu et al., 2021) but also mirrors the drive toward sustainability seen in the Iberian Peninsula study, where tailored e-flows strategies increased hydropower production by 10%–35% while preserving the environment. This underscores the importance of innovative approaches in both BT and hydropower for a more eco-conscious future (Kuriqi et al., 2020, 2019).

In addition to reducing energy consumption, sustainable blockchain must also address the issue of e-waste. As BT continues to evolve and older hardware becomes obsolete, there is a growing concern about the environmental impact of disposing of electronic waste (Dasaklis et al., 2020).

One solution to this problem is to develop more sustainable hardware that can be recycled or reused (Dasaklis et al., 2020; Cordella et al., 2021). For example, companies like Fairphone (Reuter et al., 2018) are developing smartphones that are designed to be easily repaired and upgraded, reducing the need for consumers to purchase new devices (Cordella et al., 2021; Reuter et al., 2018).

Furthermore, an essential aspect of sustainable blockchain is ensuring that the technology is used in a way that benefits society as a whole. The potential for blockchain to revolutionize various sectors, such as SCM and healthcare, is significant, by increasing transparency, mitigating fraud, streamlining operations, and improving efficiency.

However, there is also a risk that the technology could be used to further entrench existing power structures or exacerbate social inequalities. To effectively tackle this problem, sustainable blockchain solutions must prioritize inclusivity and social impact (Najjar et al., 2023).

For example, blockchain-based solutions could be developed to address issues such as financial inclusion or supply chain transparency, improving the lives of marginalized communities. In addition, sustainable blockchain solutions must ensure that the benefits of the technology are shared fairly across all stakeholders, rather than benefiting a select few. Sustainable blockchain must also address the issue of security.

While BT is widely recognized for its security features, it has not been immune to several significant hacks and security breaches in recent years. These breaches, including smart contract vulnerabilities, 51% attacks (Yli-Huumo et al., 2016), not only compromise the security of the network but also undermine public trust in the technology (Castonguay and Stein Smith, 2020).

Ensuring security is of paramount importance in sustainable blockchain solutions and must be prioritized at all stages, beginning from the network's design and extending to the deployment of security protocols. This includes developing secure smart contracts (Wright and Serguieva, 2017), using advanced encryption methods (Salama et al., 2011), and implementing robust governance structures to ensure that the network is secure and resilient.

Thus, sustainability is an important consideration for any technology, and blockchain is no exception, making it imperative to assess or review sustainable blockchain networks, their eco-friendly applications, challenges, and potential for tracking green practices.

Sustainable BT revolutionizes industries through transparent SCM, eco-friendly manufacturing, and easy sustainability compliance. It boosts energy systems with Peer-to-Peer(P2P) trading, renewables integration, and automated transactions, reducing reliance on fossil fuels. Governments use it for transparent policies, while it enhances investment transparency, appealing to socially responsible investors. Despite initial costs, it saves in the long run. It mitigates climate change by advocating for the utilization of renewable energy sources and implementing robust carbon footprint management strategies, redefines industries, builds environmental trust, and empowers nations for better environmental efforts and global sustainability targets.

This study aims to guide future research in the field by delving into these aspects. Considering its novelty, this study consolidates seven diverse sustainable blockchain applications into a single, comprehensive resources, facilitating understanding of blockchain's sector-wide impact for both novices and experts.

This Systematic Study(SS) delivers the following primary contributions:

- **Preferred Reporting Items for Systematic Reviews and Meta-Analyses(PRISMA Study):** Conduct a comprehensive review and analysis of scientific research articles using the PRISMA approach to assess the current landscape of sustainable blockchain networks.
- **Identification of Sustainable Blockchain Use Cases:** Identify and examine various applications of sustainable blockchain networks aimed at reducing environmental impact while maintaining efficiency and security.
- **Challenges and Opportunities in Sustainable Blockchain Applications:** Evaluate and discuss the challenges and limitations associated with different blockchain applications concerning sustainability, providing insights into potential advancements.
- **Blockchain for Transparent Sustainability Tracking:** Highlight the potential of sustainable blockchain networks in enabling secure and transparent tracking of sustainable practices to facilitate the transition to a low-carbon economy and promote environmental stewardship.
- **Future Research Directions:** This survey provides a roadmap for future directions and aims to stimulate further research in the field of sustainable BT.

The motivation behind a survey on applications of sustainable blockchain networks is to enhance understanding of how BT can be leveraged to support sustainable practices and contribute to a more environmentally friendly and socially responsible world.

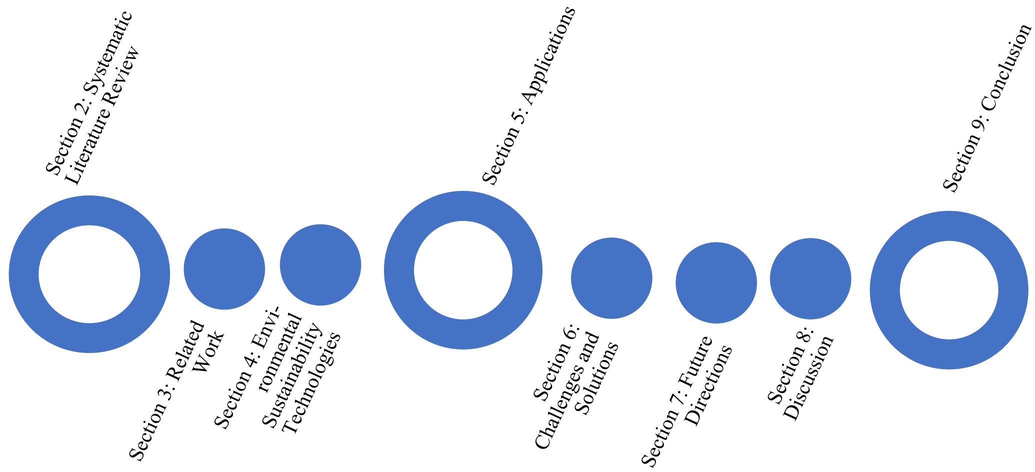

Fig. 1. Organization of the survey.

It conducts a systematic study of scientific articles from 2017 to August 2023 using the PRISMA approach to explore sustainable blockchain applications.

These applications, designed to reduce environmental impact while maintaining efficiency and security, span fields like carbon accounting, SCM, renewable energy trading, cryptocurrency and environmental monitoring.

This study aims to assess sustainability challenges, offer insights into future advancements, and promote further research. Therefore, this study follows the structure depicted in Fig. 1.

The latest advancements in sustainable blockchain research are explored, covering topics such as sustainable blockchain works flow, processes, applications, and challenges, and suggesting possible solutions.

The subsequent sections are structured in the following manner: Section 2 presents a systematic literature review process, and Section 3 discusses the related work. Section 4 presents an overview of environmental sustainability technologies. Section 5 explores several applications of sustainable BT, Section 6 synopsizes the technical challenges and solutions associated with this technology, Section 7 discusses promising future directions, Section 8 delves into the study discussion and finally, Section 9 concludes the study.

Table 1, titled ‘Glossary of Abbreviations’, offers a concise reference list detailing abbreviations and their corresponding meanings or explanations used throughout this study. It acts as a quick guide, aiding readers in understanding the shorthand notations employed within the study.

Table 1
Glossary of Abbreviations.

Abbreviations	Description
BT	Blockchain Technology
PRISMA	Preferred Reporting Items for Systematic Review and Meta-Analysis
SSCM	Sustainable Supply Chain Management
SCM	Supply Chain Management
PoW	Proof-of-Work
PoS	Proof-of-Stake
PoA	Proof of Authority
RPoS	Robust Proof of Stake
SS	Systematic Study
RQ	Research Questions
SDGs	Sustainable Development Goals
BoP	Base-of-the-Pyramid
P2P	Peer-to-Peer
NFTs	Non-fungible Tokens
AI	Artificial Intelligence
IoT	Internet of Things
REDD+	Reducing Emissions from Deforestation and Forest Degradation
ESS	Energy Storage System
LMS	Load Management System
DERs	Distributed Energy Resources

2. Methodology of systematic literature review

In SS, implementing the PRISMA (Behl et al., 2022) methodology. This well-structured approach provides a clear framework for researchers to define research questions, perform a comprehensive search, minimize bias, encourage transparent reporting, and systematically evaluate the quality of included studies (Jayawardena et al., 2021).

PRISMA, a methodical approach, streamlines the assessment of sustainable blockchain practices by guiding focused research, thorough evaluations, and transparent reporting. This methodology ensures a comprehensive overview, aiding in the identification of gaps and future avenues for research in sustainable blockchain applications.

However, while PRISMA serves as a useful tool for systematic reviews, it does have limitations. One key limitation arises from the predefined criteria outlined by PRISMA for study selection. While these criteria provide structure, they might inadvertently exclude relevant research that does not fit within these predefined parameters.

This rigidity could introduce selection bias, potentially limiting the inclusivity and comprehensive nature of the review by overlooking valuable contributions that fall outside the specified criteria.

Moreover, PRISMA often recommends including studies published primarily in certain languages, predominantly English. This language restriction could introduce language bias, neglecting non-English studies that might offer essential insights or diverse perspectives. Therefore, this exclusion might skew the conclusions and findings, resulting in a limited portrayal that does not capture the full scope of the data or information.

Another significant concern revolves around publication bias inherent in the PRISMA methodology. Emphasizing published literature might inadvertently favor studies with statistically significant results, as these are more likely to be published. Consequently, unpublished studies, which could offer crucial contradictory or nuanced information, might not be included. This omission could lead to an incomplete or biased portrayal of the overall information available (Sohrabi et al., 2021).

PRISMA involves a structured search process that comprises six distinct stages: (a) formulating Research Questions (RQ), (b) identifying relevant studies, (c) screening the identified studies, (d) assessing eligibility for inclusion, (e) evaluating the quality of selected studies, (f) extracting and analyzing data.

Formulating RQ: Selecting a systematic literature review for investigating sustainable blockchain applications ensures a methodical, comprehensive approach. It enables a detailed analysis of existing literature, offering structured insights into trends and challenges while enhancing the reliability of study findings.

This initiates the process by creating research queries that are grounded in this study's objectives and motivation.

The generated RQ are as follows:

RQ1. What strategies and best practices are being employed to enhance the energy efficiency and sustainability of BT?

RQ2. To what extent do individuals and organizations perceive BT as a sustainable solution for addressing environmental challenges?

RQ3. What are the primary barriers and challenges faced by organizations when integrating sustainability into their blockchain initiatives?

RQ4. What are the future research directions for sustainable blockchain applications?

Identifying Relevant Studies: The process of identification is a detailed and systematic procedure that involves the careful selection of pertinent research articles from a variety of data sources. This is achieved through the utilization of predetermined keywords, controlled vocabulary terms, and specific inclusion and exclusion criteria.

This meticulous process guarantees the inclusion of research articles that are relevant to the defined scope and timeframe, all while maintaining a comprehensive and impartial search strategy. Ultimately, this method enhances the robustness and credibility of the SS.

Nineteen keywords were utilized for article searches, i.e., blockchain, application, supply chain, sustainable, cryptocurrency, climate risk, conservation, environmental conservation, micro-grid, water management, carbon credits, emission trading, renewable energy, e-waste, benefits, challenges, solutions, barriers, and limitations.

It appears the provided text comprises multiple search queries using various combinations of keywords related to BT and different thematic areas. The queries cover diverse topics such as renewable energy, supply chain, cryptocurrency, environmental conservation, microgrid, carbon credits, e-waste, and more. The aim is to explore how blockchain intersects with these domains within the chosen database utilized for this study.

The keywords were chosen methodically to cover different aspects of sustainable blockchain. "Blockchain" and "sustainable" set the foundation. Specific terms like "cryptocurrency", "supply chain", and "renewable energy" delve into energy efficiency and eco-friendly practices. "E-waste" and "micro-grid" spotlight waste management and localized energy optimization.

Broader aspects like "climate risk", "conservation", and "carbon credits" signify blockchain's role in addressing environmental challenges. Keywords like "water management", "barriers", "limitations", and "future research" target specific challenges and future exploration directions in sustainable blockchain. Together, these keywords create a holistic view of strategies, challenges, and future pathways in sustainable BT. Keywords like "blockchain", "sustainable", "cryptocurrency", "supply chain", "renewable energy", "e-waste", and "micro-grid" are crucial in exploring how BT can become more energy-efficient and sustainable.

They help in investigating strategies to optimize energy in cryptocurrency mining, track environmental footprints in SCM, manage e-waste, and integrate renewable energy into blockchain networks. These terms guide research toward aligning blockchain applications with sustainable practices across various domains.

Examining the perception of individuals and organizations regarding BT as a sustainable solution for environmental challenges necessitates keywords like "climate risk", "conservation", "environmental conservation", and "carbon credits". These terms help gauge the extent to which BT is perceived as a viable tool for conservation efforts, mitigating climate risks, and establishing transparent mechanisms like carbon credits to address environmental challenges.

When investigating the barriers and challenges faced by organizations in integrating sustainability into their blockchain initiatives, keywords such as "barriers", "water management", "carbon credits", and "limitations" are instrumental. These terms shed light on the obstacles encountered when merging sustainability practices with blockchain systems, including challenges related to implementing sustainable water management systems or creating transparent carbon credit mechanisms using blockchain. Exploring future research directions for sustainable blockchain applications involves keywords like "benefits", "challenges", and "solutions".

This study conducted an exhaustive search for research articles spanning from 2017 to August 2023.

This extensive search involved the use of specified keywords and encompassed eight prominent scientific databases, namely ScienceDirect, Web of Science, Springer, IEEE Xplore, ACM Digital Library, Taylor and Francis Library, SAGE Journals, and Scopus.

The decision to utilize these databases was influenced by their unique strengths, in accordance with Monash University Library's recommendations (Hamzah et al., 2022). These databases are recognized for their proficiency in indexing highly influential and top-quality articles in the fields of applications of sustainable BT.

They are known for their capacity to perform comprehensive searches, deliver consistent search results, and provide advanced search features. To ensure an effective search, we crafted search queries using specific keywords.

These keywords were employed to extract articles from the databases through advanced search techniques involving Boolean operators (AND, OR), phrase searches, and wildcards. Distinct search queries were tailored for each scientific database to optimize the search results.

Table 2 provides a comprehensive list of these search queries for each respective database, along with the corresponding article count outcomes.

The search query produced the following results: 3953 articles from Web of Science, 3547 articles from Science Direct, 742 articles from IEEE Xplore, 3332 articles from Springer, 294 articles from ACM Digital Library, 52 articles from SAGE Journals Library, 872 articles from Taylor and Francis Online Library, and 1134 articles from Scopus.

During this identification phase, a total of 13,926 research articles that meet the criteria for the next stage of PRISMA were successfully identified.

Screening the Identified Studies: The screening process involves establishing specific inclusion and exclusion criteria for the selection of pertinent articles within SS. Table 3 outlines initial inclusion criteria, which encompass publication years ranging from 2017 to August 2023, publication type, language, article type, and the nature of findings. Initially, we eliminate duplicate articles and subsequently apply the inclusion criteria to the identified research articles.

Throughout the screening process, focus is on journal articles written in English, which must fall into the categories of review and observation types, with findings directly relevant to applications of sustainable BT.

Screening criteria led to the exclusion of 13,250 out of the initial 13,926 articles, leaving 676 articles that passed this screening phase and are now ready for the next stage of PRISMA.

Assessing Eligibility for Inclusion: The eligibility assessment, which constitutes a second round of screening, ensures that all chosen research articles align with RQ and are therefore suitable for inclusion in the SS.

The achievement of this objective relies on the careful assessment of both the title and its abstract. If the title and abstract alone do not provide sufficient information for a decision, conduct an extra evaluation of the study's methodology, results, and discussion sections.

Table 2
Search query for different scientific database.

Scientific databases	Search query	No. of articles
Science Direct	(blockchain OR supply chain), (blockchain AND application), (blockchain AND sustainable OR conservation), (blockchain OR cryptocurrency OR benefits), (blockchain OR microgrid), (blockchain OR water management), (blockchain OR carbon credits OR benefits), (blockchain OR emission trading OR sustainable), (blockchain OR renewable energy OR benefits), (blockchain OR climate risk AND sustainable), (blockchain AND environmental conservation OR benefits), (blockchain AND sustainable OR application), (blockchain AND e-waste), (blockchain OR solutions AND application)	3547
Web of Science	(blockchain OR renewable energy AND sustainable), (blockchain AND application OR sustainable), (blockchain AND solutions OR challenges), (blockchain AND cryptocurrency OR limitations), (blockchain AND microgrid), (blockchain OR water management AND conservation), (blockchain AND carbon credits OR benefits), (blockchain OR emission trading AND climate risk), (blockchain AND renewable energy OR benefits), (blockchain AND climate risk), (blockchain AND environmental conservation AND benefits), (blockchain OR sustainable OR e-waste), (blockchain AND application OR water management), (blockchain AND limitations OR application), (blockchain OR emission trading)	3953
Springer	(blockchain AND renewable energy AND supply chain), (blockchain OR application OR barriers), (blockchain AND solutions AND challenges), (blockchain AND cryptocurrency OR emission trading), (blockchain AND application), (blockchain OR microgrid OR conservation), (blockchain AND water management AND environmental conservation), (blockchain OR carbon credits OR benefits), (blockchain OR carbon credits OR climate risk), (blockchain AND e-waste AND climate risk), (blockchain AND emission trading OR benefits), (blockchain OR e-waste OR sustainable), (blockchain AND conservation OR benefits), (blockchain OR sustainable AND e-waste), (blockchain OR water management), (blockchain AND application), (blockchain AND limitations OR solutions)	3332
IEEE Xplore	((blockchain) AND climate risk), ((blockchain) AND e-waste), ((blockchain) AND applications AND challenges), (blockchain AND sustainable AND benefits), (blockchain AND carbon credits), (blockchain OR renewable energy AND application), (blockchain AND environmental conservation OR sustainable), (blockchain AND solutions AND challenges), (blockchain AND cryptocurrency OR barriers), (blockchain AND microgrid OR sustainable), (blockchain OR water management AND environmental conservation), (blockchain AND carbon credits AND emission trading), (blockchain OR application AND climate risk), (blockchain AND supply chain OR benefits), (blockchain or climate risk), (blockchain AND conservation AND benefits), (blockchain AND sustainable OR e-waste), (blockchain AND barriers OR application), (blockchain AND sustainable OR emission trading)	742
ACM Digital Library	(blockchain AND microgrid AND sustainable), (blockchain OR supply OR sustainable), (blockchain AND solutions OR limitations), (blockchain AND cryptocurrency OR limitations), (blockchain OR microgrid OR emission trading), (blockchain OR renewable energy AND conservation), (blockchain AND emission trading OR benefits), (blockchain OR e-waste AND climate risk), (blockchain OR conservation OR benefits), (blockchain AND application OR challenges), (blockchain AND environmental conservation AND conservation), (blockchain AND sustainable OR cryptocurrency), (blockchain AND benefits OR water management), (blockchain AND limitations OR application), (blockchain OR sustainable AND solutions)	294
Taylor and Francis Library	(blockchain AND supply chain OR sustainable), (blockchain AND application AND sustainable), (blockchain AND solutions OR limitations), (blockchain OR cryptocurrency OR benefits), (blockchain OR microgrid AND limitations), (blockchain OR water management AND conservation), (blockchain AND carbon credits OR application), (blockchain AND emission trading), (blockchain OR carbon credits OR climate risk), (blockchain AND renewable energy OR benefits), (blockchain AND climate risk), (blockchain AND environmental conservation), (blockchain OR sustainable OR e-waste), (blockchain OR water management), (blockchain OR limitations OR application), (blockchain AND limitations)	872
SAGE Journals	(blockchain AND conservation), (blockchain OR sustainable), (blockchain AND solutions AND limitations), (blockchain AND e-waste AND supply chain), (blockchain AND microgrid OR cryptocurrency), (blockchain OR environmental conservation), (blockchain OR water management OR renewable energy), (blockchain OR renewable energy OR application), (blockchain AND emission trading OR e-waste), (blockchain AND microgrid OR benefits), (blockchain AND carbon credits), (blockchain AND application), (blockchain AND e-waste AND emission trading), (blockchain AND water management), (blockchain OR challenges)	52
Scopus	(blockchain OR conservation OR sustainable), (blockchain OR application AND sustainable), (blockchain AND solutions OR limitations), (blockchain AND cryptocurrency OR supply chain), (blockchain AND e-waste), (blockchain OR micro grid), (blockchain AND water management), (blockchain AND carbon credits OR application), (blockchain AND emission trading), (blockchain AND renewable energy OR benefits), (blockchain AND climate risk OR conservation), (blockchain AND environmental conservation), (blockchain AND sustainable AND e-waste), (blockchain AND application AND water management), (blockchain OR challenges AND application)	1134

Initially, eliminate articles based on specific criteria, including the unavailability of full-text online access and the articles' lack of practical applicability or relevance. In the eligibility assessment phase, we conducted a cursory review of the main text of the articles.

This phase resulted in the exclusion of 601 articles and the selection of only 75 articles for the next stage of PRISMA.

Evaluating the Quality of Selected Studies: During this phase, the 75 eligible articles are subjected to a meticulous quality evaluation process, involving in-depth reading and analysis. This rigorous assessment serves to minimize bias and enables the precise identification of research articles that closely align with our RQ.

This assessment appraises the quality of the articles based on two primary criteria: (i) Are the RQ clearly and explicitly articulated within the articles? and (ii) Does the information presented in the articles demonstrate the capacity to effectively address the specified RQ?

By applying the overarching criteria, 7 articles were excluded, leaving only 68 out of the initial 75 articles that met the quality evaluation standards. Consequently, these 68 articles have been incorporated into the SS.

Table 3
Screening criteria for research article.

Data item	Inclusion criteria
Publication year	2017 to August 2023
Publication type	Journal articles
Language	English
Article type	Review and observation-based
Nature of findings	Article title related to the applications of sustainable BT

The entire process employed in this study, following the PRISMA methodology, is visually represented in Fig. 2.

This Figure illustrates the critical role of a PRISMA-based statistical analysis in article screening and selection for systematic reviews. This method ensures a standardized, bias-reducing process by transparently defining inclusion/exclusion criteria. By enhancing reliability,

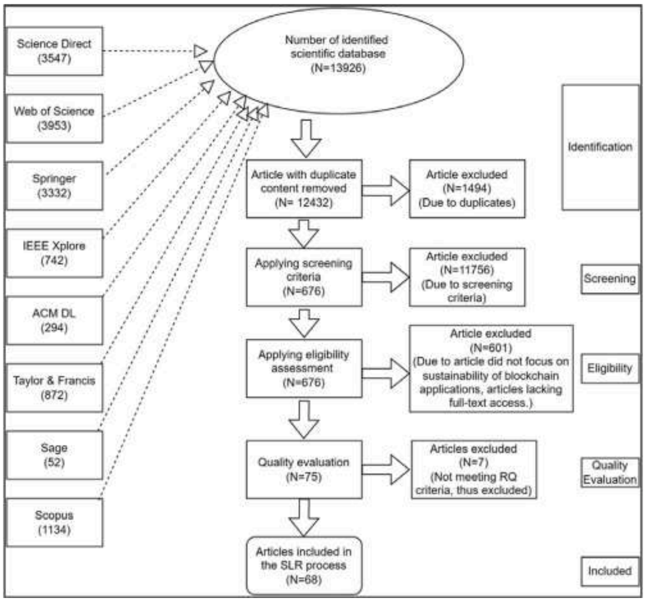

Fig. 2. PRISMA based statistical analysis of article screening and selection.

promoting replicability, and aligning with ethical research standards, it significantly bolsters the trustworthiness of the study.

Extracting and Analyzing Data: The final phase of PRISMA, known as data extraction, involves the retrieval of crucial data and information from the research articles that have been selected following the quality evaluation phase. Subsequently, we analyze the extracted data by categorizing it into predefined themes that align with our RQ.

The search strategy validation in this study was a meticulous process aimed at ensuring the reliability and thoroughness of the literature review conducted within the PRISMA framework.

Initially, pilot searches were executed to fine-tune the selection of keywords, controlled vocabulary terms, and inclusion/exclusion criteria. These preliminary searches served as an evaluation phase, allowing for the assessment of the search strategy's relevance and comprehensiveness before the full-scale search.

Additionally, meticulous documentation of each step of the search strategy was maintained. This comprehensive documentation included database selection, search queries, and criteria for inclusion/exclusion. The transparency offered by this documentation not only facilitates reproducibility but also allows for critical scrutiny and potential replication of the search process.

Fig. 3 presents a year-wise statistical analysis of the 68 articles selected through the PRISMA process. It demonstrates a linear growth in publications, indicating the expanding research trends related to applications of sustainable BT. Likewise, Fig. 4 shows the annual analysis of the 13,926 initially identified articles from multiple scientific databases.

It highlights trends, spikes, or shifts in research output over time, aiding in understanding the temporal evolution of the subject's vital attention.

2.1. Methodology comparison: Reviewing research approaches

When comparing a systematic literature review with other types of research methodologies, several distinctions become apparent:

Systematic Literature Review: Follows a structured, rigorous process with predefined methodologies to identify, select, evaluate, and synthesize relevant studies. Emphasizes minimizing bias and providing an exhaustive overview of existing literature (Rani et al., 2023b).

Narrative Review: Generally, a more subjective approach that summarizes and discusses literature without a predefined methodology. It often incorporates the author's interpretation and narrative style to present the state of knowledge on a topic (Rother, 2007).

Meta-Analysis: Involves quantitative statistical techniques to combine and analyze data from multiple studies. It aims to derive a single, precise estimate or effect size by synthesizing numerical data from various studies (Field and Gillett, 2010).

Scoping Review: Focuses on mapping existing literature on a broad topic, identifying key concepts, gaps, and the extent of available research. It may not follow as strict a methodology as a systematic review and often aims for breadth rather than depth (Munn et al., 2018).

Integrative Review: Integrates various methodologies, data sources, and theoretical frameworks to provide a comprehensive understanding of a specific topic. It often focuses on theoretical contributions or examining diverse perspectives (Whittemore and Knafl, 2005).

The Table 4 provides an overview of the characteristics and distinctions among systematic literature reviews, narrative reviews, meta-analyses, scoping reviews, and integrative reviews across different aspects such as methodology, objectives, data synthesis, focus, bias control, and applicability.

3. Related works

The analysis on sustainable BT and related issues has been thriving in recent years, with many scholars investigating different technical aspects of this field. To provide a comprehensive understanding of this area, several review articles have been published with different scopes. The author in Rana et al. (2021) discussed BT in creating a more sustainable and transparent agri-food supply chain. It explores various applications of BT, such as traceability, certification, smart contracts, and decentralized marketplaces, and discusses the potential benefits of each. The paper exclusive focus on BT advantages in sustainability might overshadow potential drawbacks or unintended consequences in the agri-food supply chain, potentially missing a balanced assessment of its overall impact on sustainability. However, further research exploring practical challenges and conducting empirical studies can refine strategies for integrating blockchain sustainably in agri-food supply chains.

The work in Paliwal et al. (2020) presents the classification framework, a useful tool for researchers and practitioners to understand the different aspects of blockchain application in Sustainable Supply Chain Management(SSCM). The exclusion of works pre-2017 may overlook foundational insights, future scope broadening sources and post-2020 insights could offer a more comprehensive view of blockchain's role in SSCM.

The author in Savelyeva and Park (2022) explores how BT can contribute to sustainable education. The authors scrutinize different scenarios where BT has been implemented in education, such as credentialing, assessment, and learner ownership, and evaluate the potential benefits and challenges inherent in the adoption of BT within the education sector. Recognized for its promise in education, blockchain encounters hurdles in scalability, interoperability, and ensuring equal access. Future efforts aim to craft specialized solutions, navigate regulatory complexities, and create inclusive models to promote educational commons and sustainability, particularly among marginalized communities.

The work in Adams et al. (2018) considers how BT can contribute to sustainability efforts in areas like energy, agriculture, and financial inclusion. BT pursuit of socially and environmentally beneficial outcomes faces implementation challenges like technical complexities and regulatory barriers. Future focus should center on exploring aligned use cases with the UN's SDGs, tackling technical and regulatory obstacles, promoting widespread adoption of Blockchain for Good initiatives, and consistently evaluating their effectiveness in advancing sustainability.

The study in Gans and Gandal (2019), a comprehensive analysis has been conducted on the economic consequences of BT. They explore

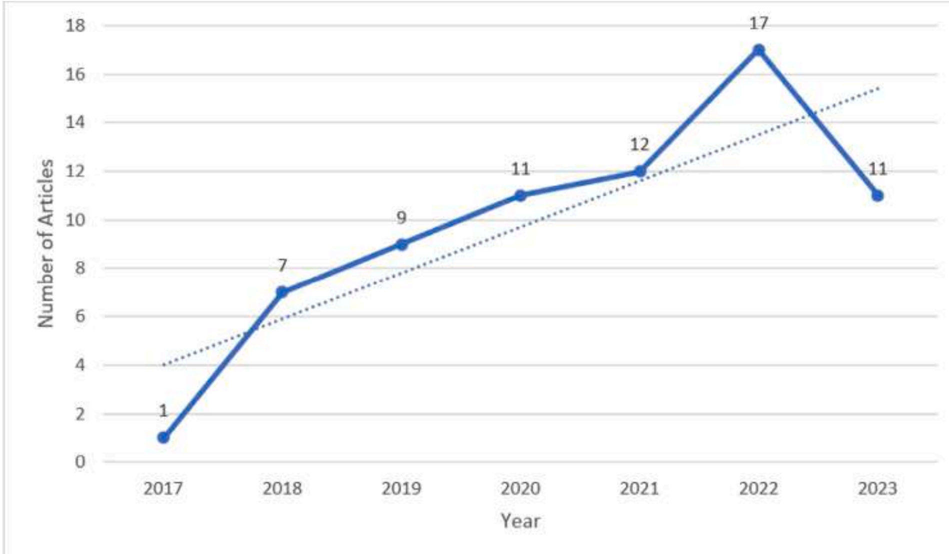

Fig. 3. Year-wise statistical analysis.

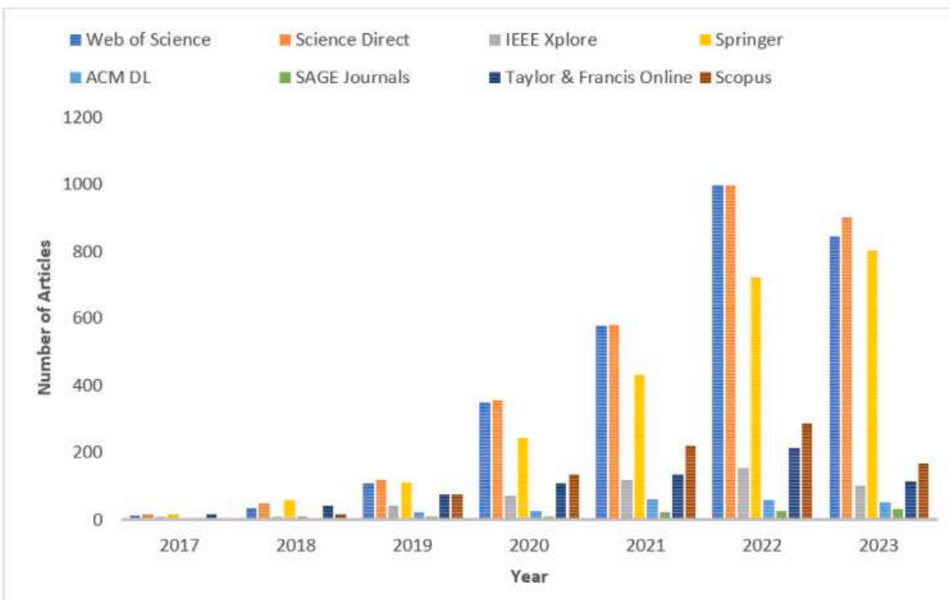

Fig. 4. Annual analysis of multiple scientific databases.

its potential applications, benefits, and limitations, including regulatory challenges and scalability issues. The authors also analyze the technology's potential impact on employment, income distribution, and the economy. They conclude that while blockchain has transformative potential, addressing its limitations is crucial to maximizing its benefits. While extending the blockchain sustainability framework to include PoS and permissioned networks, the paper focuses primarily on economic sustainability, limiting insights into other critical aspects like environmental impact and decentralization.

The author in Li et al. (2020) proposes a new consensus protocol called RPoS that aims to address the energy consumption and security issues of blockchain systems. The paper presents a mathematical model and employs the results of simulations to illustrate the effectiveness of the RPoS. The proposed protocol has the potential to contribute to the development of more sustainable and secure blockchain systems, yet its lack of empirical validation and real-world implementation might challenge its practical viability. Further exploration should prioritize live testing, scalability assessments, and long-term evaluations to solidify RPoS effectiveness and adaptability within real digital economy environments, ensuring its suitability for widespread adoption and addressing potential limitations or vulnerabilities.

The study in Wu (2022) proposes a blockchain-based solution to improve transparency, traceability, and accountability in the reverse logistics process to support sustainable logistics. The hurdles in implementing blockchain-based green reverse logistics underscore the need for advancements in scalability, data accuracy, and seamless integration. Expanding efforts to scale blockchain for traceability data and enhancing reliability while standardizing interoperability will be pivotal for integrating sustainable practices within logistics networks.

The work in Stroumpoulis et al. (2021), examine the impact of BT on reducing food waste in the hospitality industry, proposing a framework for implementing blockchain-based solutions to improve transparency and traceability in the food SCM. Blockchain integration in managing food waste within hospitality faces challenges in scalability, cost, data accuracy, and system integration. To overcome these,

Table 4
Comparative analysis of various methodologies.

Aspect	Systematic literature review	Narrative review	Meta-Analysis	Scoping review	Integrative review
Methodology	Structured, predefined	Less structured	Quantitative statistical	Varies	Integrates methodologies, data sources
Objective	Objective, minimizing bias	May include author bias	Objective through stats	Exploratory	Comprehensive understanding
Purpose	Synthesize existing literature	Summarize literature	Quantitative synthesis	Map existing research	Extensive knowledge
Data synthesis	Qualitative and/or quantitative	Narrative	Quantitative	Both qualitative/ quantitative	Various methodologies integrated
Focus	Depth on specific RQ	Subjective exploration	Specific numerical estimate	Breadth of a topic	Diverse perspectives
Extent of analysis	Comprehensive, systematic	Less exhaustive	Statistical synthesis	Broad overview	Deep insight
Bias control	Minimizes through methodology	May include author bias	Statistical control	Varies	Varied methodologies, sources
Applicability	Answering specific RQ	Broad overview	Quantitative conclusions	Mapping literature	Diverse perspectives
Suitability for research types	Various fields, specific RQ	Descriptive literature	Numerical data synthesis	Broad topics	Multiple methodologies

future endeavors should prioritize scalable solutions, cost-effective integration methods, standardized protocols, real-world pilot projects, and the evaluation of socio-economic impacts, aiming for broader acceptance and sustainable practices in this field.

The author in Sriyono (2020) proposes a conceptual framework for integrating blockchain into water management and provides case studies to demonstrate the feasibility and potential benefits of the proposed framework. The findings of the paper may attract the attention of researchers, policymakers, and professionals seeking to enhance the sustainability of water management practices. Blockchain potential in water resource management faces challenges in adoption due to technical complexities, regulatory hurdles, and data reliability concerns. Future efforts should focus on user-friendly solutions, standardized protocols, and pilot projects for broader integration, aiming to enhance trust and transparency in water management systems.

The work in Ometov et al. (2020) introduces a novel consensus protocol blending PoW, PoA, and PoS for energy-efficient blockchain operation on resource-constrained devices, substantiated through extensive testing with over two thousand smartphones, demonstrating superior battery performance compared to traditional PoW-based approaches. While utilizing constrained devices in blockchain operations shows promise, challenges in scalability, security, and device compatibility persist. Subsequent analysis will address these hurdles by developing scalable solutions, enhancing security measures, and exploring interoperability standards for broader adoption and effective utilization of constrained devices in blockchain ecosystems.

The study in Giungato et al. (2017) examines Bitcoin's sustainability, acknowledging its energy challenges, but also emphasizing the transformative potential of BT in diverse fields like healthcare, energy distribution, and governance, potentially addressing concerns raised by critics. Bitcoin sustainability challenges, such as energy-intensive mining and scalability issues, underscore the need for exploration into eco-friendly alternatives and leveraging blockchain for socially impactful solutions beyond its limitations.

The paper in Najjar et al. (2023) explores the integration of sustainability in complex multi-tier supply networks using BT, emphasizing enhanced visibility, transparency, and predictability while addressing potential adoption challenges. It bridges the gap between sustainability management and global supply networks by leveraging blockchain's capabilities.

Table 5 outlines the primary themes and principal findings gleaned from the existing literature pertaining to sustainable BT. It serves as a quick reference, summarizing diverse insights and aiding comprehension of key areas within the field.

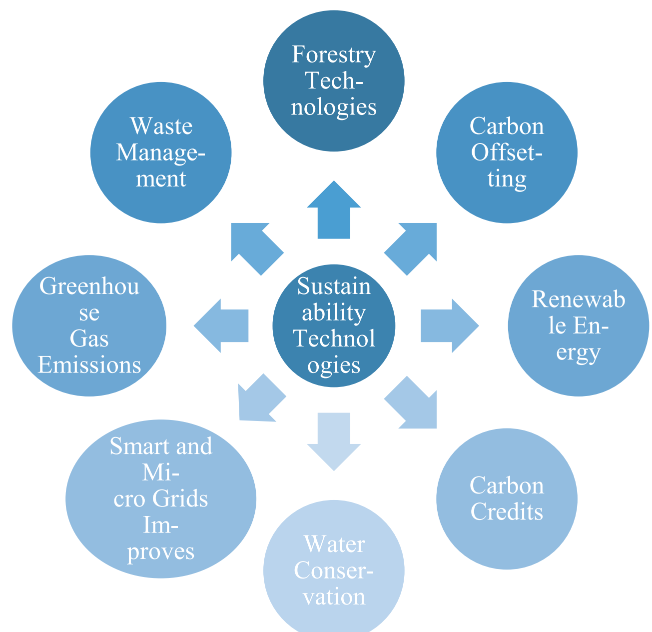

Fig. 5. Environmental sustainability technologies.

4. Environmental sustainability technologies

Environmental sustainability involves responsibly interacting with the environment to safeguard the needs of future generations. It encompasses conserving natural resources, protecting biodiversity, minimizing pollution, and addressing climate change to maintain ecosystem health. Emphasizing efficient resource use, waste reduction, and minimal human impact, it combines practices, policies, and technologies for long-term preservation (Williams et al., 2009).

Conservation is vital in environmental sustainability, focusing on protecting and responsibly using natural resources. It safeguards ecosystems, wildlife, and habitats while preserving biodiversity and ecological balance. Through sustainable practices and policies, conservation actively manages natural areas, fostering harmony between humans and the environment, ensuring resources for the future (Godet and Devictor, 2018).

Fig. 5 depicts a spectrum of technologies dedicated to environmental sustainability. It showcases diverse solutions aimed at fostering eco-friendly practices and initiatives.

Table 5
Summary of findings from existing studies on sustainable BT with comparative analysis.

Ref.	Concept used	Contribution	Limitation	Future scope
Rana et al. (2021)	Blockchain, agrifood SCM	The paper explores the potential of BT in improving the sustainability of the agri-food SCM and provides practical insights and recommendations for future research.	Possible oversight of relevant articles.	Further analysis needed on BT impact in agri-food SCM, addressing scalability, privacy, cost, and connectivity challenges.
Paliwal et al. (2020)	Blockchain, SCM	The paper is to provide a classification framework that identifies the potential of BT in addressing sustainability issues in SCM.	Possible exclusion of earlier significant publications.	Extensive exploration required for practical implementation.
Savelyeva and Park (2022)	Blockchain, education system	The paper is to explore the potential of BT in promoting sustainable education through enhancing transparency, credibility, and security of educational systems and improving students learning outcomes.	Sparse empirical evidence on blockchain's impact in inclusive education for marginalized communities.	Research is needed for blockchain-based education, assisting marginalized groups in accessing and sustaining it.
Adams et al. (2018)	Blockchain, Sustainable Development Goals (SDGs)	The potential of BT in achieving the United Nations SDGs by providing a framework for assessing BT impact on economic, social, and environmental sustainability.	Beneficial uses of distributed ledger technology beyond cryptocurrencies.	Exploring distributed ledger technology social and environmental potential.
Gans and Gandal (2019)	Blockchain, PoS	The paper explores the potential economic benefits and limitations of BT.	Focuses primarily on cost-related aspects, overlooking broader sustainability facets in diverse blockchain consensus mechanisms.	A need to explore sustainability beyond costs across diverse blockchain network models for a comprehensive framework.
Li et al. (2020)	Blockchain, RPoS	The paper proposes a new PoS consensus protocol called RPoS that goal to enhance the sustainability and security of blockchain systems.	Scalability concerns for the proposed RPoS protocol.	Further validation and scalability assessments essential for implementing RPoS in a digital economy system.
Wu (2022)	Blockchain, green reverse logistics	The paper suggests a framework for the sustainable development of green reverse logistics that incorporates BT to improve transparency, traceability, and efficiency.	Scalability of blockchain-driven green reverse logistics.	Validation needed for practical application in sustainable logistics.
Stroumpoulis et al. (2021)	Blockchain, food waste management	The paper explores the potential of BT in reducing food waste in the hospitality industry.	Scarcity of empirical evidence for blockchain's efficacy in reducing hospitality food waste.	Tackle implementation challenges in reducing hospitality food waste.
Sriyono (2020)	Blockchain, water management	The paper deliberates the potential of BT for water management and its role in promoting sustainability.	Scalability of BT for water management in resource-scarce regions.	Improving the effectiveness and scalability of water resource management.
Ometov et al. (2020)	Blockchain, consensus, smartphones	New consensus protocol: PoW, PoA, and PoS combo for energy-efficient blockchain on constrained devices, tested on 2000+ smartphones with better battery performance than PoW.	Scaling and achieving widespread adoption of blockchain on resource-constrained devices.	Extend the applicability of blockchain on constrained devices for enhanced efficiency and user experience.
Giungato et al. (2017)	Blockchain, bitcoin	It highlights the significant energy consumption associated with bitcoin mining and the maintenance of the virtual monetary system.	Challenges exist due to the high energy consumption of bitcoin mining, potentially limiting its widespread adoption.	Explore blockchain beyond bitcoin for sustainable applications in medical data sharing, decentralized energy distribution and more.
Najjar et al. (2023)	Blockchain, multi-tier supply networks	The research investigates how sustainability practices can be incorporated into complex multi-tier supply networks.	Complexities might hinder widespread adoption of blockchain in multi-tier supply networks.	To mitigate obstacles and optimize blockchain integration for SSCM.

Several technologies have a substantial impact on the environment, positively contributing to sustainability and conservation efforts:

Renewable Energy Technologies:

Renewable energy technologies represent a diversified and sustainable approach to power generation. These encompass various sources such as solar, wind, hydro, and geothermal power, which generate energy from natural resources that are replenished continuously. By relying on these sources, they notably decrease our dependence on finite fossil fuels and contribute to a substantial reduction in greenhouse gas emissions. Their pivotal role in mitigating climate change is evident through their ability to offer cleaner, more sustainable alternatives to traditional energy sources, ultimately shaping a more environmentally friendly and resilient energy landscape for the future (Liu et al., 2021).

Advantages of renewable sources, such as solar, hydro, wind, and more, lie in their minimal environmental impact. They reduce greenhouse gas emissions and decrease reliance on finite fossil fuels, promoting energy independence and reducing long-term energy costs. However, challenges arise due to the intermittency of some renewables, hindering consistent energy supply (Gawusu et al., 2022).

Moreover, the environmental implications of manufacturing and disposing of renewable infrastructure components require careful consideration.

Carbon Credits:

Carbon credits are a market-based mechanism aimed at reducing greenhouse gas emissions. They enable organizations to acquire credits symbolizing a measured reduction in emissions, encouraging investments in clean technologies and sustainable practices. These credits act as a financial incentive, motivating entities to offset their environmental impact by supporting projects that reduce or counterbalance greenhouse gases elsewhere. Ultimately, carbon credits form a significant part of the strategy to combat climate change by encouraging responsible environmental practices and supporting initiatives that contribute to a more sustainable future (Bao et al., 2020).

The advantages of carbon credits lie in their ability to create financial incentives for emission reduction, fostering investments in cleaner technologies and sustainable practices. They offer businesses flexibility in meeting emission targets while contributing to environmental projects. However, challenges arise in assessing their effectiveness due to difficulties in accurately measuring emission reductions and ensuring the credited projects genuinely lead to emission reductions.

Smart and Micro Grids:

Smart grids integrate digital tools to enhance the entire electricity distribution system. They bolster efficiency, reliability, and flexibility by employing technologies for real-time monitoring, automated controls, and optimized resource allocation (Khan et al., 2021; Venayagamoorthy et al., 2016).

However, microgrids act as smaller, localized power systems that can operate autonomously or alongside the primary grid. They offer resilience by being self-sufficient during outages or emergencies. Moreover, they optimize energy usage by harnessing local resources and managing demand more efficiently within a smaller area (Khan et al., 2021).

Both smart grids and microgrids represent advancements in energy infrastructure, aiming for greater reliability, sustainability, and adaptability in the distribution and consumption of electricity (Khan et al., 2021).

Smart grids optimize energy usage and integrate renewable sources, while microgrids offer vital resilience and localized energy generation. However, challenges persist, such as the considerable initial investment needed for smart grid implementation and the increased cybersecurity risks accompanying the integration of digital systems, requiring stringent protective measures (Venayagamoorthy et al., 2016).

Water Conservation:

Technologies focusing on water conservation, such as advanced irrigation systems, water-efficient appliances, and wastewater recycling, form a critical arsenal in combating water wastage. Their primary goal is to curtail unnecessary water use, thereby ensuring the sustainable utilization and continued availability of this indispensable resource. These innovations not only enhance efficiency but also contribute significantly to the preservation and responsible management of water, crucial for both environmental and human needs. Water conservation include advanced irrigation systems, water-efficient appliances, and wastewater recycling. These innovations aim to minimize water waste, ensuring sustainable use and availability of this vital resource (Pérez-Blanco et al., 2020).

These advancements offer numerous advantages by significantly reducing water wastage across sectors like agriculture, industry, and households. They promote water efficiency, preserving freshwater ecosystems crucial for biodiversity and sustainability. However, some of these technologies might pose challenges due to their initial costs and potential requirements for substantial maintenance and technical expertise, hindering widespread adoption (Pérez-Blanco et al., 2020).

Greenhouse Gas Emissions:

Greenhouse gas reduction technologies encompass a spectrum of methods, including carbon capture and storage, widespread adoption of renewable energy sources, and the implementation of energy-efficient practices spanning various industries. These concerted efforts aim to curtail the release of gases that significantly contribute to global warming. By employing a multifaceted approach that combines innovation, sustainable practices, and cleaner energy sources, these technologies play a pivotal role in mitigating climate change and fostering a more sustainable future for planet (Niaz et al., 2022).

The advantages of these emission reduction technologies are evident in their contribution to climate change mitigation, preserving the environment, and safeguarding public health. However, their implementation often encounters hurdles such as substantial financial investments and potential resistance, especially in industries heavily reliant on high-emission processes. Economic implications may pose challenges, hindering the widespread adoption of these technologies despite their benefits in combating climate change (Niaz et al., 2022).

Carbon Offsetting Technology:

Carbon offsetting involves counterbalancing carbon emissions by investing in projects designed to mitigate or remove an equivalent amount of carbon dioxide or other greenhouse gases from the atmosphere. These initiatives encompass diverse endeavors such as reforestation programs, renewable energy projects, and the capture of methane emissions from landfills. By supporting these efforts, carbon offsetting aims to neutralize or balance the overall carbon footprint, effectively contributing to the reduction of net greenhouse gas emissions on a global scale (Becken and Mackey, 2017).

Carbon offsetting not only addresses immediate emissions but also ignites a chain reaction of positive environmental impact. It catalyzes innovation, fostering a culture of sustainability, and amplifies awareness about responsible consumption (Becken and Mackey, 2017).

However, challenges arise in ensuring the validity and additionality of offset projects, leading to concerns about the actual impact on overall emissions reduction.

Forestry Technologies:

Forestry technologies, ranging from sustainable logging to reforestation initiatives, stand as pillars in preserving forests. These practices not only ensure responsible timber extraction but also promote biodiversity and combat deforestation. By employing sustainable logging methods, they minimize environmental impact while meeting timber demands (Tang et al., 2009; Torres-Rojo et al., 2016).

Afforestation efforts expand forests into non-forested areas, contributing to carbon sequestration and fostering diverse ecosystems. Reforestation projects restore degraded lands, enhancing carbon storage and mitigating climate change effects. These technologies play a dual role: combating deforestation while actively aiding in carbon capture (Tang et al., 2009). Their collective impact extends beyond timber yield, sequestering carbon, preserving habitats, and bolstering ecological resilience. By balancing human needs with environmental conservation, forestry technologies exemplify a sustainable approach vital for safeguarding planet's future (Tang et al., 2009).

Sustainable forestry practices and reforestation initiatives offer benefits in carbon sequestration, biodiversity conservation, and habitat restoration. However, limitations arise from factors such as land availability, maintenance requirements, and the relatively slow pace of carbon sequestration through tree growth, impacting the effectiveness of forestry technologies (Tang et al., 2009).

Waste Management Technologies:

Innovations in waste management encompass a variety of strategies, including recycling, composting, waste-to-energy processes, and advanced landfill techniques. Their primary objective is to significantly decrease the environmental impact of waste by addressing various facets of its lifecycle (Taiwo et al., 2011; Malinauskaite et al., 2017).

Recycling initiatives focus on reprocessing materials to produce new products, reducing the demand for raw resources and cutting down on waste accumulation. Composting involves the decomposition of organic waste to create nutrient-rich soil amendments, diverting organic matter from landfills and supporting sustainable agriculture (Taiwo et al., 2011; Malinauskaite et al., 2017).

Waste-to-energy processes convert waste into energy sources like electricity or heat, minimizing landfill volumes while generating usable energy. Advanced landfill techniques emphasize practices such as landfill gas capture to reduce greenhouse gas emissions from decomposing waste (Taiwo et al., 2011; Malinauskaite et al., 2017).

Table 6
Comparative analysis of technologies for environmental sustainability.

Sustainability technologies	Positive impacts	Negative impacts	Examples	Policy implications
Renewable energy	Reduces greenhouse gases, sustainable power	Intermittency, initial costs	Solar, wind, hydroelectric, geothermal	Renewable portfolio standards, feed-in tariffs
Carbon credits	Encourages emission reduction, supports clean projects	Verification challenges, potential lack of effectiveness	Supporting renewable energy initiatives, reforestation efforts	Cap-and-trade systems, kyoto protocol compliance
Smart and micro grids improves	Energy efficiency, enhances resilience	High initial investment, cybersecurity risks	Automated controls, localized power systems	Energy policy act, smart grid initiatives
Water conservation	Preserves freshwater, sustains ecosystems	Costly implementation, maintenance	Advanced irrigation, water-efficient appliances	Clean water act, water conservation incentives
Greenhouse gas emissions	Mitigates climate change, reduces emissions	Validity concerns, uncertainty in overall impact	Carbon capture and storage, renewable energy adoption	Paris agreement compliance, clean air act
Carbon offsetting	Immediate action in mitigating emissions	Validity and additionality challenges	Reforestation programs, renewable energy initiatives	Voluntary carbon markets, REDD+ policies
Forestry technologies	Contributes to carbon sequestration, biodiversity	Challenges in sustainable logging practices	Afforestation projects, habitat restoration	Forest stewardship council certification, forest conservation policies
Waste management	Reduces environmental pollution, promotes recycling	Initial investment, technological complexity	Recycling systems, waste-to-energy processes	Waste management policies, extended producer responsibility

By implementing these innovative waste management approaches, the aim is to reduce waste volumes, promote resource reuse, minimize environmental pollution, and create a more sustainable and circular economy that prioritizes resource efficiency (Taiwo et al., 2011; Malinauskaite et al., 2017). Waste management technologies significantly contribute to recycling, pollution reduction, and energy generation from waste, their advanced forms may pose challenges. Implementing these advanced technologies often demands considerable funding, infrastructure upgrades, and substantial public participation (Malinauskaite et al., 2017).

Each technology uniquely contributes to addressing environmental challenges, whether through emission reduction, resource conservation, or sustainability promotion. Their collective impact depends on their widespread adoption and integration into global efforts to combat climate change and promote environmental stewardship.

Table 6 demonstrating the comparative analysis of environmental sustainability technologies serves as a cornerstone for informed decision-making. It highlights the positive impacts of each technology, aiding in resource allocation and prioritization of efforts toward the most effective solutions. Simultaneously, recognizing their negative impacts allows for proactive measures to mitigate challenges during implementation. This analysis fosters innovation, guides policy formulation, and serves as a compass for a more sustainable future.

4.1. Traditional blockchain vs. sustainable blockchain

Traditional blockchain networks and sustainable blockchain networks differ in their approach to transaction processing and network security. Table 7 presents a comparison of traditional and sustainable blockchain networks. It helps understand their differences, aiding decision-making and guiding advancements in BT. Traditional blockchains rely on a PoW consensus mechanism (Zheng et al., 2018) that requires significant computational power and energy consumption to validate transactions and secure the network (Yli-Huumo et al., 2016). This energy-intensive process has led to concerns about the environmental impact of traditional blockchains, particularly in terms of greenhouse gas emissions (De Vries, 2018; Daian et al., 2019). In contrast, sustainable blockchain networks use alternative consensus mechanisms, such as PoS (Zheng et al., 2018; Yli-Huumo et al., 2016), Proof of Authority (PoA) (Bada et al., 2021), and Robust Proof of Stake (RPoS) (Li et al., 2020) which require less energy consumption (Rana et al., 2019) and rely on collaborative validation processes. Sustainable blockchains also often prioritize economic models that prioritize sustainability and social impact, as well as governance structures that promote inclusivity and community development (Seyedsayamdost and Vanderwal, 2020). While traditional blockchains are well-established and widely used, the emergence of sustainable blockchain networks offers a promising alternative that can address concerns about energy consumption (Rana et al., 2019) and environmental impact while still providing secure and efficient transaction processing.

5. Applications

In this section, a condensed overview of the main sustainable blockchain applications in different scenarios, such as SCM, renewable energy, environmental conservation, carbon credits, and emission trading, climate risk management and cryptocurrency as shown in Fig. 6. We highlight the latest research discoveries and advancements regarding the implementation of sustainable blockchain paradigms in these applications. Additionally, we analyze the key insights derived from the review.

5.1. SCM

BT can be used to increase transparency and traceability in SCM, which can help identify environmental and social risks and promote sustainable practices. For instance, blockchain can be used to track the origin of raw materials, the manufacturing process (Khanfar et al., 2021), and the distribution of products to ensure that they are sustainably sourced and produced. Sustainable BT holds promise in the domain of SCM as a tool to promote transparency, accountability, and sustainability (Kshetri, 2021). However, the conceptual framework in Fig. 7. illustrates how integrating BT into SCM can lead to sustainability. It impacts economic, environmental, and social aspects. Economically, this framework boosts efficiency, cuts costs, and improves financial performance. Environmentally, it reduces SCM carbon footprint and enables better product tracking. Socially, it enhances labor conditions, supports ethical sourcing, and encourages fair trade practices. Overall, blockchain adoption in SCM can positively impact the economy, environment, and society, promoting sustainability (Munir et al., 2022).

- **Traceability**

By integrating BT into the SCM tracking process, a transparent and secure platform can be established. This would allow companies and consumers to track the journey of products and materials, all the

Table 7
Traditional blockchain verses Sustainable blockchain networks.

Ref.	Feature	Traditional blockchain networks	Sustainable blockchain networks
Dabbagh et al. (2021), Bada et al. (2021) and Li et al. (2020)	Consensus algorithm	PoW	PoS, PoA, and RPoS
Kumar (2022) and Ahl et al. (2020)	Energy consumption	Consumes significant energy, leading to a carbon footprint.	Consumes less energy, leading to a lower carbon footprint.
Liu et al. (2022), Gawusu et al. (2022)	Renewable energy sources	Relies on non-renewable energy sources, e.g. coal, gas, oil.	Uses renewable energy sources, e.g. solar, wind, and hydro.
Fernando and Saravannan (2021)	Node efficiency	Energy-intensive nodes require specialized hardware and cooling systems.	Energy-efficient nodes require less hardware and cooling systems.
Wang et al. (2019)	Scalability	Limited scalability due to the energy requirements of PoW consensus.	More scalable due to the energy-efficient PoS, off-chain, and sharding techniques.
Zheng et al. (2018), Shin et al. (2020) and Salama et al. (2011)	Security	High security due to the computational power required by PoW.	High security due to the use of PoS consensus and other cryptographic techniques.
Seyedsayamdost and Vanderwal (2020)	Community	The community may focus more on profit-making than environmental sustainability.	The community may prioritize environmental sustainability and social responsibility.
Daian et al. (2019)	Mining	PoW mining requires significant energy and specialized hardware.	PoS mining requires less energy and allows for wider participation.
Dabbagh et al. (2021) and Pierro and Rocha (2019)	Transaction speed	PoW systems may have slower transaction time due to the complexity of the consensus algorithm.	PoS systems may have faster transaction time due to the simpler consensus algorithm.
Kumar (2022) and Kim and Huh (2020)	Environmental impact	Traditional blockchain systems can contribute to greenhouse gas emissions and climate change.	Sustainable blockchain systems prioritize environmental sustainability and seek to reduce their carbon footprint.
Unalan and Ozcan (2020)	Innovation	Traditional blockchain systems may be limited in their ability to innovate due to energy constraints.	Sustainable blockchain systems possess greater innovation potential owing to their utilization of energy-efficient consensus procedures and other technologies.

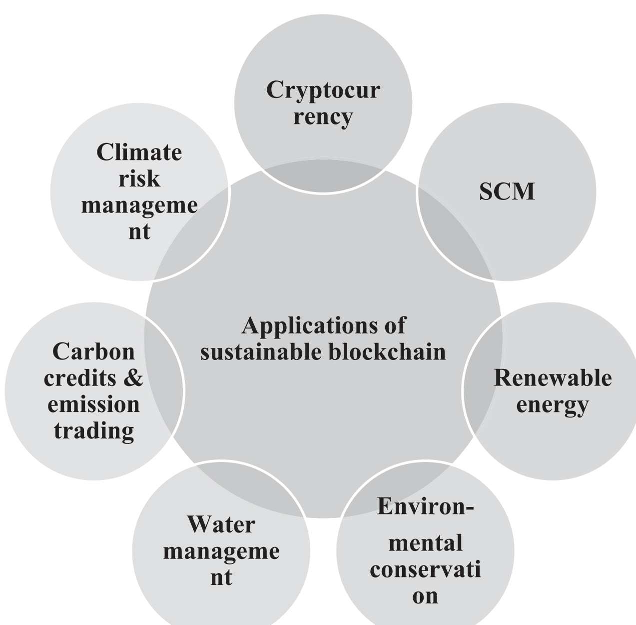

Fig. 6. Applications of a sustainable blockchain network.

way from their origin to their destination. This can help promote ethical sourcing, reduce environmental and social impacts, and improve consumer trust (Khanfar et al., 2021).

The study in Park and Li (2021) sheds light on the positive implications of BT for enhancing supply chain sustainability performance, yet it does not delve into the possible hindrances that might arise during the implementation process, opening the door for further investigation.

The work in Tsolakis et al. (2021) presents a case study on how blockchain implementation in the Thai fish industry can contribute to achieving the United Nations SDGs through a sustainable supply network design. However, the analysis lacks a comprehensive exploration of the potential challenges and limitations involved in the implementation process, creating a research gap for future studies.

The author in Cook and Zealand (2018) presents case studies demonstrating blockchain's role in ensuring transparent seafood supply chains, specifically in a Fijian tuna fishery. It highlights how BT enables traceability, empowering markets to reward ethical practices and exclude unethical ones. Additionally, the report offers valuable lessons and a roadmap for implementing similar blockchain solutions, showcasing its potential in enhancing SCM integrity.

VeChainThor is a blockchain platform applied in China for product verification and SCM. It verifies products' authenticity, quality, and origin across diverse industries, including luxury goods, pharmaceuticals, and agriculture. Its deployment in various regions demonstrates adaptability and applicability in different industry verticals and geographic locations (Kshetri, 2021).

Provenance is a blockchain solution applied globally in agriculture to provide transparency in supply chains. It tracks products from farms to consumers, ensuring authenticity and ethical sourcing. Its implementation across various agricultural products and regions underscores its versatility and relevance in different contexts (Hua et al., 2018).

Everledger's blockchain platform is deployed globally in the diamond industry to ensure the authenticity and ethical sourcing of diamonds. It tracks diamonds from mining to retail, providing transparency and combating the circulation of conflict diamonds. This global implementation demonstrates the technology's effectiveness in ensuring ethical sourcing across diverse regions (Thakker et al., 2020).

Bext360 applies blockchain in the coffee industry across Africa and South America to track coffee beans' journey from farms to consumers. It ensures fair compensation for farmers and promotes ethical sourcing. The technology's usage in multiple continents demonstrates its

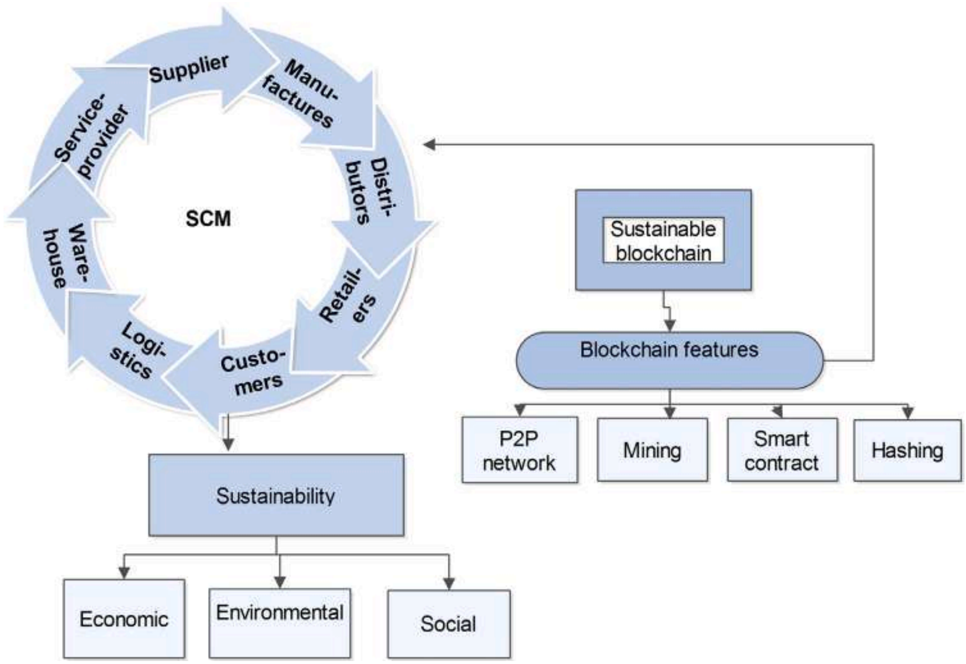

Fig. 7. The general concept of SCM with sustainability.

relevance in ensuring transparency and fairness in agricultural supply chains worldwide (Gashema, 2021).

Walmart utilized blockchain through IBM Food Trust to trace mangoes from farms in Mexico. This enabled transparent tracking of each step in the supply chain, ensuring authenticity and enabling swift identification of issues, bolstering consumer confidence (Zhang et al., 2019).

Walmart's blockchain initiatives, including collaborations with suppliers in the United States and China, aim to enhance supply chain transparency. They utilize blockchain to track various products, such as pork in China and vegetables in the USA, showcasing the technology's adaptability across different geographic regions and product categories (Zhang et al., 2019).

Adoption of blockchain faced challenges such as standardizing data formats among diverse suppliers, addressing regulatory disparities across countries, and ensuring accurate and consistent data across the supply chain.

- **Certification and Verification**

The implementation of BT can establish a secure and transparent platform for certifying and verifying the quality and sustainability of products and materials throughout the supply chain (Cocco et al., 2021). This facilitates informed decision-making by both companies and consumers, based on verified information, with the potential to promote sustainable production and consumption, mitigate environmental and social impacts, and enhance consumer confidence.

The work in Basnayake and Rajapakse (2019) contributes to enhancing agricultural product quality and consumer health by leveraging blockchain technology to establish a transparent and decentralized supply chain verification system, fostering trust through smart contracts and reputation-based tokens, ultimately ensuring the authenticity and safety of food products.

VeChain implemented blockchain to verify wine authenticity. Each bottle was assigned a unique identifier on the blockchain, offering consumers access to detailed production information, combating counterfeit products (Danese et al., 2021).

Implementing blockchain for wine authenticity verification likely faced challenges in establishing a standardized and efficient process for assigning unique identifiers to each bottle. Ensuring seamless integration of this technology across different stages of production, storage, and distribution might have been complex.

Additionally, maintaining the accuracy and consistency of the information recorded on the blockchain for each bottle could have posed challenges. Addressing these issues while ensuring the user-friendly accessibility of information to consumers would have been crucial for the success of the blockchain-based solution.

Richline, a subsidiary of Berkshire Hathaway, developed a TrustChain Initiative using blockchain to trace jewelry, including diamonds, from the mine to the consumer. It emphasizes transparency and responsible sourcing (Smits and Hulstijn, 2020).

Implementing a blockchain platform for diamond tracking likely involved challenges such as incentivizing participation across the supply chain, addressing compatibility issues with existing systems, ensuring data accuracy, and balancing transparency with data security and privacy concerns.

Tracr, developed by De Beers, is a blockchain platform revolutionizing the diamond industry by ensuring transparency and traceability throughout a diamond's journey, from its origin to the market (Smits and Hulstijn, 2020).

Tracr aims to address concerns related to authenticity, ethical sourcing, and the prevention of conflict diamonds from entering the market. By leveraging blockchain's capabilities, it seeks to instill trust and confidence in consumers by providing visibility into the entire lifecycle of a diamond, ensuring it adheres to ethical and responsible practices from mining to retail.

- **Smart Contracts**

By utilizing BT, smart contracts can be developed to automatically execute transactions and agreements according to pre-established rules and conditions. This innovation has the potential to enable companies to optimize and automate supply chain processes, diminish transaction expenses, and enhance operational efficiency and transparency (Khanfar et al., 2021).

The author in Venkatesh et al. (2020) proposes a system architecture for blockchain-based transparency in supply chain social sustainability, which can enhance trust among stakeholders and promote sustainable practices. However, the study lacks empirical validation of the proposed system, indicating a need for further research to evaluate its effectiveness in real-world applications.

Maersk, a global shipping company, collaborated with IBM to create TradeLens, a blockchain-based platform. It uses smart contracts to automate and streamline global trade processes. TradeLens digitizes documentation, tracks shipments, and automates various tasks, reducing paperwork, enhancing transparency, and minimizing errors in the supply chain. Smart contracts on the platform automatically trigger actions (e.g., release of payments) when predefined conditions are met, optimizing efficiency and reducing delays (Ahmed and Rios, 2022).

Electrify marketplace 2.0 deployed a decentralized energy marketplace using smart contracts on the blockchain in Singapore. It allows consumers to buy and sell excess renewable energy directly with each other. Smart contracts facilitate automated energy transactions based on predetermined conditions, such as price or availability. This not only empowers consumers to manage their energy consumption efficiently but also fosters transparency and trust by automating transactions without the need for intermediaries (Tushar et al., 2021).

In Lucknow, India, a pilot project on P2P energy trading is set to demonstrate Power Ledger's platform, enabling the trade of solar power generated on rooftops with neighboring households and buildings (Tushar et al., 2021).

Through a pilot trial in the Malaysian energy market, the feasibility of solar energy trading will be demonstrated, offering consumers the option to choose between clean, renewable energy and power generated from fossil fuels (Tushar et al., 2021).

Implementing blockchain-based platforms like TradeLens, Electrify marketplace 2.0, and Power Ledger's pilot projects faced challenges in interoperability, regulatory compliance, data privacy, stakeholder adoption, scalability, and technical complexities. Overcoming these hurdles was crucial for their successful deployment in shipping, energy trading, and renewable energy sectors.

- **Supplier Management**

Leveraging BT, a decentralized platform can be established for managing supplier data, allowing companies to efficiently track and manage supplier information. This can lead to an improvement in supplier compliance, mitigation of environmental and social risks, and promotion of sustainable sourcing.

The study in Khalid et al. (2015) emphasizes that incorporating SSCM practices in the Base-of-the-Pyramid (BoP) market can benefit companies financially while also creating positive social and environmental impacts. However, the paper falls into a detailed system for implementing SSCM practices in the BoP market, indicating a need for further research.

The work in Khalid and Seuring (2019) examines BoP research from a sustainable supply chain perspective and offers a framework for studying BoP markets in this context. However, the paper does not establish a strong link between ethical concerns and SSCM practices in the BoP market, so research indicates that there is a need for further investigation into the ethical implications of implementing SSCM practices in the BoP market.

- **Circular Economy**

It is possible to establish a transparent and secure platform for managing and monitoring the movement of materials and products in the circular economy by using BT. This can assist companies in reducing waste, enhancing resource utilization, and promoting sustainable production and consumption practices (Nandi et al., 2021).

The work in Cerqueira-Streit et al. (2021) highlights the importance of adopting SSCM practices in the circular economy, the analysis lacks a detailed analysis of the factors that hinder or facilitate the implementation of these practices, leaving room for further research.

The study in Upadhyay et al. (2021) presents a framework for the use of BT in promoting sustainability and social responsibility in the circular economy. However, it does not sufficiently cover all aspects of the challenges related to this technology, highlighting the requirement for additional research.

The author in Mattila et al. (2022) highlights the benefits of 5irechain but the analysis fails to comprehensively explore the potential challenges that can arise during the implementation process.

IKEA, a multinational furniture retailer, has committed to transitioning toward a circular economy model. They extensively explored the challenges and facilitators of implementing sustainable supply chain practices. IKEA focused on factors such as designing products for longevity, material recyclability, efficient logistics, and consumer engagement. Their comprehensive analysis considered obstacles like redesigning manufacturing processes, ensuring consumer acceptance of circular products, and establishing reverse logistics for product return and reuse. This detailed exploration guided IKEA's strategies to foster a circular economy within their supply chain (Bouhia, 2022).

The Ellen MacArthur Foundation established the circular economy 100 Network, a collaborative platform involving various businesses, cities, and governments aiming to accelerate the transition to a circular economy. Through this initiative, participants engaged in extensive discussions, workshops, and knowledge-sharing sessions. These interactions delved into multifaceted challenges and opportunities related to circular supply chain practices. The network's detailed exploration covered barriers like regulatory constraints, technological limitations, economic incentives, and the need for cross-sector collaboration to drive systemic change toward circularity (MacArthur and Heading, 2019).

H&M, a global fashion retailer, has embarked on circular economy initiatives, aiming to close the loop on their textile production. In their exploration, they have detailed challenges and enablers in adopting sustainable supply chain practices. This includes factors such as increasing garment collection rates, developing recycling technologies for various fabric types, and educating consumers on responsible fashion choices. Their comprehensive analysis considers obstacles like technological limitations in textile recycling, consumer behavior shifts, and establishing efficient collection systems to facilitate circularity in fashion (Ly, 2021).

Interface, a leading carpet manufacturer, introduced Mission Zero, a commitment to becoming a restorative enterprise. Their exploration of factors impacting sustainable supply chain practices involved detailed assessments of challenges and facilitators in achieving zero environmental footprint. Interface focused on challenges like redesigning product lifecycle processes, sourcing sustainable materials, and transitioning from linear to circular business models. Their exploration also highlighted the importance of stakeholder collaboration and innovation in driving circularity within the carpet industry (O'Callaghan, 2016).

With the help of BT, stakeholders in the SCM can create tamper-proof records of the products they produce, including information about the source and quality of raw materials, the process of manufacturing, and the distribution channels. This information can be shared with consumers, retailers, and regulatory bodies to promote transparency and sustainability (Kshetri, 2021; Khanfar et al., 2021).

Errors in SSCM often arise from inaccurate data, unchecked supplier claims on sustainability, and incomplete assessments of environmental impact and compliance. To improve, focus on better data accuracy, verifying supplier claims through audits, using updated environmental assessment tools, staying compliant with regulations, assessing risks, understanding consumer behavior, fostering collaboration, investing in technology, providing education and certifications, and maintaining a long-term perspective for continual improvement.

The impact of inaccuracies in SSCM can be significant. Wrong or flawed data leads to misguided decisions, impacting the achievement of sustainability goals. For policymakers and scientists addressing

Table 8
Taxonomy of SCM sustainable blockchain applications.

Ref.	Use-case	Blockchain platform	Main contribution	Limitation
Khalid et al. (2015)	SSCM in BoP research.	N/A	Insight into implementing SSCM in BoP research for positive social and environmental impacts. Emphasis on stakeholder engagement and collaboration.	No detailed analysis of challenges and limitations. No comprehensive framework or guidelines were provided.
Khalid and Seuring (2019)	BoP	N/A	A systematic review and research agenda for analyzing BoP research from a sustainable SCM perspective.	A specific recommendation for a blockchain platform for SSCM is noticeably missing from the paper.
Cerqueira-Streit et al. (2021)	Circular economy	N/A	Provides the circular economy concept and its potential to improve sustainability.	The paper's analysis of how SSCM practices can effectively contribute to the circular economy is limited in scope and depth, failing to provide a comprehensive understanding of their potential impact and significance.
Upadhyay et al. (2021)	Circular economy and sustainability	N/A	Provides an overview of the circular economy and sustainability, and their potential to benefit from BT.	There is a lack of a specific application or case study showcasing the implementation of BT for the circular economy in the paper.
Park and Li (2021)	Traceability	N/A	The paper examines how BT can enhance supply chain sustainability by improving traceability, transparency, collaboration, and verification of sustainable practices.	Lacks detailed analysis of the costs and resource requirements of BT implementation in supply chains, which may impede adoption by small or resource-constrained organizations.
Venkatesh et al. (2020)	Transparency		Blockchain-based system architecture proposed to improve social sustainability in supply chains through transparency and accountability via distributed ledger technology and smart contracts.	The paper overlooks the detailed assessment of the expenses and resource needs involved in the implementation of the proposed system architecture.
Tsolakis et al. (2021)	Traceability	Hyperledger fabric	Blockchain proposed for improving sustainability in the Thai fish industry through supply network design.	The scope is limited to the Thai fish industry case study, and no cost analysis is provided for implementing the proposed framework.
Cook and Zealand (2018)	Blockchain-enhanced seafood traceability.	Unspecified blockchain platform with distributed ledger technology and smart contracts.	Blockchain-enhanced seafood supply chain sustainability.	Limit its feasibility for small or resource-limited organizations.
Mattila et al. (2022)	The coffee supply chain in Ethiopia		The proposal of 5IRECHAIN to promote sustainable economies.	The study's generalizability may be limited due to its focus on a specific use case and geographical location.

climate change targets, this 'wrongness' can undermine the credibility of policies and scientific findings. It might result in overestimating progress, underestimating risks, or misallocating resources, hindering effective climate action. Misguided assumptions in these realms can delay or derail efforts to meet crucial climate change targets, affecting the environment, society, and the economy adversely. Formulating effective policies and strategies to combat climate change hinges on the necessity of having precise data and assumptions.

The main themes and findings from literature reviews on sustainable blockchain applications in SCM are summarized in Table 8. It offers a condensed reference, highlighting prevalent insights and guiding future research or decision-making in this domain.

Main highlights

- BT can be merged into the SCM tracking process to establish a transparent and secure platform.
- This can promote ethical sourcing, reduce environmental and social impacts, and improve consumer trust.
- BT can be utilized to create a secure and transparent platform that certifies and verifies the quality and sustainability of products and materials across the SCM.
- Blockchain can be used to manage and monitor the movement of materials and products in the circular economy, promoting sustainability and social responsibility.

5.2. Renewable energy

The application of BT can facilitate the promotion of renewable energy sources. For example, blockchain can enable the tracking of renewable energy production and distribution, incentivize its generation, and facilitate P2P energy trading. Sustainable BT can play a significant role in promoting sustainable development and reducing greenhouse gas emissions in the field of renewable energy. The work (Almutairi et al., 2023) identifies obstacles that hinder the deployment of BT in renewable energy supply chain management while acknowledging the significant difficulties involved in implementing it.

- **P2P Energy Trading**

A decentralized platform for P2P energy trading can be created using BT, providing individuals and organizations with the ability to directly buy and sell renewable energy to one another. This innovative solution promotes the direct exchange of sustainable energy resources, facilitating the transition toward a more decentralized and environmentally-friendly energy economy. This can help promote the use of renewable energy, reduce greenhouse gas emissions, and increase energy independence (Pipattanasomporn et al., 2018; Wang and Su, 2020).

The author (Juszczyk and Shahzad, 2022) provides an overview of the principles, applications, and prospects of BT for renewable energy. However, It does not thoroughly discuss the obstacles or constraints that may arise during the integration of blockchain in this specific industry.

- **Carbon Credits**

A transparent and secure platform can be created for tracking carbon credits. This platform enables individuals and organizations to effectively offset their carbon footprint by analyzing renewable energy projects. This can assist in reducing greenhouse gas emissions, promoting sustainable development, and facilitating the transition toward a low-carbon economy (Bao et al., 2020).

- **Renewable Energy Certificates**

A platform that is both secure and transparent can be established using BT to track renewable energy certificates. These certificates serve as proof that renewable energy has been generated and sold, and such a platform can encourage the utilization of renewable energy, enhance transparency, and support the transition to a low-carbon economy (Fu et al., 2023).

The work in Delardas and Giannos (2022) proposes blockchain-based solutions for renewable energy certificate markets to promote sustainability, it does not comprehensively evaluate the practical implementation and scalability of blockchain-based solutions.

- **Energy Efficiency**

A decentralized platform powered by BT can be utilized to manage energy efficiency data, allowing individuals and organizations to efficiently track and manage their energy consumption. This can effectively minimize energy waste, promote sustainable development, and contribute to the shift toward a low-carbon economy (Wang and Su, 2020).

The study in Yahaya et al. (2020) proposes a blockchain-based approach for sustainable local energy trading, which considers home energy management and demurrage mechanism. However, it does not sufficiently address whether the suggested solution can effectively operate and expand to meet the demands and challenges of implementation on a larger scale.

- **Micro Grid**

To enhance energy independence, sustainability promote the adoption of renewable energy, and facilitate the shift toward a low-carbon economy, BT can be utilized to establish a decentralized platform that manages micro grids - small-scale energy systems capable of operating autonomously without relying on the primary power grid (Wang and Su, 2020).

The generalized representation of the microgrid controller can be seen in Fig. 8. The microgrid's central component is the microgrid controller, which functions as its brain. It is responsible for connecting and coordinating the various elements within the microgrid, such as the Distributed Energy Resources(DERs), Load Management System(LMS), Energy Storage System(ESS), and islanding switch. To convert the DC power generated by the distributed energy resources, like solar panels and wind turbines, into usable AC power for the microgrid's loads, inverters are used to link them with the microgrid controller. The LMS, which regulates the energy consumption of the microgrid's loads, is also connected to the microgrid controller. The system comprises energy-efficient devices, demand response systems, and smart meters. It integrates an ESS, utilizing various technologies like batteries or flywheels to store excess energy from DERs for future when demand exceeds supply. The microgrid controller is also linked to the islanding switch, which allows the microgrid to function independently of the primary power grid in the event of a power outage (Shahgholian, 2021).

Through smart energy management, it reduces reliance on non-renewable sources during peak demand, minimizing the carbon footprint. This setup fosters resilience during outages while promoting a greener, more sustainable energy landscape.

The work in Tsao and Thanh (2021) presents a novel application of fuzzy meta-heuristics to optimize energy trading in microgrids. However, it is recommended that future research prioritize the testing of the proposed mechanism in real-world scenarios to evaluate its practicality and scalability.

By using BT, stakeholders in the renewable energy sector can create tamper-proof records of energy production and consumption, including information about the type and source of energy, the amount of energy produced and consumed, and the distribution channels. This information can be shared with consumers, utilities, and regulatory bodies to promote transparency and sustainability (Pipattanasomporn et al., 2018; Wang and Su, 2020; Yahaya et al., 2020).

Errors in renewable energy planning often stem from inaccurate resource assessments, assumptions about technology advancements, flawed cost projections, misjudgement of policy impacts, and inadequate grid integration planning. To improve, better data collection, dynamic technology evaluation, regular cost analysis, policy monitoring, and grid modernization are crucial. Updating assumptions based on real-world data and technological advancements helps enhance accuracy and effectiveness in renewable energy planning and implementation.

Inaccuracies in renewable energy planning have wide-ranging effects, impacting project feasibility and credibility in combating climate change. Flawed assessments may overstate progress or underestimate risks, leading to misdirected investments and delays in meeting crucial targets. This 'wrongness' poses a significant threat, potentially impeding climate change goals, affecting the environment, society, and the economy. Accurate assessments are vital for effective strategies to address these challenges.

A summary of the primary themes and findings identified in literature reviews exploring the application of sustainable blockchain in the renewable energy context can be found in Table 9. It serves as a quick reference, aiding comprehension and guiding decisions in this field.

Main highlights

- Microgrids, operate autonomously without relying on the primary power grid and can be managed through a decentralized platform enabled by BT, contributing to the adoption of renewable energy and the shift toward a low-carbon economy.
- A transparent and secure blockchain platform can be utilized to track carbon credits, effectively facilitating the transition toward a low-carbon economy.
- A blockchain-based approach for managing energy efficiency data can help minimize energy waste and contribute to sustainable development.
- Decentralized platforms powered by BT can effectively manage energy efficiency data, minimizing energy waste, and promoting sustainable development.
- Fuzzy meta-heuristics can be used to optimize energy trading in micro grids.
- Blockchain-based solutions for renewable energy certificate markets can be proposed to promote sustainability, but their feasibility and scalability need to be comprehensively evaluated.

5.3. Environmental conservation

It is possible to utilize BT to facilitate and encourage the adoption of environmental conservation by creating a secure, transparent, and decentralized system for managing natural resources, such as forests, oceans, and wildlife. For instance, blockchain can be used to track biodiversity, promote sustainable fishing practices, and protect endangered species (Isabelle and Westerlund, 2022). BT enables stakeholders in the environmental conservation sector to create immutable records of natural resources, they manage, including information about the location and condition of ecosystems, the species and habitats

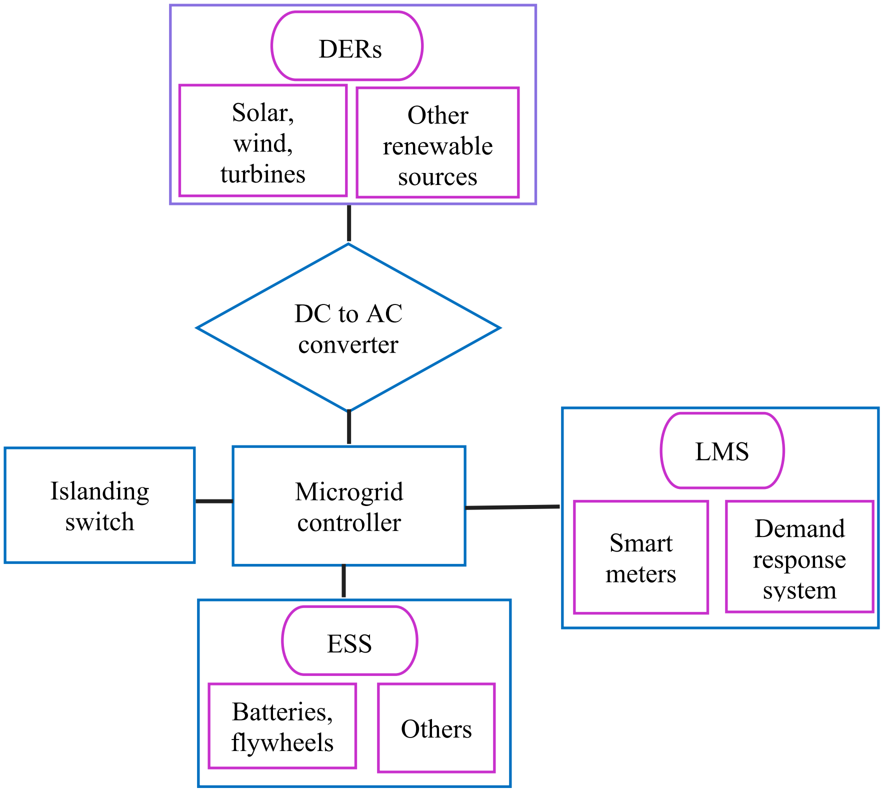

Fig. 8. The generalized concept of microgrid controller.

Table 9
Taxonomy of renewable energy sustainable blockchain applications.

Ref.	Use-case	Blockchain platform	Main contribution	Limitation
Almutairi et al. (2023)	Renewable energy SCM	N/A	Identifying the challenges of applying BT to renewable energy SCM and proposing potential solutions to address these challenges.	The paper focuses on theoretical discussions and does not include any empirical analysis or case studies.
Pipattanasomporn et al. (2018)	Solar electricity exchange	Hyperledger	The paper presents a practical, small-scale application of a blockchain network utilizing Hyperledger for enabling P2P solar electricity exchange among homes equipped with rooftop solar photovoltaics.	The paper does not delve deeply into the business, legal, and financial aspects of blockchain in the energy sector.
Wang and Su (2020)	Energy sector	N/A	The paper offers an overview of the research trends in BT application to the energy sector, indicating a growing interest, especially in developing countries. It suggests blockchain's potential role in advancing renewable energy adoption and sustainability.	The study mainly focuses on the research landscape and trends rather than going into detailed technical aspects or implementations of energy blockchain projects.
Juszczyk and Shahzad (2022)	P2P energy trading, SCM, and carbon credits trading	N/A	Overview of BT potential to improve efficiency, transparency, and security in renewable energy transactions.	The paper limits analyzing the challenges and limitations of implementing BT in the renewable energy sector and lacks a specific case study or use case example.
Yahaya et al. (2020)	Sustainable local energy trading	Ethereum	Proposing a blockchain-based system for sustainable local energy trading.	Limited to a theoretical study and lacks practical implementation of Blockchain.
Delardas and Giannos (2022)	Renewable energy certificates tracking and trading	Suggest public blockchain.	Proposes the use of BT to track renewable energy certificates and support sustainability commitments in the energy sector.	The proposed system may require significant resources both for its development and ongoing maintenance.
Tsao and Thanh (2021)	Sustainable microgrids	Ethereum	Proposes a BT-based P2P energy trading mechanism for sustainable microgrids.	The proposed fuzzy meta-heuristic approach may not be suitable for all types of microgrid systems, as its effectiveness depends on the complexity and variability of the energy demand and supply.

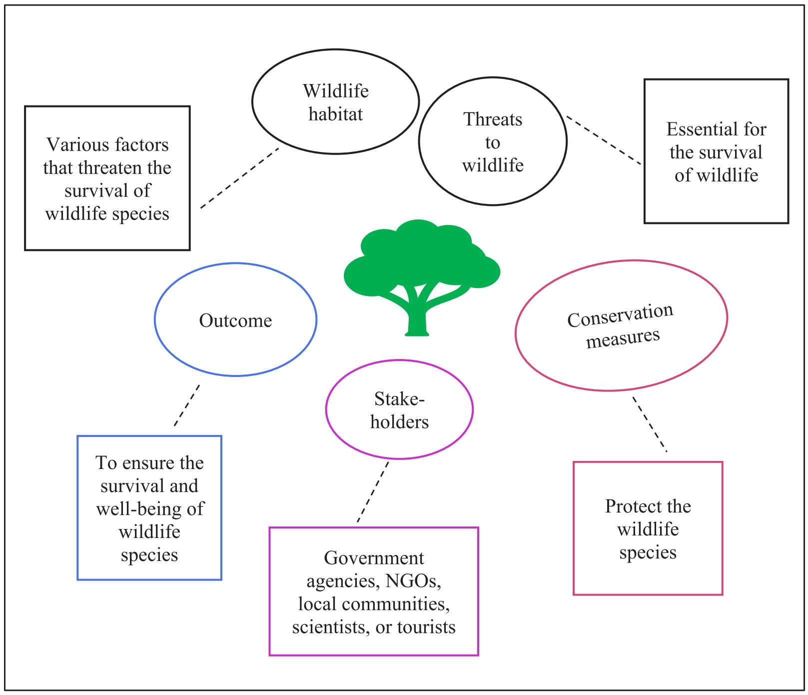

Fig. 9. The general concept of wildlife conservation.

present, and the conservation measures being taken. This information can be shared with policymakers, researchers, and other stakeholders to promote transparency and sustainability.

- **Forest Conservation**

The use of BT has the potential to monitor the supply chain of timber, validating its legal and sustainable sourcing to prevent deforestation, promote sustainable forestry practices, and protect biodiversity (Isabelle and Westerlund, 2022; Howson et al., 2019).

The author in Peng and Huang (2022) proposes using blockchain and sharing culture to promote sustainable forest management in tribal communities, providing a decentralized, transparent, and culturally sensitive approach to conservation and management. This innovative approach shows promise in addressing the limitations of traditional management models.

- **Wildlife Conservation**

The use of BT, a decentralized platform can be developed to promote wildlife conservation by enabling individuals and organizations to donate funds toward conservation projects. This platform has the potential to safeguard endangered species, encourage sustainable tourism, and provide vital support to local communities (Isabelle and Westerlund, 2022). Fig. 9 shows the general concept of wildlife conservation. Wildlife habitat refers to the natural environments where wildlife species thrive, including forests, grasslands, wetlands, and other ecosystems. However, wildlife faces threats such as habitat loss, poaching, climate change, pollution, and disease, which necessitate identification and mitigation. Conservation measures, such as establishing protected areas, enforcing anti-poaching laws, reducing human-wildlife conflicts, and promoting sustainable land use, are crucial for safeguarding wildlife. Engaging stakeholders like government agencies, non-governmental organizations, communities, scientists, and tourists is vital in developing and implementing effective conservation strategies. The ultimate objective is to ensure the survival and well-being of wildlife, measured by factors like population size, habitat quality, and ecological balance. Establishing sustainable wildlife conservation systems is key to protecting wildlife for future generations (Adams, 1994).

The work in Gehlot et al. (2022) proposes a novel approach, called Dairy 4.0, which integrates blockchain and Internet of Things (IoT) technologies to ensure the welfare of cattle and enhance the efficiency of dairy farming. However, the paper lacks empirical evidence or real-world implementation of the proposed system to evaluate its effectiveness in improving cattle welfare and dairy farming operations. The study in Mofokeng and Fatima (2018) proposes the use of NFTs as a novel way to fund wildlife conservation by selling digital assets to tourists, providing an innovative solution to the challenges of traditional funding models.

- **Water Conservation**

A decentralized platform for water conservation can be created using BT, enabling individuals and organizations to monitor and manage their water usage. Such a platform can contribute to the reduction of water waste, encourage the adoption of sustainable water management practices, and provide essential support for sustainable agriculture (Isabelle and Westerlund, 2022).

The author in Stuit et al. (2022) provides a critical analysis of the impacts of digitization and commodification on conservation, highlighting the need for more nuanced and context-specific approaches to conservation.

Potential errors in environmental conservation can originate from inaccurate data, misconceptions about ecosystems, flawed policies, limited community engagement, and neglecting climate change impacts. Improvements lie in refining data collection, embracing adaptive management, involving communities, and integrating climate considerations. These enhancements drive informed decisions, align strategies with ecosystem needs, empower communities, and fortify against climate challenges, fostering more impactful and sustainable conservation practices.

In environmental conservation, inaccuracies can compromise biodiversity and ecosystem health. This 'wrongness' undermines policy credibility, leading to misinformed decisions and delayed climate change targets. Such inaccuracies could delay vital climate change targets, impacting the environment, society, and the economy adversely.

Table 10 provides a compact summary of literature reviews related to sustainable blockchain applications in environmental conservation,

Table 10
Taxonomy of environmental conservation sustainable blockchain applications.

Ref.	Use-case	Blockchain platform	Main contribution	Limitation
Stuit et al. (2022)	Environmental sector, including carbon trading, biodiversity offsetting, and water rights management.	N/A	The paper explores BT potential to enhance environmental sustainability and nature conservation by enabling secure and transparent tracking and trading of environmental assets such as carbon credits, biodiversity offsets, and water rights.	The paper emphasizes the need to address challenges in implementing blockchain-based solutions in the environmental sector, including technical and regulatory obstacles, as well as social and ethical considerations.
Gehlot et al. (2022)	Animal welfare monitoring	Suggests the use of a private blockchain.	The paper proposes a system called Dairy 4.0 that uses blockchain and IoT technologies to monitor the welfare of dairy cattle and facilitate communication among stakeholders.	Lacks regulatory challenges associated with implementing Dairy 4.0. Additionally, the system may require significant resources to develop and maintain.
Mofokeng and Fatima (2018)	NFTs and wildlife conservation	suggests that any platform that supports NFTs.	The paper proposes the use of NFTs as a means of incentivizing tourists to engage in wildlife conservation efforts, by offering them unique and exclusive experiences and rewards.	The paper acknowledges that the application of NFTs for conservation is a novel concept, and it highlights the need to address technical, economic, and ethical challenges before widespread adoption can occur.
Isabelle and Westerlund (2022)	Endangered species protection	N/A	The paper explores Artificial Intelligence (AI) potential applications in addressing sustainable development goals 14 and 15, offering a conceptual framework and real-world examples for wildlife, ocean, and land conservation.	The paper may not consider the regional or geographical variations in conservation challenges and AI solutions, which can vary significantly across different ecosystems and countries.
Howson et al. (2019)	Cryptocarbon initiatives	N/A	The work explores how blockchain is used to address challenges in market-based forest protection, specifically focusing on 'cryptocarbon' initiatives and their potential impact.	The paper acknowledges the benefits of blockchain in forest protection but also highlights its ambiguous outcomes and challenges.
Peng and Huang (2022)	Sustainable forest management	Ethereum	A BT-based system is proposed to advance sustainable forest management in tribal communities. It enables secure and transparent tracking of timber products while fostering knowledge and resource sharing.	Challenges to implementing the proposed system include limited technical expertise, restricted technology access, and cultural barriers.

outlining the primary themes and findings. This compact summary aids quick understanding and decision-making in this field.

Main highlights

- BT and embracing a sharing culture, sustainable forest management in tribal communities can be promoted. This approach offers a decentralized, transparent, and culturally sensitive method for conservation and management practices.
- NFTs can be used as a novel way to fund wildlife conservation by selling digital assets to tourists, providing an innovative solution to the challenges of traditional funding models.
- Integrating BT and IoT technologies can enhance the efficiency of dairy farming while ensuring the welfare of cattle.
- Digitization and commodification can have impacts on conservation, highlighting the need for more nuanced and context-specific approaches to conservation.
- Decentralized platforms for conservation can contribute to reducing waste, encouraging sustainable practices, and supporting sustainable agriculture.
- Employing BT, conservation organizations can more effectively address the challenges of illegal logging and poaching, promoting sustainable and legal practices.

5.4. Water management

BT presents an opportunity to create a decentralized water management framework that ensures transparency, security, and efficiency (Chohan, 2019). Fig. 10 shows the framework of water conservation. The framework presents a model for a smart water conservation management system that utilizes sensors to gather data on water consumption and quality. This data is then stored on a blockchain network, ensuring secure and tamper-proof records. Machine learning algorithms analyze the data to identify areas for improvement, and edge computing ensures real-time monitoring and control of water usage. a smart contract system enables automatic water supply and billing through a decentralized network, promoting water conservation and efficient water management practices This framework can help to effectively monitor and manage water resources, encourage water conservation practices, and provide incentives for sustainable water use in agriculture and other sectors (Poberezhna, 2018; Mukheibir, 2010).

Applying sustainable BT to water management presents a viable solution to tackle the worldwide water crisis in yet another field. According to the United Nations, over two billion people lack access to safe drinking water, and climate change is expected to exacerbate this problem by increasing water scarcity and droughts (UN, 0000).

The author in Dogo et al. (2019) proposes the integration of blockchain and IoT technologies for an intelligent water management system.

- **Water Rights**

Water rights encompass legal privileges that grant individuals or entities the authority to utilize or access water resources, usually for agricultural, industrial, or domestic purposes.

These rights are often subject to regulation by government agencies to ensure sustainable water management and promote water conservation (Mukheibir, 2010; Liu and Shang, 2022). The study in Paiva et al. (2019) suggests using BT to improve water governance by boosting transparency, traceability, and accountability in multifaceted water flow systems. Nonetheless, it lacks concrete evidence and practical

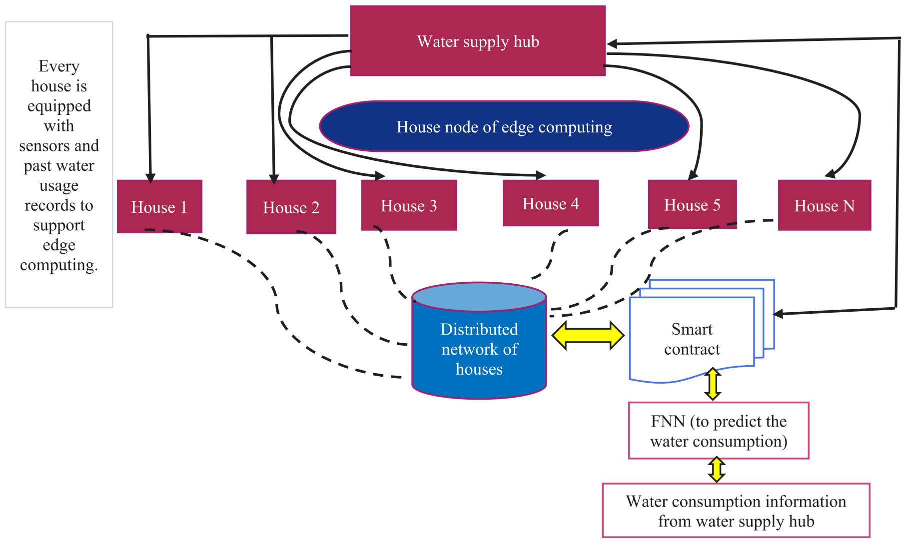

Fig. 10. The general framework of water conservation.

implementation necessitates further research to assess the feasibility and effectiveness of the proposed strategy.

- **Water Quality Monitoring**

BT has the capability to enable real-time monitoring of water quality through the utilization of sensors and IoT devices. This approach can provide early detection of water contamination, thereby helping to prevent potential public health crises (Moparthi et al., 2018).

The work in Thakur et al. (2021) proposes a machine learning and blockchain-enabled decentralized edge computing network for smart water conservation, providing a reliable and efficient solution to the challenges of traditional water conservation techniques.

- **Water Trading**

A decentralized platform for water trading can be created using BT, enabling the buying and selling of water rights by farmers, municipalities, and industries. This can promote water conservation, increase water efficiency, and reduce water scarcity (Mukheibir, 2010; Liu and Shang, 2022).

The author in Asgari and Nemati (2022), contributes to the ongoing discourse on the adoption of distributed ledger platforms in the water sector, helping policymakers and practitioners make informed decisions about its potential use.

- **Disaster Relief**

A platform ensuring both security and transparency is established for tracking donations and aid distribution can be created using BT to facilitate disaster relief efforts. This can ensure that aid is efficiently and quickly delivered to those in need (Poonia et al., 2021).

The work in Angara and Saripalle (2022) proposed virtual water currency for industrial products using BT and presents a novel solution to water accounting and management challenges in industrial production.

The work in Predescu et al. (2021) suggests a new way of collecting data on the status of urban water infrastructure through a serious gaming approach with blockchain support. This offers a decentralized and innovative method for water infrastructure management. However, BT offers a sustainable solution to tackle the global water crisis by managing water resources more efficiently (Mukheibir, 2010). It can register and manage water rights (Liu and Shang, 2022), monitor water quality (Moparthi et al., 2018), incentivize water conservation, facilitate water trading (Liu and Shang, 2022), and improve disaster relief efforts. Implementing BT can create a sustainable and equitable water system that promotes the health of the planet and its inhabitants (Mukheibir, 2010).

In sustainable water management, errors might originate from inaccurate data, misjudging climate impacts, flawed policies, outdated infrastructure assumptions, and insufficient community involvement. To improve, focus on enhanced data accuracy, advanced modeling for climate effects, adaptive governance, infrastructure upgrades, and engaging communities. These steps enhance precision, adaptability, infrastructure efficiency, and inclusivity in sustainable water management strategies.

Errors in sustainable water management can disrupt resource allocation, conservation, and climate resilience. This ‘wrongness’ undermines policy trust, risking misallocated investments and misjudged water availability. Such discrepancies delay progress, potentially impeding critical climate targets and harming water resources, ecosystems, and communities. Precise evaluations are crucial for crafting impactful policies to tackle water challenges driven by climate change. Table 11 provides an abridged overview of literature reviews concerning sustainable blockchain applications in water management, capturing the Primary areas and insights. This concise presentation encapsulates key areas and vital insights, offering a swift and informative reference for understanding this niche, aiding decision-making processes in the domain.

Main highlights

- The system collects data on water consumption and quality, identifies areas for improvement, and enables automatic water supply and billing through a decentralized network.
- BT can improve water governance by boosting transparency, traceability, and accountability in multifaceted water flow systems.
- Real-time monitoring of water quality through sensors and IoT devices can help prevent potential public health crises.
- A virtual water currency using BT can offer a novel solution to water accounting and management challenges in industrial production.
- Serious gaming approaches with blockchain support can offer a decentralized and innovative method for water infrastructure management.
- Implementing BT can create a sustainable and equitable water system that promotes the health of the planet and its inhabitants.

Table 11
Taxonomy of water management sustainable blockchain applications.

Ref.	Use-case	Blockchain platform	Main contribution	Limitation
Thakur et al. (2021)	Various water-intensive industries	Ethereum	The proposal of a smart water conservation system that utilizes machine learning, blockchain, and decentralized edge computing.	The limitation is the feasibility of IoT sensors and infrastructure costs.
Dogo et al. (2019)	Water-intensive industries	N/A	The water management system integrates blockchain and IoT technologies.	Reliability of the system.
Angara and Saripalle (2022)	Industrial production processes	Ethereum	A virtual water currency system that uses blockchain technology.	The paper evaluates the accuracy, reliability of data, and industry willingness to adopt the system.
Predescu et al. (2021)	Urban water infrastructure management, and the blockchain	Ethereum	A serious gaming approach is employed for crowd-sensing in urban water infrastructure.	The availability and engagement of participants.
Paiva et al. (2019)	Water governance.	N/A	The paper explores the potential of combining BT and complex flow systems to foster innovation in water governance.	The adoption and effectiveness of the proposed systems may be limited by technical and social barriers, such as data interoperability, regulatory frameworks, and stakeholder engagement.
Asgari and Nemati (2022)	Water quality monitoring, water trading	Ethereum, and Hyperledger fabric	The paper examines studies on using distributed ledger platforms in smart water systems, discussing the benefits and challenges involved.	The limitations of the reviewed studies may vary, including the small sample size, limited geographic scope, and lack of empirical validation of the proposed solutions.

5.5. Carbon credits and emissions trading

The trading of carbon credits and emissions reductions can be made more efficient with the use of BT. Blockchain creates a secure, transparent, and auditable system for tracking carbon credits and emissions reductions (Al Kawasmi et al., 2015; Khaqqi et al., 2018). The case study on Reducing Emissions from Deforestation and Degradation (REDD+) implementation in Tanzania's Kilosa District provides insights into vital aspects of the project. It emphasizes the need for rigorous certification, land-use planning, and mitigation strategies for deforestation drivers. Findings highlight the influence of REDD+ payments on climate-smart agriculture adoption and increased land values, contributing to a better understanding of the challenges and dynamics within such conservation initiatives (Quail, 2020). The data shown in Fig. 11 is stored within a web application server, which serves as a repository for various types of information, including Verification data, greenhouse gas data, and other relevant data.

The network maps data, utilizing Deep Learning engines for analysis. Real-time tracking servers handle databases and analysis, sending results to the web app server. Neural Network data is secured via a smart contract algorithm and saved for future predictions. Exceptional data goes to a Processable server, while real-time tracking data is stored separately. Ultimately, all data ends up on the main database server for dashboard display, facilitating seamless insights for businesses and researchers (Kim and Huh, 2020).

This setup not only streamlines information for businesses and researchers but also promotes environmental sustainability. By harnessing advanced analytics, it optimizes resource utilization, minimizing waste and enhancing operational efficiency. Furthermore, predictive modeling aids in proactive decision-making, facilitating eco-friendly practices and reducing environmental impact in various industries.

- **Traceability**

The possession and exchange of carbon credits and emissions allowances can be monitored with the help of BT, enabling easy verification of the legitimacy of these credits and allowances. This approach can prevent fraudulent activities and ensure that credits and allowances are not traded more than once (Richardson and Xu, 2020). The study in Al Sadawi et al. (2021) proposes a comprehensive hierarchical blockchain system for carbon emission trading utilizing the blockchain of things and smart contracts. The aim is to overcome the challenges of transparency, accountability, and efficiency in carbon markets.

- **Automation**

Utilizing smart contracts enables the automation of carbon credit and emissions allowance transactions, simplifying the process of buying and selling. This can help reduce transaction costs and increase efficiency in the carbon market. The study in Hartmann and Thomas (2020) proposes a blockchain-based solution for the australian carbon market to overcome challenges such as double-counting and lack of trust among participants.

The author in Zhao et al. (2022) proposes a new market system for blue carbon trading using BT, but it should be noted that the study's focus is exclusively on blue carbon trading, which means its findings and conclusions may not be directly applicable to other carbon markets.

- **Standardization**

A standardized carbon market can be achieved with the aid of BT, which can establish a unified platform for registering and trading carbon credits and emissions allowances. This strategy has the potential to boost liquidity in the market and reduce the intricacy of trading (Al Kawasmi et al., 2015).

The work in Woo et al. (2020) presents a theoretical framework for enhancing the application of carbon credit acquisition in the building sector using BT, but its practical applications are yet to be demonstrated.

- **Verification**

BT can enhance the credibility of the carbon market by validating the emission reduction or removal claims of carbon projects. This approach has the potential to reduce the risk of greenwashing, thereby increasing transparency and accountability (Richardson and Xu, 2020).

The work in Al Sadawi et al. (2020) proposes a framework for unified carbon emission trading using a blockchain of things network to enhance transparency, interoperability, and accountability in carbon markets.

Through the integration of sustainable BT, carbon credits and emissions trading can be made more transparent, secure, and efficient. By utilizing BT to enhance traceability, automation, standardization, incentivization, and verification, it becomes feasible to establish a more sustainable and equitable carbon market that effectively tackles climate change (Khaqqi et al., 2018; Richardson and Xu, 2020).

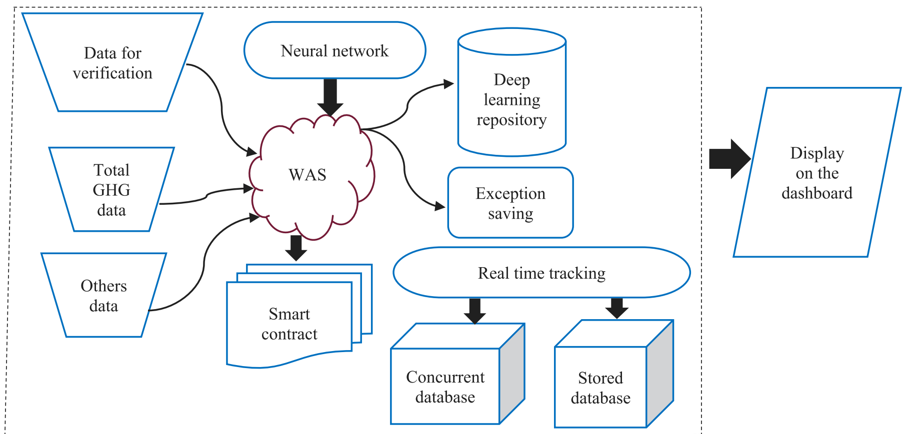

Fig. 11. The general framework of carbon trading.

Errors in Carbon Credits and Emissions Trading can stem from inaccurate data, market misinterpretations, regulatory complexities, verification lapses, and insufficient risk assessments. To enhance accuracy, better data collection, in-depth market analysis, compliance expertise, stringent verification processes, and comprehensive risk assessments are pivotal. These measures bolster reliability and effectiveness in emissions trading.

Inaccuracies in Carbon Credits and Emissions Trading erode trust in climate initiatives, leading to misinformed policies and stalling progress on climate targets.

The Core motifs and revelations identified in literature reviews on sustainable blockchain applications in carbon trading are presented succinctly in Table 12.

Main highlights

- The ownership and transfer of carbon credits and emissions allowances can be easily monitored and their legitimacy ensured through the use of BT, thereby preventing fraudulent activities.
- Smart contracts streamline the buying and selling of carbon credits, reducing transaction costs and improving efficiency in the carbon market.
- Blockchain can incentivize entities to reduce greenhouse gas emissions or invest in low-carbon projects by rewarding positive environmental actions.
- Verification of carbon reduction or removal claims of projects can be enhanced through BT, reducing the risk of greenwashing and increasing transparency and accountability.
- The adoption of sustainable practices can be encouraged through BT.
- **Blockchain can foster a more sustainable and fair carbon market.**

5.6. Climate risk management

A decentralized and transparent system for tracking and mitigating climate risks can be created using BT, to help manage climate risk. For instance, blockchain can be used to track climate-related risks, such as extreme weather events, rising sea levels, and food and water shortages, and facilitate the development of climate-resilient strategies (Chen, 2018b).

Within a sustainable blockchain framework, effective climate risk management as shown in Fig. 12 necessitates the establishment of well-defined and measurable key performance indicators that align with sustainability goals and climate risk management objectives.

These key performance indicators provide a quantifiable framework to assess the effectiveness of sustainability initiatives. Utilizing the blockchain infrastructure, data collection, integration, and standardization from various sources become more efficient, ensuring the accuracy and reliability of the information. Smart contracts play a crucial role in automating the tracking and recording of sustainability-related transactions and events.

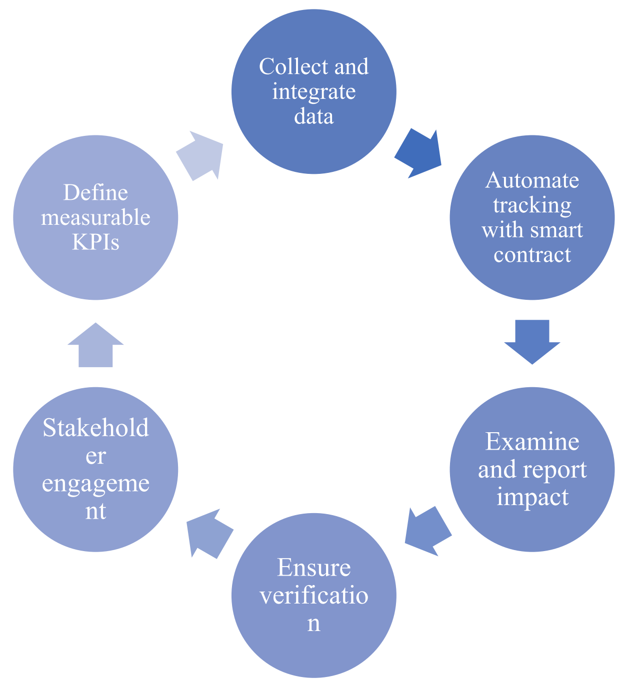

Fig. 12. Represents a generalized concept for impact monitoring.

This automation enables real-time data capture, minimizing manual errors and ensuring a comprehensive and auditable record of actions.

To evaluate the impact of sustainability initiatives, data analytics tools are employed to analyze the collected data and generate meaningful insights. Periodic reports and dashboards are then shared with stakeholders to foster an understanding of the impact and progress made.

To ensure the integrity of reported data and engender trust, verification mechanisms such as independent audits are implemented. Stakeholder engagement is also essential, involving them in the impact monitoring process to enhance transparency, accountability, and collective decision-making. By following these key points, organizations can effectively manage climate risks while promoting sustainability through BT (Baruah et al., 2019; Aiello et al., 2021).

Table 12
Taxonomy of carbon trading sustainable blockchain applications.

Ref.	Use-case	Blockchain platform	Main contribution	Limitation
Al Sadawi et al. (2021)	Carbon emission trading	N/A	The system aims to track and verify carbon emissions, facilitate carbon credit trading, and promote sustainability by reducing greenhouse gas emissions.	Scalability, IoT integration complexity, and regulatory compliance.
Woo et al. (2020)	Building sector	Suggest hyperledger fabric	To enhance the utilization of carbon credits in the building sector.	Further empirical research is necessary to evaluate the effectiveness and feasibility of the proposed framework.
Al Sadawi et al. (2020)	Carbon trading market	N/A	Contribute to carbon emission reduction by promoting sustainable development and offering a trustworthy platform for carbon trading.	The paper lacked discussion on the environmental impact of utilizing blockchain and IoT technologies in the carbon emission trading market.
Zhao et al. (2022)	Trading of blue carbon	Ethereum	To provide a practical solution for managing blue carbon credits, which are credits generated by preserving or restoring coastal and marine ecosystems.	The limitations associated with the implementation of the proposed system, such as scalability, regulatory environment, and market manipulation.
Hartmann and Thomas (2020)	Australian carbon market	Ethereum	To present a conceptual system for a BT-based carbon trading platform that can provide transparency, security, and efficiency in the carbon market.	Further research is needed to assess the efficacy of the proposed system in mitigating fraud and ensuring the accuracy of carbon credits.
Richardson and Xu (2020)	Emissions trading systems	N/A	The paper contributes by presenting a model for a permissioned blockchain implementation designed around the european union emissions trading system.	The paper does not provide specific technical details about the blockchain platform used in the proposed model, making it challenging to assess its feasibility and implementation.

- **Data Sharing**

Sustainable BT can enhance collaboration and information sharing among stakeholders by securely and transparently sharing climate risk data. By enabling access to accurate and real-time information, this initiative can facilitate informed decision-making, leading to more effective and efficient outcomes. The author in Howson (2020) raises important questions about the ethical implications of BT.

- **Risk Assessment**

Real-time risk assessments based on climate risk data can be performed using BT. This can aid in identifying potential risks and prioritizing actions to mitigate them Chen (2018b) and Chen (2018a).

The author in Dorfleitner et al. (2021) analyzes existing blockchain applications for climate protection globally, identifying their use cases and providing insights into their implementation. However, it does not propose new solutions and is limited in its sample of applications.

- **Impact Monitoring**

BT can be leveraged to continuously monitor and track the impact of climate risk management measures. This provides a reliable and transparent way to assess the effectiveness of these measures and refine future risk management strategies based on real-world data (Lee et al., 2021).

The study in Hull et al. (2021) examines the discourses surrounding the use of BT for climate governance in international climate politics, highlighting the promises and perils of "climate crypto-governance".

- **Climate Insurance**

Sustainable BT can enable the facilitation of climate insurance by establishing a secure and transparent platform for registering and managing insurance policies. This can increase accessibility to climate insurance and reduce the financial impact of climate risks, ultimately contributing to a more resilient and sustainable future (Pagano et al., 2019).

The author in Schulz and Feist (2021) presents an innovative framework that utilizes BT for climate finance within the green climate fund.

Applying sustainable BT to climate risk management can enhance the accuracy, transparency, and effectiveness of climate risk management strategies. By utilizing BT to gather and exchange climate risk data, conduct risk evaluations in real-time, monitor outcomes, and enable climate insurance, we can create a more robust and sustainable world (Lee et al., 2021; Chen, 2018a; Pagano et al., 2019).

In Climate Risk Management, errors may result from incomplete data, flawed models, underestimating scenarios, policy misinterpretations, and societal oversights. Improving involves enhancing data, refining models, considering diverse scenarios, understanding policies, and integrating societal perspectives for more accurate risk assessments.

However, inaccuracies disrupt policy effectiveness, potentially causing misdirected strategies and delayed responses to climate challenges. These errors hinder progress toward achieving climate change targets, impacting ecosystems, communities, and economies. Accurate risk assessments are imperative for informed decisions and proactive adaptation, ensuring a more resilient and sustainable future against climate-related risks.

Table 13 provide findings extracted from literature reviews on sustainable blockchain applications in climate risk management.

Main highlights

- BT can facilitate the accumulation and storage of climate risk data.
- It can enhance collaboration and information sharing among stakeholders by securely sharing climate risk data.
- Real-time risk assessments can be performed using BT.
- Sustainable BT can enhance the accuracy, transparency, and effectiveness of climate risk management strategies.
- BT can increase accessibility to climate insurance and reduce the financial impact of climate risks.
- This collaborative effort can establish a robust and transparent platform for registering and managing climate insurance policies, ensuring their security and transparency.

5.7. Cryptocurrency

Cryptocurrency serves as a application of sustainable BT by reimagining the traditional financial landscape with efficiency and environmental consciousness. Unlike conventional banking systems that rely heavily on energy-intensive processes, cryptocurrencies leverage blockchain's decentralized ledger to create a transparent, secure, and

Table 13
Taxonomy of climate risk management sustainable blockchain applications.

Ref.	Use-case	Blockchain platform	Main contribution	Limitation
Dorfleitner et al. (2021)	Climate protection	N/A	By fostering collaboration among diverse stakeholders, such as governments, non-governmental organization, and the private sector, to achieve effective implementation of BT in climate protection.	Fails to present specific use cases or case studies of blockchain-based systems for climate protection.
Schulz and Feist (2021)	Green climate fund	Ethereum	To enhance the efficiency and transparency of the green climate fund.	Lack explores the social and economic factors.
Hull et al. (2021)	International climate politics	N/A	The discourses around BT in international climate politics.	Lacks specific recommendations for addressing blockchain's limitations and risks in climate governance, and the case study has a narrow focus.
Howson (2020)	Crypto-colonialism	N/A	Warns of the risk of crypto-colonialism and negative impacts of BT on vulnerable communities in the global south affected by climate change.	Lacks substantiating empirical evidence to support its claims.
Baruah et al. (2019)	IoT revolution	N/A	The paper analyzes IoT impact, domains, revolutionizing industries, and improving efficiency.	The paper neglects to address the constraints or drawbacks associated with the implementation of IoT.

tamper-resistant platform for P2P transactions. This reduction in intermediaries not only lowers transaction costs but also minimizes the carbon footprint associated with maintaining large data centers. By fostering financial inclusion and reducing reliance on energy-intensive infrastructure, cryptocurrencies demonstrate how BT can align with sustainability goals while revolutionizing the world of finance (Hamilton, 2023).

- **Carbon Offsetting**

Some cryptocurrency projects like Nori, Climatecoin, and many more allow users to purchase carbon offsets or contribute to sustainable initiatives using digital currencies. This can help individuals and organizations offset their carbon footprint more easily and transparently (Chen, 2018b).

- **Reforestation Initiatives**

Cryptocurrencies can support reforestation efforts by enabling individuals to sponsor the planting of trees or participate in initiatives that use blockchain to track tree growth and carbon sequestration (Smajgl and Schweik, 2022).

- **Conservation Funding**

Cryptocurrencies can be used to raise funds for conservation efforts and environmental protection projects through token-based fundraising campaigns and donations. Leading organizations like the wildlife conservation society, and world wildlife fund (Nicholls, 2011) have embraced this technology.

- **Investment in Green Transportation**

Cryptocurrencies can also be used for fundraising and investment in green transportation projects. Initial coin offerings or initial public offerings (Prosmitrellis, 2019; Essaghoolian, 2019) could be used to raise funds for developing eco-friendly transportation infrastructure.

Cryptocurrency risks include security vulnerabilities, regulatory uncertainties, market volatility, transparency issues, and technology limitations. Enhancements require bolstering security measures, navigating regulations, managing market volatility, promoting transparency, and advancing BT for scalability and reliability.

Cryptocurrency inaccuracies undermine trust, regulatory clarity, and broader adoption. They hinder the envisioned potential of cryptocurrencies and BT across industries. It is imperative to rectify these flaws to rebuild trust, refine regulations, and expand the scope of blockchain.

Table 14 summarizes the findings of literature reviews that explored sustainable blockchain applications in the field of cryptocurrency.

Main highlights

- Cryptocurrency reimagines finance with a focus on efficiency and environmental consciousness.
- Cryptos enable financial inclusion.
- They aid reforestation and offer blockchain tracking of tree growth.
- Cryptos raise funds for conservation and environmental protection.
- They can be used for eco-friendly transportation project investment.

6. Challenges and solutions

The sustainable blockchain challenge pertains to the hurdles that require resolution to ensure that the utilization of BT is sustainable in environmental, social, and economic aspects (Li et al., 2018).

Table 15 Represents the various associated challenges and solutions of sustainable blockchain.

To ensure that BT is environmentally, socially, and economically sustainable, it is necessary to overcome the challenges presented by the sustainable blockchain challenge.

Enabling transparent and secure transactions, reducing fraud, and improving efficiency, BT holds promise for supporting sustainable development. Nevertheless, to ensure its sustainable usage, addressing various challenges is necessary.

The details of these challenges are:

6.1. Energy consumption

Fig. 13 illustrates the considerable energy consumption attributed to mining cryptocurrencies such as bitcoin, which stands as one of the foremost challenges confronting sustainable blockchain initiatives.

Fig. 14 showcases how the energy consumption involved in blockchain operations contributes to carbon emissions, thereby compromising the sustainability benefits associated with the technology.

Reducing the energy consumption of blockchain networks poses a significant challenge, but one promising solution involves leveraging renewable energy sources to power these networks (Yildizbasi, 2021).

Achieving sustainability in blockchain networks is crucial due to the substantial energy consumption associated with the mining process.

Table 14
Taxonomy of cryptocurrency sustainable blockchain applications.

Ref.	Use case	Blockchain platform	Main contribution	Limitation
Hamilton (2023)	Financial inclusion, Digital payments	N/A	The paper highlights the invention of BT for bitcoin, emphasizing its role as a digital, decentralized ledger for recording P2P transactions.	It does not discuss potential drawbacks or challenges related to cryptocurrency adoption, which could provide a more balanced perspective.
Chen (2018b)	Climate crisis mitigation	N/A	It points out that blockchain has the potential to enhance accountability in carbon markets and promote the development of renewable energy micro-grids.	The drawbacks and challenges of incorporating blockchain solutions in carbon and energy markets are not effectively addressed.
Smajgl and Schweik (2022)	Groundwater management	N/A	It introduces the idea that blockchain or Distributed Ledger technology could complement institutional designs by offering new ways to incentivize and monitor behavior, potentially improving resource management.	The feasibility and scalability of using blockchain for global resource management are not discussed.
Prosmitrellis (2019)	Energy trading	N/A	It recognizes the digitalization of the energy market as a crucial aspect of sustainability and addresses how technology can contribute to energy generation, transmission, and trading.	It outlines the benefits of BT, cryptocurrencies, and AI in the energy sector, it does not explore drawbacks, risks, or obstacles associated with their adoption.
Essaghoolian (2019)	Initial coin offerings for cryptocurrencies	N/A	Raises awareness about the popularity of cryptocurrencies and the significant capital flowing into initial Coin Offerings.	It highlights the inconsistent regulation of initial coin offerings by different U.S. government agencies but does not delve into the complexities and challenges of regulating cryptocurrencies effectively.

Table 15
Challenges and solutions of sustainable blockchain network.

Ref.	Challenges	Solutions
Vranken (2017), Yildizbasi (2021) and Huh and Kim (2019)	Energy consumption	Use renewable resources
Chaudhary et al. (2021) and Salmon et al. (2021)	E-waste	Reuse, Repair, Recycle
McCorry et al. (2021), Hashim et al. (2021) and Gangwal et al. (2023)	Scalability	Sharding, Layer-2 solution, Off-chain
Rikken et al. (2019) and Goldsby and Hanisch (2022)	Governance	Decentralized structure
Yeoh (2017) and Cermeño (2016)	Regulation	Promote regulations
Woodside et al. (2017), Kouhizadeh et al. (2021) and Jani (2019)	Adoption	Promote education and awareness
Xihua and Goyal (2022) and Mezquita et al. (2022)	Privacy	Zero-knowledge proof, Ring signatures, Homomorphic encryption
Mohanty et al. (2022) and Qin and Gervais (2018)	Interoperability	Cross- chain solution

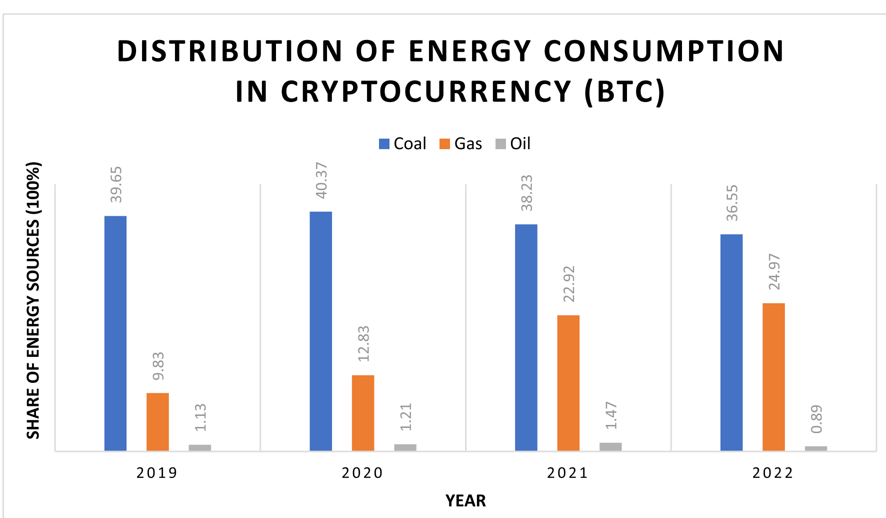

Fig. 13. Traditional energy consumption in the mining process.

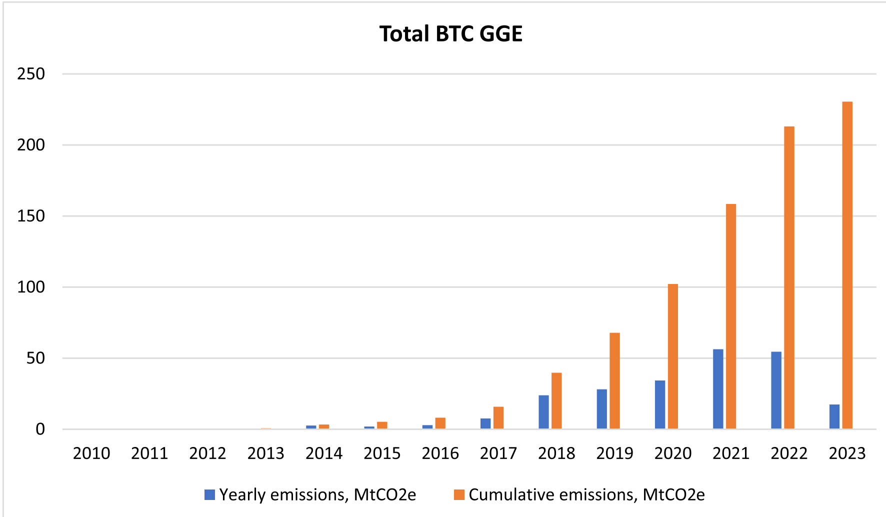

Fig. 14. Greenhouse gas emission in the mining process.

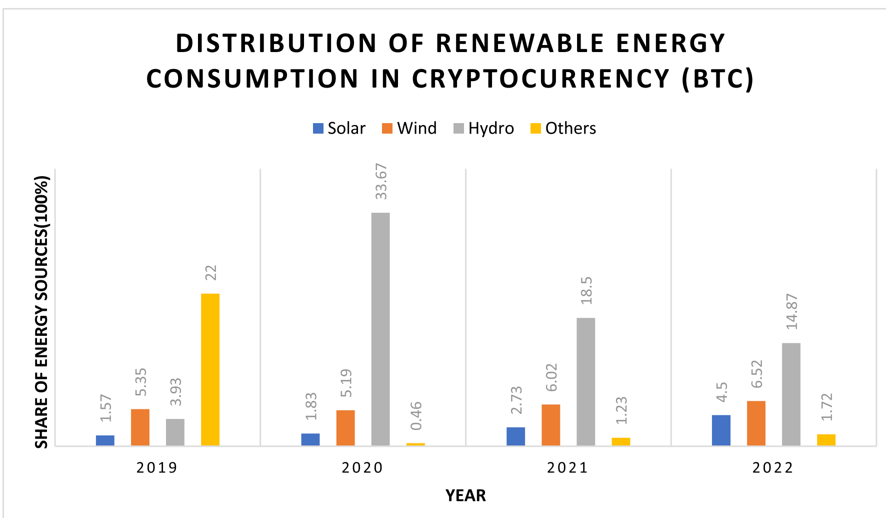

Fig. 15. Renewable energy consumption in the mining process.

This energy-intensive task of verifying transactions demands significant computational power, leading to a substantial electricity requirement. However, this high energy consumption not only contributes to carbon emissions but also undermines the overall sustainability advantages of BT.

Various strategies have been suggested as solutions to mitigate the high energy consumption of blockchain networks. Fig. 15 demonstrates that one of the suggested strategies to mitigate the high energy consumption of blockchain networks is the adoption of renewable energy sources. This can reduce the carbon footprint of blockchain and align it with sustainability goals. Some blockchain networks are already experimenting with renewable energy sources for mining, like the Solar-Coin project, which rewards miners for using solar energy (Schmidt, 0000). Another approach is to improve the efficiency of mining hardware and procedures. To exemplify, some blockchain networks have adopted consensus mechanisms that require less computational power than traditional PoW algorithms (Miraz et al., 2021).

Other networks are exploring the use of energy-efficient mining hardware, such as application-specific integrated circuits, which consume less electricity than traditional graphics processing units (Taylor, 2017). Finally, to mitigate energy consumption, certain blockchain networks are actively exploring the implementation of off-chain solutions like sidechains or inter-chains. These solutions aim to decrease the volume of on-chain transactions, thereby reducing the overall energy consumption of the network (Kim et al., 2018).

6.2. E-waste

E-waste poses a significant challenge in sustainable blockchain practices, primarily due to the constant need for upgrading mining hardware to support cryptocurrency mining. This frequent hardware upgrade results in a substantial generation of E-waste (De Vries and Stoll, 2021).

It is harmful to the environment, as it can release toxic substances and contribute to pollution. Blockchain networks rely on specialized hardware that needs to be frequently upgraded. This can lead to a significant amount of e-waste and harm the environment if not properly disposed of. The rapid turnover of hardware in the blockchain industry can lead to a significant amount of e-waste.

This can be mitigated by using renewable energy sources for mining and ensuring that devices are recycled properly (Gundaboina et al., 2022). Several strategies are being explored by sustainable blockchain initiatives to tackle the issue, of reducing e-waste.

One strategy is to mitigate this concern, an effective strategy is to focus on designing hardware that is characterized by enhanced durability and a longer lifespan. This approach aims to minimize the frequency of upgrades required, thereby reducing E-waste generation within the context of sustainable blockchain practices.

Another strategy is to recycle and refurbish hardware whenever possible, rather than dispose of it. Another viable approach involves exploring alternative consensus mechanisms that necessitate reduced computational power, consequently reducing the reliance on specialized hardware (Miraz et al., 2021). For example, PoS consensus mechanisms rely on users holding and staking their cryptocurrency holdings, rather than on expensive mining hardware. This reduces the need for specialized mining hardware and, therefore, the amount of e-waste generated by the blockchain network (Chaudhary et al., 2021; Salmon et al., 2021).

6.3. Scalability

BT is currently in its nascent stages, and several networks are still striving to achieve the necessary scalability levels for broader adoption. This can limit the potential impact of blockchain on sustainability. The existing blockchain systems face limitations in scalability, as they are unable to handle the substantial volume of transactions necessary for achieving widespread adoption (Wang et al., 2019), as the verification process for transactions can become slow and resource-intensive as the network grows with more users and transactions. To address this concern, various strategies have been suggested to enhance the scalability of blockchain networks.

One such approach is the utilization of off-chain solutions like payment channels or sidechains, which aim to decrease the volume of on-chain transactions (Yang et al., 2020). Off-chain solutions allow for faster and more efficient transactions by processing them outside of the main blockchain network, while still ensuring the security and immutability of the blockchain (McCorry et al., 2021).

Another technique proposed to enhance the scalability of blockchain networks is sharding. This method involves partitioning the blockchain network into smaller interconnected shards, each capable of processing transactions independently (Chauhan et al., 2018).

This can significantly increase the number of transactions that can be processed by the blockchain network, while still maintaining the security and immutability of the blockchain (Hashim et al., 2021; Gangwal et al., 2023). Finally, some BT networks are analyzing the use of layer-two solutions, such as Lightning Network or Plasma, to improve the scalability of blockchain networks.

Layer-two solutions allow for faster and more efficient transactions by processing them outside of the main blockchain network, while still ensuring the security and immutability of the blockchain (Gangwal et al., 2023).

6.4. Governance

Governance is a crucial element of sustainable blockchain, as it helps to ensure that the blockchain network operates in a transparent, accountable, and responsible manner (Laatikainen et al., 2023).

Governance in sustainable blockchain involves establishing mechanisms for decision-making, enforcing rules and standards, and ensuring that the interests of all stakeholders are represented (Laatikainen et al., 2023).

To tackle governance challenges, various approaches have been suggested, One approach is to establish formal standards that govern energy consumption, data privacy, and environmental impact. These standards can be enforced through audits and certifications, ensuring that blockchain networks comply with established norms.

Another approach is self-regulation, where blockchain networks voluntarily adopt a set of rules and standards to ensure responsible and sustainable operations without external regulation or oversight.

Participatory governance is also essential, involving stakeholder engagement and public consultations to ensure democratic decision-making and transparency (Beck et al., 2018). This approach ensures that the interests of all stakeholders are represented in the decision-making process (Rikken et al., 2019; Goldsby and Hanisch, 2022).

6.5. Regulation

Regulation is crucial in promoting sustainable blockchain, but due to its newness, there is a lack of established regulatory frameworks. To overcome this challenge, strategies such as regulatory sandboxes, collaborative regulation, self-regulation, adapting existing frameworks, and global coordination can be pursued to promote innovation while mitigating risks and ensuring compliance with sustainability goals (Yeoh, 2017; Cermeño, 2016).

6.6. Adoption

Adoption is a critical challenge in sustainable blockchain due to its newness and lack of understanding, trust, and regulatory frameworks. Strategies such as education and awareness, industry standards and best practices, user-friendly interfaces, and pilot projects can help overcome this challenge by promoting understanding and trust, creating a predictable regulatory environment, reducing technical complexity, and showcasing the technology's potential benefits (Woodside et al., 2017; Kouhizadeh et al., 2021; Jani, 2019).

6.7. Privacy

Ensuring privacy in the blockchain is a major challenge for its sustainable development, as the technology is designed to be transparent and immutable. One solution is to use privacy-enhancing technologies like zero knowledge proof, ring signatures, and homomorphic encryption to protect sensitive information while maintaining the integrity of the BT (Feng et al., 2019).

An alternative approach would be to integrate privacy policies and regulations that offer instructions regarding the gathering, utilization, and disclosure of personal data within blockchain networks. Nevertheless, there exist obstacles in adopting and implementing these measures, such as the requirement for standardization and interoperability of privacy-enhancing technologies, as well as the delicate balance between privacy and the principles of transparency and accountability. Additionally, there is a need for education and awareness-raising initiatives to inform stakeholders about the importance of privacy in sustainable blockchain and the available solutions (Xihua and Goyal, 2022; Mezquita et al., 2022).

6.8. Interoperability

Interoperability refers to the seamless exchange and sharing of information among distinct blockchain networks, eliminating the necessity for intermediaries. However, challenges such as technical differences, security risks, and governance models can hinder interoperability in sustainable blockchain. Proposed solutions to these challenges include standardization through common protocols, bridging mechanisms using intermediary networks, and governance frameworks facilitating coordination between networks (Mohanty et al., 2022; Qin and Gervais, 2018).

7. Future directions and opportunities

The future of sustainable blockchain applications is highly promising and holds immense potential for addressing some of the most pressing sustainability challenges. In this section, we will discuss some of the future directions and opportunities for sustainable blockchain. In light of the insights presented in Fig. 16, it becomes apparent that the future holds numerous possibilities and prospects for the advancement of sustainable blockchain.

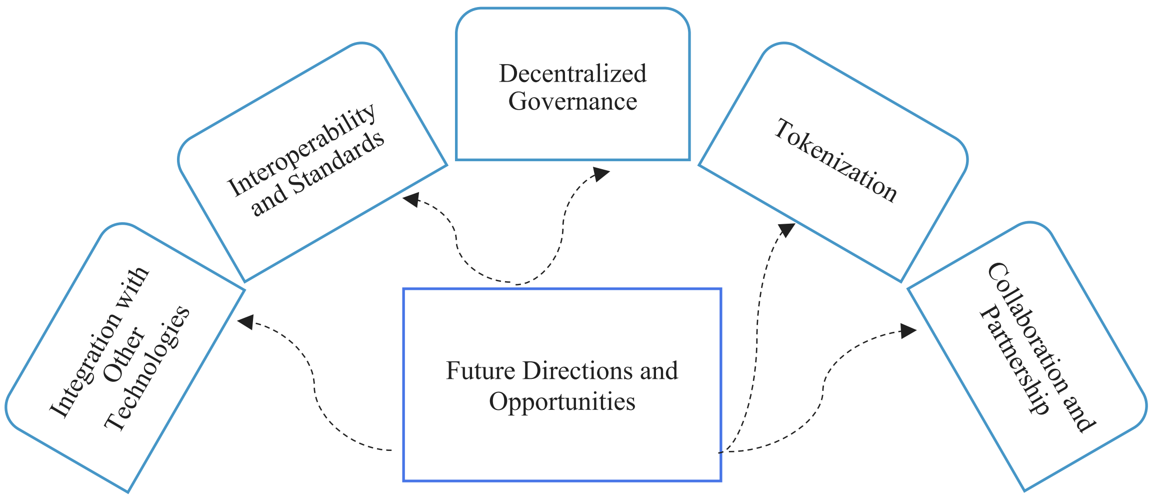

Fig. 16. Future directions and opportunities for sustainable blockchain.

7.1. Integration with other technologies

Integration with other technologies is a crucial future direction for sustainable BT applications. By combining BT with other emerging technologies, we can develop more sophisticated and efficient systems for managing and monitoring sustainability-related data. IoT is one of the key technologies that can be seamlessly integrated with blockchain.

IoT devices can collect vast amounts of data on energy consumption, carbon emissions, and other sustainability-related metrics. By integrating BT with IoT, we can develop more secure and transparent systems for managing and analyzing this data (Alamri et al., 2019).

A system built on BT can facilitate secure and transparent sharing of data among IoT devices and networks, enabling more efficient and accurate monitoring of sustainability-related metrics. By integrating BT with AI (Gulati et al., 2020), organizations can leverage AI capabilities to analyze and derive insights from extensive datasets, including those on sustainability.

This integration enables the efficient processing and comprehension of sustainability-related data. By combining BT with AI, we can develop more sophisticated and accurate systems for analyzing sustainability-related data, enabling better decision-making and management of sustainability initiatives.

Big data analytics is another technology that can be integrated with blockchain. The integration of BT ensures a secure and transparent environment for sharing data, among different stakeholders, enabling more efficient and accurate analysis of sustainability-related data.

A system based on blockchain technology has the potential to facilitate secure and transparent data sharing among stakeholders in the SCM to securely and transparently share data on the environmental impact of their operations, enabling a more accurate analysis of the overall sustainability of the SCM. In conclusion, integrating BT with other evolving technologies like that IoT (Atlam et al., 2020), AI, and big data analytics (Deepa et al., 2022) can enable more sophisticated and efficient systems for managing and monitoring sustainability-related data . This integration can enable better decision-making and management of sustainability initiatives, leading to more effective and impactful solutions (Sharma et al., 2021; Badidi, 2022).

7.2. Decentralized governance

Decentralized governance is another important future direction for sustainable blockchain applications. It is the adoption of BT to create more democratic and decentralized decision-making processes for sustainability related initiatives. The ability of BT to create decentralized and transparent systems is one of its key advantages. This can be especially valuable within the realm of sustainability-related initiatives, where there is often a need for more democratic and transparent decision-making processes. By using BT, we can develop more decentralized systems for managing and governing sustainability-related initiatives. An instance of decentralized governance in the sustainability context is the implementation of voting systems based on BT (Rani et al., 2022). Blockchain-based voting systems can enable more secure and transparent voting processes, leading to more democratic decision-making in sustainability-related initiatives. For instance, a voting system built on BT can empower stakeholders involved in a sustainability initiative to participate in decision-making processes, such as voting on resource allocation or the creation of new sustainability projects. Another example of decentralized governance can also be exemplified through the utilization of smart contracts built on BT (Balcerzak et al., 2022). These self-executing contracts are stored on the blockchain and offer a means to establish decentralized frameworks for governing and managing sustainability-driven projects. Smart contracts have the capability to automate the distribution of resources within such initiatives, guaranteeing transparent and democratic resource allocation. By leveraging smart contracts, sustainability-related initiatives can achieve greater efficiency, fairness, and accountability in their governance structures. In conclusion, decentralized governance is an important future direction for sustainable blockchain applications. By using BT to create more democratic and decentralized decision-making processes for sustainability-related initiatives, we can enable more effective and impactful solutions (Balcerzak et al., 2022; Oliveira et al., 2020).

7.3. Tokenization

Another potential future direction of tokenization is in the creation of loyalty programs and incentives for sustainability-related behaviors. For example, a sustainability-focused retailer could create a loyalty program where customers earn tokens for making sustainable purchases or participating in sustainability-related activities. These tokens could be redeemed for rewards or used to support sustainability related projects (Vadakkepatt et al., 2021). By representing real-world assets as digital tokens on a blockchain network, we can create more efficient, transparent, and decentralized systems for managing resources and assets, as well as new financing mechanisms and incentives for sustainability-related behaviors (Beshkardana, 2022).

7.4. Collaboration and partnership

Collaboration and partnership are important factors for the success of sustainable blockchain applications. Collaboration among stakeholders can help to ensure that sustainable blockchain initiatives are well-designed, well-implemented, and well-supported. One promising area for collaboration is the development of blockchain-based standards and frameworks for sustainability efforts. This fosters interoperability, scalability, and effectiveness. It also ensures inclusivity and responsiveness to diverse stakeholder needs. Collaborative partnerships are crucial in sustainable blockchain applications, such as in SCM (Rejeb et al., 2021), cryptocurrency (Ertz and Boily, 2019), and renewable energy sectors. By teaming up with organizations and experts in these areas, initiatives can access complementary resources and expertise. For example, a blockchain project tracking carbon emissions could partner with carbon offset providers, data analytics firms, and sustainability-focused investors to ensure robust funding, informed decisions, and successful implementation (Wang et al., 2020).

7.5. Interoperability and standards

Interoperability and standards are important considerations for sustainable blockchain applications. Interoperability refers to the capability of various blockchain networks to communicate, exchange information, and collaborate, while standards refer to the technical specifications and protocols that ensure consistency and compatibility between different blockchain networks (Lohachab et al., 2021). Interoperability and standards are important because they can help to facilitate the adoption and scaling of sustainable blockchain applications. Through the establishment of interoperability protocols, diverse blockchain networks can now communicate and interact with each other, interoperability can help to create more integrated and seamless solutions for sustainability-related challenges. For example, a sustainable blockchain application focused on tracking and managing SCM could benefit from interoperability with other blockchain networks focused on related areas such as logistics and finance (Al-Rakhami and Al-Mashari, 2022). Standards are also important because they can help to ensure consistency and compatibility between different blockchain networks. Establishing common technical specifications and protocols, standards can help to ensure that different blockchain networks can work together seamlessly and efficiently. This can assist in mitigating the expenses and hazards linked with implementing and maintaining sustainable blockchain applications. One example of a standard that is important for sustainable blockchain applications is the International Organization for Standardization 14 001 standard for environmental management (Bugdol et al., 2021). This standard offers a structured approach for organizations to effectively handle their environmental obligations in a systematic and integrated way. By incorporating this standard into sustainable blockchain applications focused on environmental management, we can ensure that these applications are consistent with established best practices and can help to achieve meaningful environmental outcomes. In the future, we can expect to see more efforts toward developing interoperability standards and protocols that enable different blockchain networks to communicate and share data seamlessly.

8. Discussion

Sustainable BT offers extensive and diverse applications, attracting considerable attention for its potential across various industries. It revolutionizes sectors by promoting transparent supply chains, eco-conscious practices, and streamlined energy systems. it supports governments, encourages socially responsible investments, drives cost reductions, and empowers global sustainability efforts aimed at combating climate change.

In this discussion, the limitations of the PRISMA approach, impacts the study by recognizing potential exclusions of relevant studies due to strict criteria, the focus will be on exploring some of the key findings and implications of a study on the applications of sustainable BT. Firstly, it is worth noting that the study found that sustainability is a key driver of interest in BT, with many respondents citing its potential to reduce energy consumption, lower transaction costs, and enhance transparency and accountability in SCM.

This aligns with broader trends toward sustainable development and corporate social responsibility, as companies seek to mitigate their environmental impact and enhance their reputational standing.

In terms of specific applications, the study found that SCM is one of the most promising areas for sustainable BT. Through the establishment of a transparent and secure ledger of transactions and product movements, BT can help to ensure that goods are ethically sourced, reduce waste and fraud, and enhance traceability and accountability across the SCM.

This can be particularly valuable for industries such as food and fashion, where there is growing consumer demand for sustainable and ethical products. Another key area of interest is in the energy sector, where blockchain can potentially enable the creation of decentralized energy systems and facilitate P2P energy trading.

This holds the potential to enhance energy security, reduce carbon emissions, and enable greater participation in the energy system by individuals and communities. Finally, the study found that there is a notable level of interest in employing BT for social impact initiatives, such as improving financial inclusion and reducing corruption in developing countries.

By establishing a system that ensures the safety and openness of transaction records, BT can potentially help to reduce fraud and improve accountability in areas such as water management, waste management and government procurement.

By incorporating a reflection on the researchers' diverse perspectives and expertise, the study gains depth and clarity. The researchers' backgrounds, whether in technological innovation, sustainability studies, or industry practices, shape the study's focus on particular applications of BT. For instance, if the team comprises experts in SCM or energy systems, it could explain the emphasis on these sectors within the study.

Similarly, experiences in social impact initiatives or regulatory compliance could influence the exploration of BT potential in such domains. Acknowledging these influences illuminates the study's direction, revealing potential biases or lenses that might have shaped its findings. This reflexivity fosters transparency, guiding readers to comprehend how the researchers diverse backgrounds might have influenced the selection of applications, the interpretation of data, and the study's overall focus.

Consequently, it empowers readers to critically evaluate the study's context and the implications drawn from the research, ensuring a more nuanced understanding of the field's potentials and limitations.

Overall, the study highlights the increasing interest in sustainable BT and its ability to generate favorable social and environmental outcomes across a range of industries.

However, it is important to note that there are still challenges to be addressed in terms of scalability, interoperability, and regulatory frameworks, and further research and development will be necessary to fully realize the potential of this emerging technology.

9. Conclusion

This study focuses on the applications of sustainable BT, emphasizing their diverse and promising roles in promoting sustainability and addressing global challenges. The transformative potential of sustainable BT is evident across various sectors, revolutionizing processes, and advancing sustainability.

Its impact spans SCM, engineering, energy systems, governance, finance and more, fostering transparency, eco-friendly practices, and adherence to sustainability standards. In engineering, it revolutionizes processes by establishing transparent SCM, optimizing manufacturing for eco-friendly outcomes, and simplifying adherence to sustainability standards through immutable ledgers. Energy systems benefit from its decentralized nature, enabling peer-to-peer trading, boosting renewable integration, and automating transactions, reducing reliance on fossil fuels. Governments harness its potential to enforce transparent and sustainable policies in crucial sectors like supply chains and energy, aligning with conservation goals. Financially, it transforms investment transparency, fostering ESG inclusivity and appealing socially responsible stakeholders. Although initial implementation costs exist, offset by long-term savings from optimized processes. Pertaining to climate change, sustainable blockchain promotes renewables and transparent sustainability, mitigating climate effects and facilitating better carbon footprint management through its transparency. This innovation not only redefines industry practices and elevates environmental trust but also empowers nations to bolster environmental efforts and accountability, encouraging ongoing research, integration into regulatory frameworks, and diverse applications to meet global sustainability targets and policy objectives.

These applications demonstrate the versatility and scalability of sustainable blockchain networks, as they can be adapted to different contexts and use cases, while also addressing sustainability challenges. However, sustainable blockchain networks still face several challenges, including governance, regulation, adoption, and interoperability.

These challenges require coordinated efforts from industry stakeholders, policymakers, and regulators to establish common standards, best practices, and regulatory frameworks that can promote sustainable blockchain development and adoption.

Indeed, these case studies exhibit the diverse applications of blockchain technology in fostering sustainability. Verra's REDD+ program incentivizes forest conservation via carbon credits. IBM Food Trust's blockchain-enhanced SCM, seen in collaborations like Walmart, bolsters transparency, food safety, and waste reduction. The Wildlife Conservation Society employs blockchain to combat illegal wildlife trade, ensuring authenticity in conservation efforts. In conclusion, while the PRISMA approach is beneficial for systematic reviews, its strict criteria may limit the inclusion of relevant studies. Acknowledging these limitations is crucial. Future research could explore refined strategies to improve comprehensiveness, fostering more nuanced investigations. Awareness of PRISMA constraints enables researchers to adapt methodologies for more robust studies.

Looking ahead, future endeavors should focus on advancing this innovation. These efforts involve refining blockchain's applicability, scalability, and interoperability across industries to optimize its potential in revolutionizing supply chains, energy distribution, financial sectors, and more. Prioritizing data privacy, and fostering cross-industry collaboration while following international standards for sustainability will strengthen blockchain's impact for a more sustainable future.

CRediT authorship contribution statement

Pritam Rani: Writing – review & editing, Writing – original draft, Conceptualization. **Pratima Sharma:** Writing – review & editing, Supervision. **Indrajeet Gupta:** Supervision.

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.

Data availability

No data was used for the research described in the article.

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