Research Article

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Blockchain Technology as a Catalyst for Sustainable Development: Exploring Economic, Social, and Environmental Synergies

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Abstract

This paper explores the transformative potential of blockchain technology (BT) as a catalyst for sustainable development, addressing the tri-fold aspects of environmental, economic, and social sustainability. Through a comprehensive review and theoretical framework, it delves into how BT can significantly contribute to achieving the United Nations Sustainable Development Goals (SDGs). The study highlights BT's role in enhancing transparency, ensuring product traceability, and promoting resource efficiency, thereby facilitating a more equitable economic growth and environmental stewardship. By examining various applications of BT across industries including supply chain management, renewable energy, and conservation efforts, the paper illustrates BT's capability to reduce carbon emissions, improve resource allocation, and support sustainable business practices. Furthermore, it identifies challenges such as scalability, energy consumption, and regulatory hurdles, proposing strategic recommendations for overcoming these obstacles. The research emphasizes the need for collaborative efforts among stakeholders, including policymakers, practitioners, and researchers, to leverage BT effectively for sustainable development. It contributes to both theoretical understanding and practical implementation of blockchain as a powerful enabler for sustainability, offering insights for future research and policy-making in this evolving domain.

Keywords: *Blockchain technology (BT), Environmental, Economic, Social, Sustainability*

1. Introduction

Sustainable development, a pressing global challenge, has gained significant attention from researchers and policymakers (Liu et al., 2011). In the business context, sustainability is increasingly crucial for survival due to rising regulatory pressures and evolving production practices (Hahn and Figge, 2018). Sustainability, as defined by Clark (2007), involves responsible behavior towards the environment, society, and future generations. Corporate sustainability is viewed as meeting the needs of various stakeholders, shareholders, employees, customers, regulatory bodies, and society at large,

without compromising the ability of future stakeholders to meet their own needs (Mani et al., 2016). Sustainable development efforts currently focus on balancing environmental, social, and economic objectives to meet present needs without compromising future generations. Key goals include tackling climate change, promoting clean energy, ensuring economic growth, and fostering social inclusion. However, challenges remain significant.

Environmentally, the world faces urgent issues like climate change, loss of biodiversity, and pollution (Luna et al., 2024; Dehshiri and Amiri, 2024; Arshad et al., 2023). Efforts to reduce carbon emissions and increase renewable energy adoption are progressing, but not at the pace required to meet international climate goals. Economically, sustainable development aims to reduce poverty and inequality. While there has been progress, global economic disparities persist, exacerbated by factors like insufficient infrastructure in developing countries and the economic impacts of the COVID-19 pandemic. Socially, challenges include ensuring equal access to quality education, healthcare, and employment opportunities. There's also a need to strengthen social safety nets and promote gender equality.

The modern world's need for sustainability is a complex subject that necessitates a thorough, critical examination. It includes comprehending how problems like pollution, resource depletion, and climate change are interrelated. This entails realizing how individuals' actions affect the environment and how crucial it is to lessen this harmful influence (Yang et al, 2023).

Economic aspects to consider sustainability can result in long-term economic gains, despite the misconception that it impedes economic growth. This includes the emergence of new markets and employment prospects, especially in renewable energy. Furthermore, social aspects of sustainability must be considered including fair labor practices, equitable resource access, and considering future generations' needs. Analyzing the impact of our actions and activities on the community and wider, throughout the world, now and in the future is crucial (Shayan et al., 2022). Reaching sustainability necessitates a substantial shift in both personal conduct and societal expectations. This is a difficult task that requires knowledge of and control of the sociological and psychological elements that shape human behavior.

In addition, technological innovation has a dual function: it both causes sustainability (environmental) issues and provides answers to them. To comprehend the possibilities and constraints of these technical solutions, critical analysis is required (Sarfraz et al., 2023; Dehshiri and Amiri, 2024).

In an era where sustainability is not merely an option but a necessity, BT emerges as a pivotal tool in harmonizing the trinity of social, economic, and environmental dimensions of sustainability (Carter and Easton, 2011).

At the juncture of the Fourth Industrial Revolution, blockchain stands out as a transformative force, capable of fostering a synergy between technological advancement and sustainable development. Blockchain is a decentralized ledger that offers an immutable, secure, and distributed database that can facilitate the verifiable exchange of information and assets, reducing the dependency on intermediaries and enhancing peer-to-peer transactions (Yli-Huumo et al., 2016; Galen et al., 2018) and significantly boost the efficacy of sustainable development endeavors by promoting transparency and trust (Horner and Ryan, 2019).

This article seeks to inform and guide stakeholders, from policymakers to practitioners, on the effective deployment of blockchain solutions for economic, social, and environmental sustainability. The article's theoretical contributions lie in the creation of a conceptual framework to elucidate the intricate relationship between blockchain and sustainability dimensions. Practically, it aims to unearth best practices, discern obstacles to implementation, and recommend pathways to leverage blockchain for a more sustainable future.

The upcoming sections will delve into the theoretical underpinnings of blockchain in sustainability, outline the challenges and limitations of incorporating blockchain for sustainable solutions, present a comprehensive framework that explicates the relationship between blockchain and environment, economic, and social sustainability, and offer conclusions with strategic

recommendations for future research and policymaking.

2. Sustainability Definition

Scholars have put forth numerous definitions of sustainability encompassing various aspects. Prior to 1990, literature focused on three dimensions of sustainability and sustainable development: social justice, environmental preservation, and economic prosperity (Purvis et al., 2019). Thus, sustainability can be conceptualized as a triple bottom line comprising social responsibility, environmental stewardship, and economic viability (Kapfere and Denizeau, 2017).

Subsequently, Gladwin et al. (1995), through content analysis of multiple definitions, identified additional critical elements of sustainable development, such as inclusiveness, prudence, connectivity, security, and equity. The most widely accepted definition of sustainability in scholarly works is "meeting the needs of the present without compromising the ability of future generations to meet their own needs" (Brundtland Report, 1987, p. 8).

Sustainability in the modern world is a complex issue, requiring a deep understanding of the links between environmental concerns like pollution, resource depletion, and climate change, and the importance of mitigating our environmental impact.

Economically, it offers long-term benefits and opportunities, particularly in renewable energy, challenging the notion that it hinders growth. Socially, it involves ensuring equitable resource distribution, fair labor, and considering future generations, requiring a global perspective on the impact of our actions. Technologically, it poses both challenges and solutions, necessitating critical analysis of innovation's potential and limitations (Sarfraz et al., 2023).

In essence, sustainability is about harmonizing environmental, economic, and social interests to ensure the well-being of current and future generations, facilitated by technological innovation, cultural shifts, effective policy, and a balanced global-local approach (Hariram, 2023).

2.1 Fundamentals of blockchain: a comprehensive analysis of its functionality and benefits to sustainability

The term "blockchain" initially surfaced on the internet in 2008 and has exerted a substantial impact on public institutions, private enterprises, and emerging businesses. The BT is primarily employed as an innovative approach for facilitating transactions between two entities. It functions as a decentralized and secure ledger, enabling direct trades between two anonymous individuals without the requirement of a trusted intermediary. This technology introduces a new operating framework for enterprises and institutions. According to Palacio (2018), it can serve as a viable tool for tackling worldwide difficulties and facilitating the realization of the United Nations' sustainable development goals (SDGs) across all countries.

2.1.1 The salient sustainable characteristics of BT

Several salient facets of BT provide advantages in terms of the advancement of sustainability.

- Transparency: The concept of transparency refers to the quality or state of being open, honest, and accountable. The ledger system of the blockchain provides a transparent account of transactions. The utilization of this function is of utmost importance in the surveillance of sustainable sourcing practices of products, ensuring compliance with environmental rules, and mitigating the likelihood of unethical operations within the supply chain.
- Authenticity: The ability to track the trajectory of a product from its initial source contributes to the verification of sustainable practices' authenticity. This holds particular importance in industries such as agriculture, where it is important to closely observe the movement of products from the manufacturer to the end consumer (Prashar, et al., 2020;

Bhusal, 2021).

- Decentralization: Through the utilization of a decentralized network, BT mitigates the necessity for intermediaries or centralized governing bodies. This might potentially lead to the development of more equitable and efficient systems, hence reducing carbon emissions and improving resource allocation (Risso et al., 2023).
- The cryptographic nature of blockchain ensures the guarantee of data integrity and security. Ensuring the protection of sensitive environmental data and maintaining the accuracy and reliability of sustainability records is imperative.
- Smart contracts are agreements capable of executing themselves, as they have the agreement's conditions explicitly encoded into their code. One potential strategy to streamline operations and reduce administrative burden is the use of automated systems for monitoring and implementing sustainability commitments and regulations (Dal Mas et al., 2020).
- The implementation of BT can greatly reduce the need for excessive paperwork and manual processing involved in monitoring and verifying sustainable practices. This technological advancement can enhance operational efficiency and mitigate environmental consequences.
- Through the implementation of BT, resource management may be significantly enhanced by facilitating accurate monitoring and projection capabilities. This, in turn, fosters waste reduction and promotes the efficient utilization of resources (Parmentola et al., 2022).
- The provision of a shared and dependable platform for the exchange of information can foster cooperation among many stakeholders involved in sustainability endeavors, including corporations, governmental bodies, and individuals (Schulz et al., 2020).

Figure 1 shows the connection between the sustainability-related features of BT with sustainable practices. Through these attributes, BT can significantly influence several sustainability-related concerns, such as the conservation of resources, preservation of the environment, and promotion of sustainable business practices.

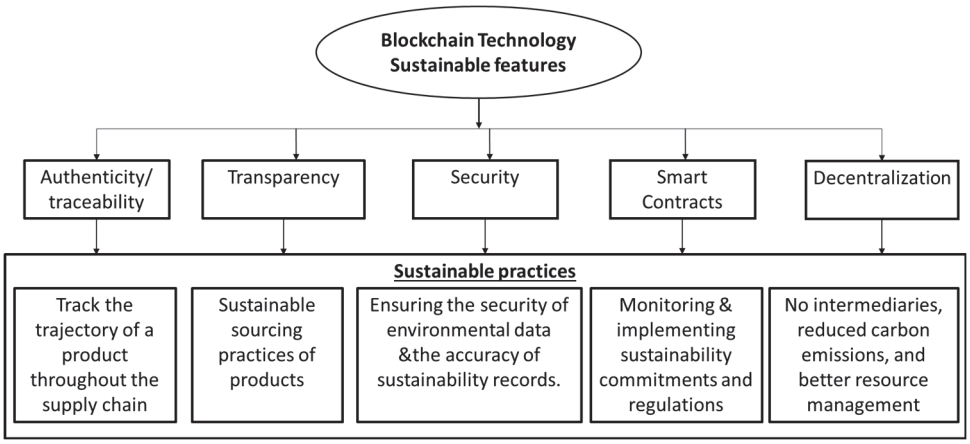

Figure 1: Sustainability-related features of BT
Source: Authors' own work

2.1.2 Historical context: blockchain in sustainability-driven projects

The historical backdrop of using BT into sustainability-focused initiatives can be traced back to its inception within the financial industry, specifically with the advent of Bitcoin in 2009. However, the recognition of BT's promise for sustainability occurred a few years later when other businesses and

organizations commenced exploring its wider range of uses.

The implementation of BT in supply chain management has emerged as an early and noteworthy application within the realm of sustainability. Organizations have come to recognize that the transparency and traceability attributes of BT may effectively guarantee ethical sourcing and production procedures. One example of blockchain use in the food industry is IBM's Food Trust, which was developed in partnership with Walmart. This platform utilizes BT to monitor the entire supply chain of food goods, tracing their path from the farm to the retail shop. By doing so, it aims to enhance food safety measures and minimize wastage. Another illustration may be found in Everledger, a company that uses BT to track the provenance and life cycle of various items. Its primary emphasis is on diamonds, with the aim of guaranteeing their ethical sourcing and absence of involvement in conflicts (Everledger, 2023).

BT has gained traction within the energy sector, mostly to advance renewable energy initiatives and enhance the efficiency of energy distribution systems. Power Ledger and WePower are examples of companies that have utilized BT to facilitate peer-to-peer energy trading. This innovative approach enables customers to engage in the buying and selling of surplus renewable energy, thereby fostering the adoption of sustainable energy resources (Ahmad, 2023).

BT has also been utilized in the realm of environmental conservation. One example of a platform that aims to modernize the energy sector is VAKT. This platform is designed to establish a safe and unchangeable digital environment specifically for the processing of physical post-trade activities in the energy industry. The use of this solution aids in the reduction of administrative documentation and facilitates the establishment of an effective and environmentally conscious energy trading system (Thoughtworks, 2023). An additional illustration may be found in the Aerial platform, which leverages BT to establish a heightened level of transparency and accountability in the monitoring of carbon emissions and credits (Aerial, 2023).

The concept of "green bonds" and sustainable investments has also experienced advantages through the utilization of BT in the realm of sustainable finance. Platforms like as BanQu contribute to the establishment of economic prospects for underprivileged communities by offering a digital identity and financial record, which are essential for gaining access to financial services and engaging in sustainable economic endeavors.

The utilization of BT by organizations such as Plastic Bank is being employed to address the issue of plastic waste in marine environments, namely by providing incentives for recycling activities in developing nations. Individuals have the capacity to gather plastic waste and subsequently trade it for digital tokens, so facilitating the establishment of a circular economy and mitigating the adverse effects of environmental pollution (Böckel et al., 2021).

To summarize, the historical backdrop of blockchain in the realm of sustainability is characterized by its evolution from a singularly financial instrument to a multifaceted technological solution that tackles diverse aspects of sustainability. The impetus for this change can be attributed to the increasing recognition of environmental concerns and the imperative for transparent and efficient solutions across various industries. Organizations worldwide have been actively engaging in the exploration and implementation of BT to address sustainability objectives, thereby showcasing its adaptability and capacity for fostering favorable ecological outcomes.

2.2 Review of the relevant literature

This section synthesizes the existing blockchain technology (BT) focused literature and elaborates on the key themes listed in Table 1 from the literature review. Studies included in this section were identified using the Scopus database, using the following combination of keywords (TITLE ("Blockchain technology") AND TITLE ("Sustainability"). This approach is similar to the approach employed by existing review articles on various topics (Dwivedi, et al., 2023)

Existing research reviewed for this article is categorized into the following major themes: Blockchain Technology, research in the environment, economic and social domains, and application.

Table 1: Sustainability theme-based categorization of BT articles

Theme	Sub-theme	Description	References
Environment	Renewable Energy	Research related to renewable energy.	Alhasan and Hamdan 2023; Cui, 2023; Ahmad, 2023; Zuo, 2022; Bai et al., 2022; Thakur et al., 2021; Howson, 2020; Brilliantova and Thurner, 2019; Teufel et al., 2019;
	Climate Change Mitigation	Studies on mitigating climate change.	Arshad et al., 2023; Khan et al., 2023; Truby et al., 2022; Wang, 2022; Fu et al., 2021; Olivier et al., 2017;
	Environmental Conservation	Research focused on environmental conservation.	Luna et al., 2024; Dehshiri and Amiri, 2024; Arshad et al., 2023; Tyagi, 2023; Yang et al., 2023; Naqash et al., 2023; Rodríguez 2023; Waqar, 2023; Singh et al., 2023; Sipthorpe et al., 2022; Jiang and Zheng, 2021; Park and Li, 2021; Kim et al., 2021; Richardson, 2020; Allena, 2020; Schulz et al., 2020
	Sustainable Agriculture	Studies pertaining to the role of BT on developing sustainable agriculture.	Dehshiri and Amiri, 2024; Gazzola et al., 2023; Bosona and Gebresenbet, 2023; Dal Mas et al., 2023; Yontar. 2023; Pandey, 2022; Bhusal, 2021 Prashar et al., 2020; Mirabelli and Solina, 2020
Economic	Sustainable supply chain management	Research related to BT integration to enhance supply chain management, lower costs, and achieve a competitive edge	Dehshiri and Amiri, 2024; Jabbar and Bjørn, 2018; Bett′ın-D′ıaz et al., 2018; Kshetri, 2018; Tian, 2016
	Promoting fair trade	The role of BT on ehancing transparency within fair trade practices.	Cozzio, 2023; Tafuro et al., 2023; Balzarova et al., 2022; Cozzio, 2023; Francisco and Swanson, 2018
	Employment and Income Distribution	The influence of BT on employment and income distribution	Tartan, 2023; Shabaltina et al., 2021; Novak, 2019
Social	Equality and social inclusion	Research that discusses equality and social inclusion such as financial inclusion, secure identity verification, transparent government, education and credential verification, and decentralized markets	Gazzola et al., 2023; Chaudhuri et al. 2023; Fallah Shayan et al., 2022; Thanasi-Boçe et al., 2022; Al-Issa et al., 2022; Bőckel et al., 2021; Khanfar et al., 2021; Venkatesh et al., 2020; Dal Mas et al., 2020; Konashevych, 2020; Chen et al., 2020; Martin et al., 2011; Carter and Rogers, 2008.
	Business ethics and effective corporate governance	Research related to the relation between BT and corporate ethics and performance.	Ronaghi and Mosakhani, 2023; Rai et al., 2021; Tang, 2018; Mani et al., 2016; Lashley, 2016; Krechovská and Prochazkova, 2014; Krishna et al., 2011; Aguilera et al., 2009; Carter and Rogers, 2008
	Enhancing quality of life: -Sustainable production and consumption -Product authentication and traceability	Research focused on improving the quality of life through the impact of BT on: -environment -satisfying consumers' needs for products and services	Gazzola et al., 2023; Vishwakarma, 2023; Chaudhuri et al., 2023; Sikder, 2023; Al-Issa et al., 2022; Khanfar et al., 2021; Khanfar et la., 2021; Lu et al., 2020; Rai et al., 2021; Mani et al., 2016

Source: Authors' own creation

2.3 Blockchain and environmental sustainability

Environmental sustainability, as outlined in the United Nations Sustainable Development Goals (SDGs), refers to the responsible interaction with the environment to avoid depletion or degradation of natural resources and allow for long-term environmental quality (UN, 2023). In a time when environmental issues are becoming ever more complicated and interconnected, environmental sustainability is not merely a requirement but a worldwide obligation. In this effort, the SDGs of the United Nations function as a guiding framework, delineating the complex aspects of sustainability.

These goals underscore the urgent need to address critical issues such as climate action (Goal 13) to combat climate change, protect oceans and marine life (Goal 14), and sustain terrestrial ecosystems (Goal 15). They emphasize the necessity of clean water and sanitation (Goal 6), affordable and clean energy (Goal 7), and responsible consumption and production (Goal 12) to ensure efficient use of resources and waste reduction. Additionally, these goals highlight the importance of global partnerships (Goal 17) for effective implementation and policy coherence, incorporating aspects of international cooperation and technology transfer to achieve environmental sustainability.

Achieving environmental sustainability demands innovative strategies, with emerging technologies such as blockchain offering novel avenues for progress. Policymakers can make more informed decisions by comprehending the effects of market interventions and weighing their options, mindful of potential disruptions. The insights gained can guide political institutions in shaping the necessary political and legal frameworks to foster the creation of effective green blockchain applications (Arshad et al., 2023).

As the exploration of blockchain's potential in promoting sustainability progresses, it becomes essential to examine its influence on specific domains that are important for the environmental agenda.

2.3.1 Supply chain management

Supply chain may be made much more transparent with the use of BT (Kouhizadeh et al., 2021; Risso et al., 2023). Every transaction or movement of products may be tracked on a tamper-proof ledger by utilizing BT (Yap et al., 2023). As a result, parties involved in the supply chain can identify inefficiencies and sources of waste and pollution by tracking the origin, path, and present state of products (Kim et al., 2021). By utilizing BT to document every stage of a product's supply chain, it becomes feasible to verify the purchase of items from practices that promote biodiversity conservation (Park and Li, 2021; Tyagi, 2023; Dehshiri and Amiri, 2024).

By fostering sustainable supply chains, this directly promotes SDG 12 (Responsible Consumption and Production). It can also impact SDG 13 (Climate Action) by helping reduce emissions associated with production and logistics.

2.3.2 Water resource management

The implementation of BT has the potential to safeguard the integrity and transparency of water usage and quality data, similar to its application in managing supply chain information and energy data (Rodríguez 2023). The recording of every water usage event, such as extraction, purification, and distribution, has the potential to be documented on a blockchain (Naqash et al., 2023). Initiatives such as IBM's blockchain-based water management system facilitate the establishment of transparent systems for the administration of water rights and consumption data, thereby promoting fair and sustainable practices in water distribution and utilization. It aligns with SDG 6 (Clean Water and Sanitation) by promoting sustainable management of water resources.

2.3.3 Energy efficiency

Assisting in the management of the complexities of a decentralized energy system and enhancing energy operations along the entire value chain are two ways in which BT is anticipated to transform the energy industry (Brilliantova and Thurner, 2019). BT enables the verification, automation, and security of energy transfers without intermediaries (Teufel et al., 2019). BT can be used to create decentralized energy grids and systems that reward energy-saving behaviors. For example, smart contracts on a blockchain can automatically compensate individuals or organizations that reduce their energy consumption. This supports SDG 7 by promoting energy efficiency and SDG 13 by reducing energy-related emissions.

2.3.4 Renewable energy certificate (REC)

In the realm of renewable energy, blockchain can play a pivotal role in issuing, tracking, and verifying RECs (Zuo, 2022; Cui, 2023). By guaranteeing each certificate's authenticity and distinctiveness, this system eliminates fraud and double counting. This is in line with SDG 13 and SDG 7 since it encourages the use of renewable energy sources.

As blockchain redefines the paradigms of transparency and traceability in supply chains, it opens new avenues for mitigating GHG emissions and empowering renewable energy markets. Through its ability to verify the authenticity of RECs and carbon credits, blockchain enables a more robust and trustworthy system for environmental accounting (Sipthorpe et al., 2022). Its role in incentivizing energy efficiency further illustrates its utility in the pursuit of a low-carbon economy.

2.3.5 Carbon credits

The utilization of BT facilitates the establishment of a reliable yet readily transparent infrastructure for the distribution, exchange, and suspension of this approach is designed to prevent the duplication of carbon credits and to verify that each credit corresponds to a genuine decrease in emissions (Richardson, 2020). This action helps the achievement of SDG 13 by facilitating the implementation of a mechanism that allows for the compensation of greenhouse gas emissions. It serves as an incentive for enterprises and nations to allocate resources towards programs aimed at reducing emissions (Sipthorpe et al., 2022).

2.3.6 Green building and sustainable construction:

Similarly to monitoring REC and ensuring energy efficiency, the utilization of BT within the construction industry facilitates the monitoring and assessment of the sustainability of building materials and construction methodologies (Waqar, 2023; Singh et al., 2023). Information about the sourcing, production, and transportation of materials can be stored on a blockchain. The tracking of construction materials' origin and environmental impact is a capability that stakeholders need. The implementation of this transparency measure guarantees compliance with specific environmental criteria and facilitates the adoption of sustainable construction methods (Jiang and Zheng, 2021). Sustainable materials are key to reducing the environmental footprint of buildings (Yang et al., 2023). This relates to SDG 11 (Sustainable Cities and Communities), focusing on sustainable construction practices.

2.3.7 Sustainable agriculture and food systems:

The application of BT in enhancing supply chain transparency is highly relevant in the context of sustainable agriculture and food systems since it enables the seamless monitoring of products from their origin to the final consumer (Mirabelli and Solina, 2020; Bosona and Gebresenbet, 2023; Dal Mas et al., 2023). The entire process, spanning from production to retail, is meticulously documented, thereby guaranteeing the implementation of food safety protocols and sustainable practices. It has the capacity to fundamentally transform the processes of food production, distribution, and consumption (Yontar. 2023; Pandey, 2022). This directly corresponds to the objectives of establishing resilient agricultural practices and guaranteeing sustainable food production systems, addressing SDG 2 and SDG 12 (Dehshiri and Amiri, 2024). AgriDigital and provenance are two important initiatives that provide blockchain-based solutions for the traceability of agricultural products. This approach promotes more transparency and provides valuable support for the adoption of sustainable farming methods.

The global importance of food safety and quality has been highlighted by recent high-profile incidents, raising public interest in food traceability (Prashar et al., 2020).

Due to its ability to track food through all stages of its life cycle, the World Health Organization encourages a cooperative approach among governments, producers, and consumers to ensure safety through information sharing in complex food networks. Profit-driven businesses often use information systems to track food, enhancing safety and potentially increasing profits. Gazzola et al. (2023) investigated how BT can contribute to this area, particularly in building positive consumer relationships.

The utilization of BT has promise for establishing a more secure, environmentally conscious, and dependable agricultural food system in the forthcoming years (Bosona and Gebresenbet, 2023). Despite being in its nascent phases and facing obstacles including high implementation costs, privacy concerns, security issues, scalability limitations, and performance challenges, the integration of this technology has the potential to bring about a substantial transformation in the agricultural sector (Bhusal, 2021).

2.3.8 Environmental policy compliance and governance:

Blockchain can monitor compliance with environmental policies and regulations, akin to verifying carbon credits and managing RECs. It ensures a decentralized and unalterable ledger of emissions data and adherence to environmental regulations. Governments can manage environmental subsidies and penalties with BT, ensuring policy implementation is transparent and efficient (Luna et al., 2024; Allena, 2020; Schulz et al., 2020). The promotion of open and accountable governance contributes to the achievement of SDG 13 and SDG 16 (Peace, Justice, and Strong Institutions).

2.3.9 Public participation and awareness in environmental conservation

The utilization of BT has the potential to improve public involvement in environmental initiatives using tokenization, thereby enabling anyone to engage in conservation programs through investment or direct participation, like how blockchain encourages participation in renewable energy markets (Alhasan and Hamdan, 2023; Bai et al., 2022; Thakur et al., 2021; Howson, 2020)

Platforms like Earth Token facilitate individuals' ability to invest in environmental assets, hence fostering public engagement in initiatives aimed at environmental preservation. Supports various SDGs by fostering inclusive participation in sustainable development (SDG 17 - Partnerships for the Goals).

2.3.10 Sustainable transportation and electric vehicles (EVs):

The utilization of BT can facilitate the effective management and optimization of electric vehicle (EV) charging stations, as well as their easy integration into smart power grids (Fu et al., 2021; Wang, 2022; Khan et al., 2023). Blockchain is being investigated by initiatives such as MOBI (Mobility Open Blockchain Initiative) to determine the identity, history, and utilization of vehicles; this research may promote the adoption of more environmentally friendly transportation methods. Aligns with SDG 11 and SDG 13 by promoting sustainable urban transportation systems and contributing to climate action.

2.3.11 Innovative climate-conscious projects:

As the world deals with the effects of climate change, which include loss of species, extreme weather, and an imbalance in the environment, countries must focus on long-term economic growth. Even though the world's economy grew by an average of 3.4% per year from 2012 to 2018, rising greenhouse gas (GHG) emissions cast a shadow over this progress. This is mostly because of practices that use a lot of energy and resources (Olivier et al., 2017). The Intergovernmental Panel on Climate Change (IPCC) reports and the growing support for green projects in the public and political spheres, which led to important agreements like the Paris Agreement of 2015, show how important it is to act quickly to stop climate change. Climate markets need to become open to the world because people are more aware of the effects of climate change (Truby et al., 2022; Arshad et al., 2023) and to spend and come up with new ways to make them more resilient.

Several projects utilizing BT have been developed to address the challenge of climate change. These include various platforms designed for monitoring and mitigating emissions, projects that

provide incentives for adopting sustainable behaviors, and structures that facilitate climate finance and investment in projects aimed at promoting sustainability. These projects can contribute to multiple SDGs, including SDG 13, SDG 11, and SDG 15 by promoting actions that mitigate climate change and its impacts.

Each of the previously discussed topics is connected to the broader theme related to a specific SDG and is interconnected with the previously identified areas such as: monitoring carbon footprints with blockchain; enhancing renewable energy markets; waste management and recycling and climate change. This methodology offers a systematic framework for comprehending the interplay and contributions of different aspects of sustainability and BT to these broad concepts. Below in Table 2 we show a categorized table that aligns each theme placed under the broader topic where its impact is most significant.

Table 2. Environmental sustainability-related themes

Broader Topics	**Sustainability-related Themes**
Monitoring Carbon Footprints with Blockchain	- Supply Chain Management - Environmental Policy Compliance and Governance
Enhancing Renewable Energy Markets	- Renewable Energy Certificates (RECs) - Energy Efficiency - Sustainable Transportation and Electric Vehicles (EVs)
Waste Management and Recycling	- Sustainable Agriculture and Food Systems - Green Building and Sustainable Construction
Climate Change	- Public Participation and Awareness- Innovative Climate - Conscious Projects

Supply Chain Management and Environmental Policy Compliance and Governance are key in monitoring carbon footprints, as they involve tracking emissions and ensuring regulatory adherence. RECs, Energy Efficiency, and Sustainable Transportation/EVs enhance renewable energy markets by promoting the use of clean energy and efficient energy practices. Sustainable Agriculture and Food Systems and Green Building and Sustainable Construction contribute to waste management and recycling through sustainable practices and resource efficiency. Public Participation and Awareness and Innovative Climate-Conscious Projects are crucial for addressing climate change, as they involve engaging the public and implementing novel solutions to climate challenges.

Table 3 provides a clear overview of how BT is being applied in various sectors to address environmental challenges and sustainability goals. Each application demonstrates the potential of blockchain to contribute to a more sustainable and environmentally conscious world.

Table 3. Application of blockchain for environmental sustainability

Broader Topic	Specific Application	Description
Monitoring Carbon Footprints with Blockchain	- Smart contracts for emission tracking	Companies use blockchain-based smart contracts to automatically track and report emissions, integrating sensors and IoT devices.
	- Decentralized carbon - Emission trading platforms	Blockchain enables the creation of platforms for transparent and efficient trading of carbon credits, as seen with IBM and Energy Blockchain Labs.
Enhancing Renewable Energy Markets	- Blockchain in microgrids	Projects like Brooklyn Microgrid use blockchain to create local energy networks for buying and selling renewable energy.
	- Tokenization of renewable energy assets	Blockchain is used for tokenizing renewable energy assets, facilitating investment in renewable energy projects (e.g., WePower).

Broader Topic	Specific Application	Description
Waste Management and Recycling	- Recycling incentivization programs	Blockchain-based platforms like Plastic Bank offer tokens for collecting and recycling materials, incentivizing proper recycling practices.
	- Supply chain transparency for recycling	Blockchain is used to track the lifecycle of products, ensuring responsible recycling (e.g., Arianee project for luxury goods).
Climate Change	- Climate finance and investment platforms	Blockchain platforms facilitate investments in climate change mitigation projects, such as the Poseidon Foundation supporting forest conservation efforts.
	- Tracking and verifying climate data	Projects like the Open Earth Foundation use blockchain for transparent and tamper-proof climate data, aiding in climate policy and modeling.

2.4 Blockchain in economic sustainability

Economic sustainability, as per the United Nations' SDGs, refers to the practice of managing resources and developing economically in a way that ensures long-term economic health without harming the environment or compromising the ability of future generations to meet their own needs. It involves a balanced approach that integrates economic growth with social inclusion and environmental protection (UN, 2023).

The SDGs encompass various facets of economic sustainability through distinct objectives. Goal 8 advocates for sustained, inclusive economic growth and decent work, emphasizing productivity, innovation, entrepreneurship, and the separation of economic growth from environmental harm. Goal 9 targets the development of resilient infrastructure, sustainable industrialization, and innovation as key drivers of economic progress. Goal 10 is focused on reducing inequalities both within and among countries, promoting equitable distribution of wealth and resources as a cornerstone of sustainable economic development. Lastly, Goal 12 aims to establish sustainable patterns of consumption and production, prioritizing efficient resource use, and waste reduction, and minimizing the environmental impact of economic activities.

2.4.1 Promoting fair trade

Economic sustainability can be bolstered by enhancing transparency within fair trade practices. Fair trade relies on consumer willingness to pay premiums based on the assurance of superior quality and ethical practices within supply chains. Ecolabels must therefore demonstrate attributes such as traceability, accountability, and ecological sustainability to build trust. Blockchain technology (BT) is posited as an improvement over traditional marketing strategies, with Balzarova et al. (2022) noting its net positive impact on food supply chains. Francisco and Swanson (2018) argue that BT could significantly improve transparency and traceability in agricultural supply chains. This technology facilitates consumer trust, providing self-verification mechanisms that can potentially replace reliance on ecolabels (Cozzio, 2023).

In assessing the adoption of blockchain in fair trade, Balzarova et al. (2022) utilized the Technology Readiness Index (TRI), unveiling five themes: the conditional benefits of BT, the duality of transparency outcomes, consumer behavior factors, and implementation barriers, highlighting the practical challenges of BT adoption. Fairtrade certification to blockchain adoption begins with the firm's expertise and willingness to implement BT (Holmberg et al., 2022). Moreover, public-private partnerships (PPPs) often face transparency and accountability issues, impacting trust and collaboration. Tafuro et al. (2023) examined blockchain's potential to address these issues in PPPs,

suggesting that despite its complexities, blockchain can enhance the efficacy of PPPs and contribute to sustainable development goals.

2.4.2 Sustainable Supply Chain Management

Blockchain technology (BT) has emerged as a transformative force in supply chain management, offering unparalleled benefits in terms of transparency, security, and operational efficiency, which are pivotal for sustainable economic growth. This technology's core advantage lies in its ability to create a decentralized, immutable ledger that enables real-time tracking of products from their point of production to delivery (Sarfraz et al., 2023; Waqar et al., 2023; Yontar et al., 2023; Risso et al., 2023; Khanfar et al., 2021; Kouhizadeh et al., 2021). This capability is instrumental in reducing losses associated with counterfeit and gray market trading, while also promoting environmentally friendly production methodologies (Carter and Easton, 2011; Yap et al., 2023). Moreover, blockchain facilitates the automation of sustainability agreements through smart contracts (Dal Mas, et al., 2020), ensuring compliance with eco-friendly criteria and fostering the circular economy by meticulously documenting products' lifecycle for future reuse (Yap et al., 2023).

Despite the promising potential of blockchain in revolutionizing supply chains, its integration into existing systems is fraught with challenges. These include the need for substantial technology infrastructure development, regulatory support, and overcoming the general reluctance towards adopting new technologies. Specific hurdles such as user-friendliness, the proprietary nature of blockchain solutions, and the seamless integration of virtual and physical tracking mechanisms are significant (Dehshiri and Amiri, 2024; Jabbar and Bjørn, 2018; Kshetri, 2018; Tian, 2016). The reconciliation of blockchain's virtual capabilities with the physical tracking of items poses a complex problem that research has yet to fully address, often focusing more on the virtual benefits than on practical physical applications.

In addition to revolutionizing supply chain management, blockchain significantly enhances business efficiency by simplifying processes, eliminating intermediaries, thus reducing costs and saving time. For instance, in the energy sector, blockchain enables efficient peer-to-peer energy trading, facilitating the use of renewable energy sources and contributing to a more sustainable energy supply. Technology also allows for the tokenization of physical assets, such as real estate, making these markets more liquid and efficient by enabling assets to be traded on blockchain platforms (Carter and Easton, 2011).

The deployment of blockchain technology in supply chain management not only ensures greater transparency, security, and cost efficiency but also facilitates the real-time tracking of the entire production and delivery process. This aspect significantly mitigates the risks associated with counterfeit and gray market trading, thereby endorsing sustainable business models (Thanasi-Boçe et al., 2022). Blockchain's ability to enhance product quality, prevent counterfeits, and achieve stakeholder transparency is pivotal for monitoring resource utilization and promoting sustainable manufacturing practices. Furthermore, smart contracts play a critical role in ensuring suppliers adhere to environmental standards, thereby incentivizing responsible production (Yap et al., 2023).

Despite its potential, integrating BT into supply chains poses challenges, including the necessity for developing technology infrastructure, regulatory support, and overcoming the reluctance towards new technologies. Issues such as ease of use, the proprietary nature of blockchain solutions, and the integration of virtual and physical tracking systems represent significant hurdles. Bridging the gap between blockchain's virtual capabilities and the physical tracking of items remains a complex challenge, with current research focusing more on the technology's virtual advantages than its application in physical item tracking (Dehshiri and Amiri, 2024; Jabbar and Bjørn, 2018; Kshetri, 2018; Tian, 2016). Furthermore, most research has focused on blockchain's benefits for companies, with less emphasis on consumer information. Bett'ın-D'ıaz and colleagues (2018) suggested a methodology for developing traceable supply chains with consumer considerations, but detailed strategies for conveying information to customers are limited.

Addressing the challenges of blockchain integration within supply chains necessitates the development of a robust technological infrastructure and sustainable methodologies, bolstered by collaborative investments and regulatory frameworks among supply chain partners (Dehshiri and Amiri, 2024). The ease of use and the capacity to integrate blockchain within existing infrastructures are essential for promoting user adoption and overcoming resistance towards new technologies (Jabbar and Bjørn, 2018).

2.4.3 Impact on Employment and Income Distribution

The influence of BT on employment and income distribution is a fluctuating and complex matter. BT has the potential to generate novel employment prospects and possibilities, notably in domains such as software development, consulting, and auditing. Conversely, other authors claim that the use of BT may result in workforce reduction within specific industries, given its capacity to automate functions and procedures presently executed by human labor (Novak, 2019). The utilization of BT possesses the capacity to exert influence on employment and income distribution through several avenues, including both advantageous and detrimental outcomes, as provided is in Table 4.

Table 4: The impact of blockchain on employment and income distribution

Impact	Positive or Negative (+/-)	Explanation
Job creation	(+)	BT could provide jobs in blockchain development, cybersecurity, data analysis, and smart contract audits. The growing acceptance of BT is creating job opportunities for skilled workers in connected fields.
Streamlining of processes	(+)	BT can simplify and streamline manual processes, reducing middlemen and administrative staff. This technique may replace jobs in some locations, but it can save companies money and improve operations.
Decentralization	(+)	BT enables decentralized platforms and apps, boosting the gig economy. This phenomenon has pros and disadvantages. Peer-to-peer networks allow people to make money by completing activities, sharing resources, and selling services. This could improve income distribution.
Financial inclusion	(+)	Banks can use BT to provide financial services to those who don't have access to them. This allows people to work and participate in the formal economy, empowering them.
Income inequality	(-)	Blockchain wealth concentration among early adopters and significant enterprises may aggravate economic inequality. Individuals with significant computer power and resources may have an advantage.
Reskilling and education	(+)	The growing demand for BT skills spurs investment in educational and training programs, giving people the chance to learn new skills and boost their income (Fleener, 2022).
Regulatory uncertainty	(-)	Regulatory ambiguity in the blockchain business can hinder investment and job growth. Businesses are hesitant to expand in uncertain legal environments.

Additionally, BT has a positive impact on reducing fraud and corruption. Blockchain's immutable ledger ensures that records cannot be altered after the fact, which can significantly reduce fraud and corruption, particularly in public sectors such as land registries and government contracts.

2.5 Blockchain for social sustainability

BT significantly affects social sustainability, addressing systemic issues across various key areas to foster a more equitable, transparent, and sustainable society. This transformative technology

underpins efforts aligned with the United Nations' Sustainable Development Goals (SDGs), enhancing quality of life and promoting social inclusion (UN, 2023; Mani et al., 2016). The key areas of social impact where blockchain demonstrates its substantial contributions are discussed below. In each of the discussed areas, blockchain technology not only addresses pressing social and environmental challenges but also promotes a more equitable distribution of resources and opportunities, underscoring its profound impact on fostering a sustainable and inclusive global society (Lu et al., 2020; Rai et al., 2021).

2.5.1 Promoting equality and social inclusion

Blockchain technology has the potential to promote equality and social inclusion through several key mechanisms. By providing a decentralized and transparent ledger system, it offers innovative solutions to systemic problems that hinder equality and social inclusion. The discussion below focuses of the ways blockchain can contribute to these goals:

2.5.2 Financial inclusion

Blockchain facilitates access to financial services for the unbanked and underbanked populations, who are often excluded from traditional banking systems. By enabling peer-to-peer transactions without the need for intermediaries, blockchain can lower transaction costs and make financial services more accessible to everyone, regardless of their geographic location or socioeconomic status. This increased access to financial services can help reduce poverty and boost economic participation among marginalized communities.

Blockchain plays a crucial role in bridging the financial gap for unbanked and underprivileged populations. Platforms like BanQu provide digital identities and secure, accessible financial transactions, offering disenfranchised individuals, including refugees, access to banking and financial services, thereby facilitating economic participation and empowerment (Fallah Shayan et al., 2022).

2.5.3 Secure identity verification

Blockchain can provide secure and immutable digital identities, offering a solution for individuals without official documents or those whose records have been lost due to conflicts or disasters. A blockchain-based identity system can enable these individuals to access essential services such as healthcare, education, and banking, thereby promoting social inclusion.

2.5.4 Transparent and fair governance

Blockchain secures electoral systems and enhances civic engagement through transparent and trustworthy voting mechanisms. By ensuring that votes are tamper-proof and accurately recorded, blockchain can foster a more inclusive and fair political process, giving marginalized groups a stronger voice and promoting political equality. Projects like Voatz show the potential of blockchain to increase participation in democratic processes, strengthen democratic governance, and encourage citizen involvement in decision-making processes (Carter and Rogers, 2008).

2.5.5 Supply chain transparency

Blockchain can track the provenance of products from origin to consumer, ensuring fair trade and ethical practices (Balzarova et al., 2022). This transparency can empower consumers to make informed choices that support social and economic fairness, benefiting small producers and workers in developing countries by ensuring they receive a fair share of profits.

2.5.6 Education and credential verification

Blockchain can securely store and verify academic credentials, enabling individuals from disadvantaged backgrounds to prove their qualifications and skills easily. This can improve access to job opportunities and higher education, breaking down barriers to social mobility and promoting equality.

2.5.7 Education and employment

Blockchain enhances the mobility and employability of individuals by authenticating academic credentials and professional achievements. Through initiatives like the MIT Media Lab's Digital Certificates Project, blockchain ensures the integrity and verifiability of educational records, streamlining employment processes and supporting lifelong learning (Thanasi-Boçe et al., 2022). This enables individuals from disadvantaged backgrounds to prove their qualifications and skills easily. Also, it can improve access to job opportunities and higher education, breaking down barriers to social mobility and promoting equality.

2.5.8 Decentralized markets

By facilitating decentralized marketplaces, blockchain allows small businesses and entrepreneurs from marginalized communities to participate in the global economy directly. This can level the playing field, reducing the dominance of large corporations and empowering individuals and small enterprises (Dal Mas et al., 2020).

2.5.9 Protection of property rights

In countries where land and property rights are not adequately documented and enforced, blockchain technology has the potential to offer a record of ownership that is both secure and unchangeable. This has the potential to safeguard the rights of vulnerable communities against encroachment and disputes, so fostering economic stability and social inclusion simultaneously (Konashevych, 2020; Chen et al., 2020).

2.5.10 Enhancing quality of life

Blockchain technology has the potential to enhance the quality of life through several key mechanisms that are discussed below:

2.5.11 Environmental stewardship and circular economy

Blockchain incentivizes recycling and responsible waste management through projects like Plastic Bank, addressing environmental challenges and promoting the principles of the circular economy. By tokenizing waste and facilitating the trade of recyclable materials, blockchain contributes to sustainable practices and environmental conservation.

2.5.12 Establishing consumer trust and transparency through authenticity and traceability

BT is increasingly vital for brands in various sectors to ensure product authenticity and traceability, which is fundamental in establishing consumer trust and transparency. This decentralized and transparent technology enables brands to authenticate their products and track their supply chain journey, meeting the growing consumer demand for ethical and environmentally responsible production (Thanasi-Boçe et al., 2022) especially in the growing e-commerce (Sikder, 2023).

Key applications of blockchain for product authenticity and traceability illustrated with examples include:

Supply Chain Management: Blockchain is used to document and track every stage of a product's progression, from raw material acquisition to final delivery (Venkatesh et al., 2020). For instance, IBM Food Trust is a blockchain-based platform employed by major retailers like Walmart to trace the origin of food products, such as leafy greens. Consumers can access this information by scanning a QR code on the packaging, ensuring the product's legitimacy and source.

Food and Agriculture: Farmers can document crop-related data on blockchain, enhancing food safety and integrity. An example is the BeefLedger project in Australia, which uses blockchain to trace the source of beef products. Consumers can scan a QR code on meat packaging to access details about the cattle's breed, origin, diet, and processing methods, thereby verifying food provenance and quality using product labels.

Luxury Goods: Luxury brands are leveraging blockchain to provide digital certificates of authenticity. LVMH, the conglomerate that owns luxury brands like Louis Vuitton, has launched the AURA blockchain platform. It allows consumers to verify the authenticity and origin of luxury items, such as designer bags and watches. Each product comes with an NFC chip linked to blockchain, providing a digital certificate of authenticity and detailed information about the product's history. This shift towards sustainable luxury aligns with contemporary values, setting new standards in the luxury industry for technological innovation and ethical practices (Al-Issa et al., 2022).

Pharmaceuticals: In the pharmaceutical industry, blockchain is used to monitor medication lifecycles and reduce counterfeit products. Chronicled is a blockchain platform employed to combat counterfeit drugs. It enables tracking the production and distribution of pharmaceuticals, ensuring that medications are genuine. Patients can authenticate prescriptions using QR codes.

Copyright and Digital Content: Creators can establish ownership of their work through blockchain timestamps. For example, Verisart is a blockchain-based platform used by artists and creators to certify the authenticity of digital art and collectibles. It provides a timestamped certificate of authenticity on the blockchain, making it easy for buyers to verify the originality of digital content.

Automotive Industry: Car manufacturers are exploring blockchain applications to maintain comprehensive records of vehicle maintenance, accidents, and ownership changes. BMW, for instance, aims to create a tamper-proof history of used cars, recording maintenance, accident history, and ownership transfers on the blockchain. Buyers can access this information to make informed decisions when purchasing a pre-owned vehicle.

In summary, BT offers a reliable and immutable method for maintaining a verifiable record of a product's journey, enhancing its credibility and traceability across various sectors. The Italian coffee roaster Lavazza's successful implementation of blockchain for product tracking demonstrates the importance of collaborative supply chain efforts and innovation in adapting to socioeconomic trends (Gazzola et al., 2023).

2.5.13 Sustainable production and consumption

Sustainable consumption refers to the use of products and services that satisfy basic needs and improve quality of life while minimizing the impact on the environment, so future generations can also fulfill their needs. Chaudhuri et al. (2023)' study highlights the importance of customer education and engagement, along with cultivating local partnerships, as essential behavioral strategies for enhancing social sustainability and mitigating risks in the context of BT.

The utilization of BT has a profound influence on the promotion of sustainable production and consumption (Böckel et al., 2021) through the augmentation of transparency, traceability, and accountability within supply chains across diverse sectors (Khanfar et al., 2021). BT enables consumers to achieve supply chain transparency by providing them with the ability to trace the origins of items, thereby certifying their validity and ensuring ethical sourcing practices. The promotion of openness fosters the adoption of sustainable practices, including the responsible

management of resources and the establishment of fair labor conditions. The immutability of BT presents a formidable obstacle to the proliferation of counterfeit goods in markets, thereby guaranteeing that consumers are provided with authentic, secure, and ecologically sustainable products.

2.5.14 Renewable energy adoption

Facilitating peer-to-peer energy trading, blockchain projects such as the Brooklyn Microgrid enable consumers to trade locally produced renewable energy. This democratization of energy production promotes environmental sustainability and incentivizes the shift towards renewable energy sources, contributing to reduced carbon footprints and supporting clean energy goals.

2.5.15 Humanitarian aid and disaster relief

In the realm of humanitarian aid, blockchain improves the efficiency and transparency of aid distribution. The World Food Programme's Building Blocks project exemplifies how blockchain delivers food assistance directly to beneficiaries, minimizing transaction costs and fraud risks, thus ensuring that aid reaches those in need more effectively (Martin et al., 2011).

2.5.16 Business ethics and effective corporate governance

Business ethics and effective corporate governance are instrumental in achieving social sustainability (Ronaghi and Mosakhani, 2023). Business ethics, fundamental to workplace social interactions, has a significant impact on an organization's social aspect (Lashley, 2016).

Blockchain introduces unparalleled transparency in global supply chains, enabling verification of ethical sourcing and adherence to fair labor practices. By documenting the journey of goods from their origin, initiatives like Everledger and Fairfood International leverage blockchain to combat the trade in conflict minerals and ensure products are produced under ethical conditions, empowering consumers with information to make responsible choices (Tang, 2018).

Krishna et al. (2011) identified a positive relationship between business ethics and corporate performance. Other authors have examined corporate governance, influencing organizational social behaviors through stakeholder monitoring and power structures (Schultz et al., 2020; Aguilera et al., 2009), and the interaction between sustainability concepts and corporate governance concerning corporate performance (Krechovská and Prochazkova, 2014).

2.6 Challenges of BT implementation and proposed solutions in sustainability programs

In the review of scholarly literature, it has been established that the incorporation of blockchain technology (BT) into sustainability initiatives is not without its challenges. These obstacles are extensively examined in the works of Mulligan et al. (2023) and Khanfar et al. (2021), among others, and warrant careful consideration in the discourse on the advancement of BT within sustainability programs:

- *Scalability and security issues*: Scalability is a critical technical challenge for blockchain, as increased transaction volumes can reduce system performance and efficiency. Security is also a concern; despite inherent protections, blockchain is susceptible to cyber threats like the 51% attack, and new vulnerabilities may emerge as the technology evolves.
- *Energy consumption:* Blockchain networks, especially those using proof-of-work (PoW) mechanisms, require significant computational resources, leading to high energy consumption, as seen in Bitcoin mining. This poses environmental concerns, particularly regarding sustainability objectives aimed at reducing carbon emissions.

- *Regulatory and ethical considerations*: The decentralized and transnational nature of blockchain creates complex regulatory challenges. Compliance with varying international regulations on digital currencies, data protection, and cross-border transactions is crucial. Ethical issues, such as data privacy and the potential for blockchain to enable illicit activities, also need to be addressed.
- *Resistance to change and adoption hurdles*: Resistance to adopting new technologies like blockchain is common, often due to limited understanding or concerns about potential impacts. Integrating blockchain into existing systems can be complex and costly, posing significant challenges for organizations, especially smaller ones with limited resources.
- *Economic implications*: BT's impact on employment and income distribution is complex. While it can offer new job opportunities, financial inclusivity, and skill development, it also has the potential to disrupt traditional employment structures and exacerbate income inequalities. Addressing these issues requires regulatory frameworks, educational initiatives, and industrial adjustments to ensure equitable benefits distribution.

The successful and sustainable adoption of BT requires overcoming these challenges through the development of more energy-efficient consensus mechanisms, robust security measures, effective regulatory management, and stakeholder education about the technology's benefits and implementation. Table 5 presents comprehensive strategies required to address the multifaceted challenges of integrating blockchain technology into sustainability initiatives. These solutions span technical innovations, regulatory adjustments, ethical considerations, educational efforts, and economic policies, highlighting the need for collaborative efforts among all stakeholders to harness blockchain technology's full potential for sustainable development.

Table 5. Strategies of integrating blockchain technology into sustainability initiatives

Challenge Category	Solution	Description
Scalability and security	Layered architecture and off-chain solutions	Investigating off-chain solutions and implementing a layered blockchain architecture can improve scalability by offloading transaction processing, reducing congestion and increasing efficiency while maintaining security.
	Sophisticated consensus mechanisms	Implementing streamlined consensus mechanisms like PoS or DPoS to reduce computational and energy demands, addressing scalability and security concerns simultaneously.
Energy utilization	Transition to energy-efficient consensus mechanisms	Moving from PoW to more energy-efficient mechanisms like PoS to significantly reduce blockchain's energy consumption and advance sustainability goals.
	Implementation of renewable energy sources	Promoting the use of renewable energy sources in blockchain operations through regulations and incentives to minimize environmental impact.
Ethical and regulatory considerations	Frameworks for international regulations	Developing harmonized international frameworks to manage the decentralized nature of blockchain, ensuring privacy, data protection, and prevention of illegal activities.
	Establishing ethical standards and guidelines	Setting up ethical guidelines and standards for blockchain applications to uphold user privacy and contribute positively to societal goals.
Resistance to change and adoption	Capacity building and education	Providing educational initiatives and resources on blockchain to demystify the technology and reduce opposition, emphasizing the importance of training for developers, users, and stakeholders.
	Collaborations and pilot projects	Implementing pilot projects and fostering collaborations between industries, governments, NGOs, and blockchain developers to demonstrate the practical benefits and feasibility of blockchain, reducing integration complexity and costs.
Economic consequences	Inclusive economic policies	Developing policies that support financial inclusivity and SMEs to mitigate adverse effects on employment and income distribution, ensuring equitable benefits from blockchain technology.
	Programs for skill development and job transition	Investing in skill development and retraining programs to prepare the workforce for new opportunities in the blockchain sector, positively impacting employment and income distribution.

2.7 Framework for BT impact on environment, economic, and social domains

This framework outlines the multifaceted impact of blockchain technology across environmental, economic, and social domains. For the environment, blockchain aids in monitoring carbon footprints and enhancing renewable energy markets, among other benefits. Economically, it supports fair trade, improves supply chain management, and promotes financial inclusion, thereby driving efficiency. Socially, blockchain ensures product authenticity and traceability, bolsters business ethics, and contributes to sustainable production practices. The framework also identifies challenges such as scalability and regulatory compliance, while highlighting blockchain's sustainable features like transparency and decentralization.

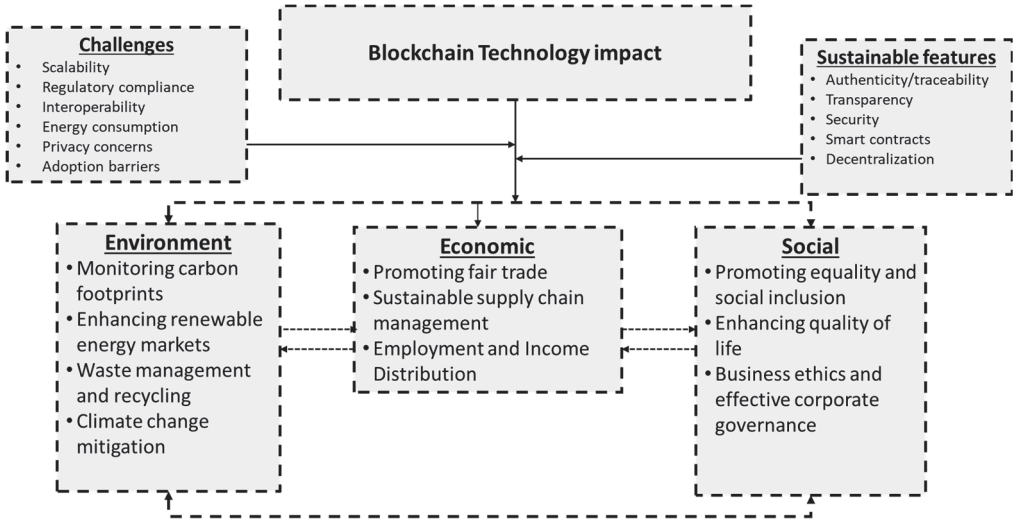

Figure 2. BT impact framework
Source: Authors' own work

3. The Future Outlook of Sustainability Blockchain Integration

The trajectory of blockchain integration in sustainability shows promise across technological advancements, policy considerations, and economic impacts. Innovations in BT are expected to address issues like energy consumption and scalability, such as transitioning from Proof of Work (PoW) to more sustainable mechanisms like Proof of Stake (PoS) or Proof of Authority (PoA), reducing blockchain's ecological impact.

Blockchain's application across various industries could enhance supply chain transparency, optimize renewable energy distribution, and facilitate resource management, with smart contracts and decentralized applications enforcing sustainability standards. Governments play a critical role in shaping the future of blockchain for sustainability, requiring legal frameworks that balance innovation with potential risks, including data privacy and financial stability concerns. Policymaking might incentivize blockchain adoption in sustainable practices, such as subsidies for companies using blockchain for sustainable supply chain tracing or legislative support for blockchain-based renewable energy solutions (Mulligan et al., 2023).

International collaboration is essential, given blockchain's global nature and sustainability challenges. Harmonizing regulatory approaches can improve cross-border blockchain initiatives, contributing to global sustainability goals. The economic impact of blockchain in various sectors

could be significant, enabling new markets and opportunities, especially in sustainable goods and services. Blockchain's potential to disrupt market structures, reduce intermediaries, lower transaction costs, and democratize market access could redistribute economic power. It may also influence investment patterns, as its ability to verify and track sustainable practices could attract more investments into sustainable projects, impacting capital flows in global markets.

In conclusion, blockchain's convergence with sustainability is a dynamic area with the potential for significant advancements in technology, policy, and economics. Despite challenges, the ongoing development of blockchain, supportive government policies, and its growing economic influence could advance global sustainability efforts.

4. Conclusion and Future Research Directions

This article offers an in-depth analysis of blockchain technology's potential to significantly contribute to sustainable development across environmental, economic, and social dimensions. It meticulously explores how BT can act as a transformative tool, addressing global sustainability challenges by enhancing transparency, promoting resource efficiency, and facilitating equitable economic growth.

One of the key topics discussed in this paper is how BT can serve as a powerful enabler for achieving sustainability goals by ensuring the traceability and authenticity of products, which is crucial for environmental stewardship and social justice. Through various applications, such as in supply chain management, renewable energy sectors, and conservation efforts, BT has the potential to reduce carbon emissions, improve resource allocation, and support sustainable business practices.

Furthermore, BT fosters a unique synergy among environmental, economic, and social dimensions by enabling transparent, secure, and efficient operations across various sectors. Its immutable ledger ensures the traceability of products, promoting environmental sustainability through the verification of ethical sourcing and waste reduction practices. Economically, blockchain reduces operational costs by streamlining transactions and eliminating intermediaries, while also providing financial inclusion for underserved populations through decentralized financial services. Socially, the technology enhances transparency and trust among consumers, businesses, and communities, supporting fair labor practices and equitable resource distribution. This multifaceted impact not only encourages responsible consumption and production but also empowers individuals and communities by democratizing access to resources and services. By addressing these pillars simultaneously, BT creates a holistic approach to sustainable development, aligning with global efforts to achieve the UN-SDGs. Its application across industries represents a transformative shift towards a more sustainable, equitable, and interconnected world, showcasing the potential of technology to resolve complex global challenges harmoniously.

The paper also highlights the importance of addressing the challenges and limitations associated with the implementation of BT for sustainable solutions, including concerns over scalability, energy consumption, and regulatory barriers. The authors emphasize the need for strategic recommendations and a comprehensive approach that balances the opportunities and obstacles of using BT in sustainability efforts.

In conclusion, this research underscores the transformative potential of BT in promoting sustainable development. It calls for a collaborative effort among stakeholders, including policymakers, practitioners, and researchers, to leverage BT effectively. By addressing the identified challenges and harnessing the capabilities of BT, there is a significant opportunity to advance towards a more sustainable, equitable, and environmentally friendly future. The findings of this paper contribute to both theoretical understanding and practical implementation of blockchain technology as a catalyst for sustainable development, offering guidance and insights for future research and policy-making in this evolving domain.

However, to fully harness the sustainability potential of blockchain, further technological advancements are necessary to address and minimize its environmental impact. In anticipation of future investigations, the forthcoming study must direct its attention toward a few crucial domains:

- Explore and advance blockchain technologies characterized by reduced energy consumption to address environmental issues related to energy efficiency.
- The establishment of regulatory frameworks is crucial for the effective governance of BT, ensuring its deployment is in line with global sustainability objectives. These frameworks encompass the development of comprehensive rules and regulatory guidelines.
- Investigate scaling solutions that may effectively manage higher transaction volumes while maintaining optimal levels of energy efficiency and security.
- Investigate the cross-sector applications of BT, with a specific focus on its potential contributions to sustainable practices in non-traditional industries such as agriculture, healthcare, and public governance.
- Evaluate the wider socio-economic implications of BT in facilitating sustainability, specifically examining its influence on market dynamics and global trade.
- Finally, the utilization of BT shows great potential in promoting sustainability objectives. However, it is crucial to exercise prudent oversight in its implementation to guarantee a favorable contribution to the overall ecosystem. Ongoing advancements in innovation, research, and policy formulation will play a crucial role in effectively leveraging this technology to achieve a more sustainable future.

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