Blockchain technology for ecological and environmental applications

Anuradha Yadav[1], Shivani Shivani[2,*], Vijaya Kittu Manda[3], Vikramaditya Sangwan[4], Anna Demkiv[5,*]

[1]REVA University, Bangalore, Karnataka, India
[2]Department of Higher Education, Haryana, India
[3]PBMEIT, Visakhapatnam, Andhra Pradesh, India
[4]National Institute of Technology, Kurukshetra, Haryana, India
[5]Department of Fire Prevention and Life Safety of the Civilian Population of the Institute of Public Administration and Research in Civil Protection, Kyiv, Ukraine

[*]Corresponding author e-mail: narwalshivani@gmail.com; tva-1958@ukr.net

Received: 22 April 2024 / Accepted: 21 July 2024

Abstract. This research study examines the use of Blockchain technology for ecological and environmental applications. The study presents a conceptual view aided by a literature survey to identify three major Blockchain themes connecting with the research topic - Transparency and Traceability, Conservation and Incentives, and Data Management and Monitoring. The goal of the study is to use the features offered by Blockchain Technology for sustainability, ecology, and environmental applications. As this research shows, technology can help in conservation and incentive practices such as conservation finance, tokenized rewards for ecosystem services, and rewards for sustainable practices. Blockchain has good data management and monitoring practices that can help secure environmental data, monitor various environmental parameters in real time, and provide a decentralized platform/infrastructure for environmental data analytics. Findings from this study can help environmental practitioners and researchers, research bodies, and Governmental agencies keen to use technology to preserve ecology and the environment and encourage sustainable practices.

Keywords: green technology, circularity, circular economy, traceability systems, wildlife trade

1. Introduction

Technology is a double-edged sword, offering advantages and disadvantages that can lead to creation or destruction. Blockchain is a type of Distributed Ledger Technology (DLT). DLT refers to a type of database (collection of data, say environmental parameters) that is shared across a network of computers. Blockchain was initially designed to simplify peer-to-peer financial payments but has later seen diversified applications in various fields. This study explores how Blockchain can positively change ecological and environmental applications.

The development of Blockchain in 2009 led to the Bitcoin revolution and later inspired newer forms of financial assets such as Cryptocurrencies and Non-Fungible Tokens (NFTs). NFTs are form of unique digital tokens that are issued for easy exchange with one another. Over time, new features were added to Blockchain, allowing it to expand its role from being a narrow cryptocurrency for use in financial service applications to more diverse and varied real-life applications. Its core features, such as Decentralization, Transparency and Immutability, Smart Contracts, Tokenization, Oracles, Interoperability, Rapid Settlement and Cost Reduction, and Privacy, bring above novel benefits to the applications built on top of it (Chalkias et al., 2024). These features can significantly help in environmental and ecological areas.

Blockchain technology has undergone four significant upgrades since its first development. The Blockchain 2.0 era, for example, incorporated the concept of Smart Contracts that allowed automatic execution of programs based on business agreements/logic. Blockchain 3.0 includes the concept of Distributed Applications (DApps). DApps are computer applications (such as software) that are run on a distributed network. Blockchain 4.0 begins working closely with other industry infrastructure-based ecosystems such as the Internet of Things (IoT) (Kryvenko et al., 2022). IoT is a technology put in small miniature devices to capture information from sensors, signals, amongst others. IoT is used in environment monitoring, precision agriculture, forest management, and wildlife conservation. Enhancements and advancements in Information and Communication Technologies (ICT) and modern disruption technologies can work hand-in-hand and can help improve ecology (Baimukhanbetova et al., 2020) and build a sustainable world (Frosch, 1995). ICTs can be used to address a wide range of environmental challenges, including climate change, water scarcity, and deforestation. For example, technologies such as computer vision, acoustic monitoring, radar, and molecular methods were found to protect insect ecology (Van Klink et al., 2022). Figure 1 shows that Blockchain Technology provides a cyber-resilient approach toward the EU Green Deal and UN Sustainable Development Goals.

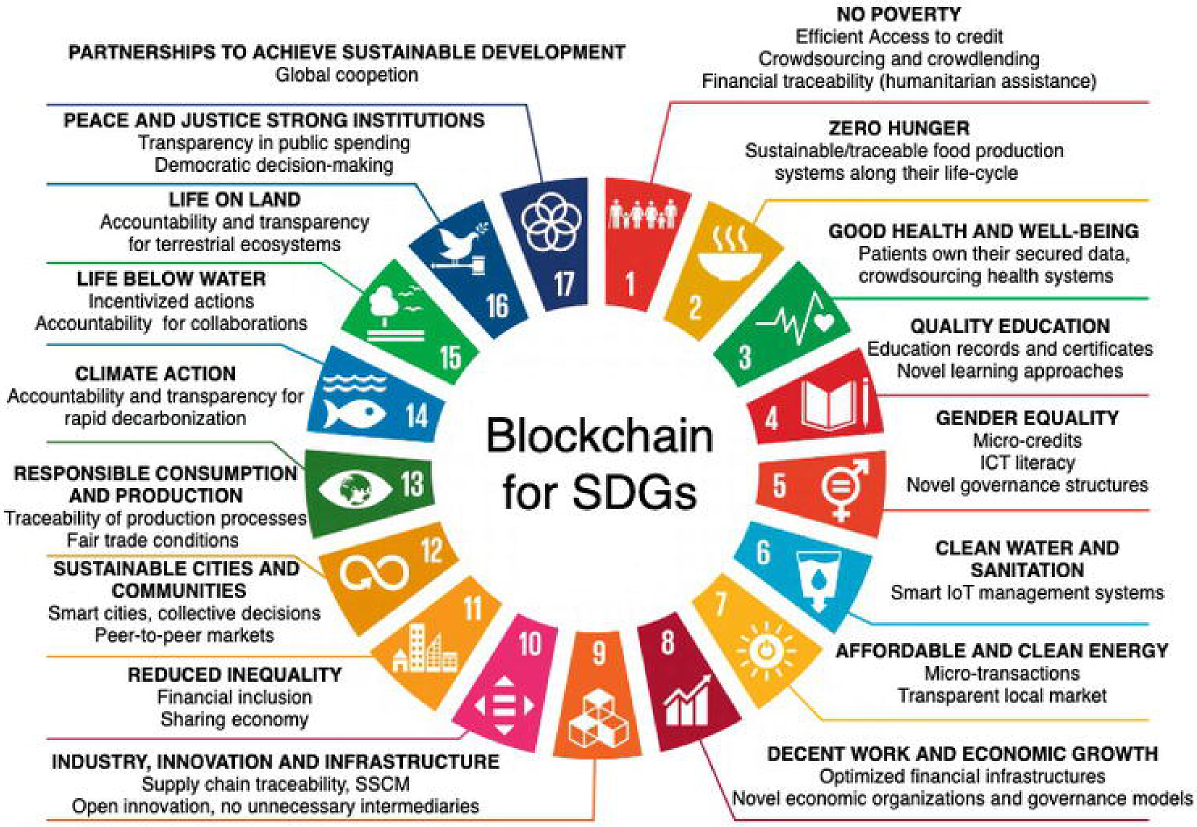

Figure 1. Blockchain use cases for SDGs. Source: (Fraga-Lamas & M. Fernández-Caramés, 2020)

2. Literature Study

Biodiversity loss and ecosystem collapse were assessed as the #3 risk among the ten risks faced in the next ten years, per a Statista survey. Blockchain is considered a technology for environmental sustainability because it facilitates various sub-systems, especially in smart cities, and as a drive for vertical and horizontal information sharing for sustainable innovation. For instance, it can help reduce waste and manage supply chains (Sousa et al., 2024). How Blockchain can revolutionize ecological conservation and management efforts and ultimately lead to more sustainable ecosystems is scantly covered in academic circles (Nazarov et al., 2023). Several research papers mentioned applications such as logistics and transportation showing economic and ecological benefits (Negueroles et al., 2024). Similarly, with Green Product Platforming (GPP), fundamental frameworks can be built to bring sustainability practices in the agri-food industry, resulting in production efficiency and digitally delivering diverse green products (Camel et al., 2024).

2.1. Literature Review Plan

The literature review followed conceptual review methodology to synthesize conceptual knowledge to understand the topic better. The literature review search was conducted using a keyword search for “blockchain sustainability applications,” “blockchain ecology applications,” and “blockchain environment applications.” The search was conducted mainly on Scopus and Web of Science. Authoritative published journal papers are searched for on Springer owing to the technical nature of the research. Considering the recency of the subject, only those works published between 2015 and 2024 are considered.

2.2. Research Gap

The literature review helps us identify the knowledge void gap (knowledge gap). This is because the desired research findings do not exist sufficiently. Hence, this study is conducted to bridge the knowledge void existing on the topic. By identifying and filling knowledge gaps, the researchers are attempting to contribute to advancing knowledge in the field of both Blockchain technology and in the areas of ecology and environment.

3. Materials & Methods

3.1. Research Objectives

The prime objective of this research study is to appraise how Blockchain can help in ecology and environmental applications.

3.2. Research Questions

Based on the research objectives, the following research questions are proposed to sharpen the study's focus:

1. Can Blockchain technology significantly improve transparency and traceability in environmental applications?
2. Does Blockchain facilitate adequate conservation finance and incentivize sustainable practices through tokenized rewards?
3. How effective is Blockchain in managing and monitoring environmental data in real time?

3.3. Significance of the study

Research on Blockchain technology holds significance for its potential to enhance ecological and environmental applications through increased transparency, data security, and incentive structures for conservation.

3.4. Research Method

This Qualitative study follows the Descriptive Research Method and uses a Literature Study approach to gain insights.

3.5. Data Collection

Secondary data is collected through a comprehensive literature review to identify existing knowledge and current trends in applying Blockchain technology for ecological and environmental applications. Various online databases were used to access journals and academic books to gain insights.

4. Results & Discussion

The study focuses on three major areas:

1. Transparency and Traceability
2. Conservation and Incentives
3. Data Management and Monitoring

Figure 2 summaries the key findings from this study

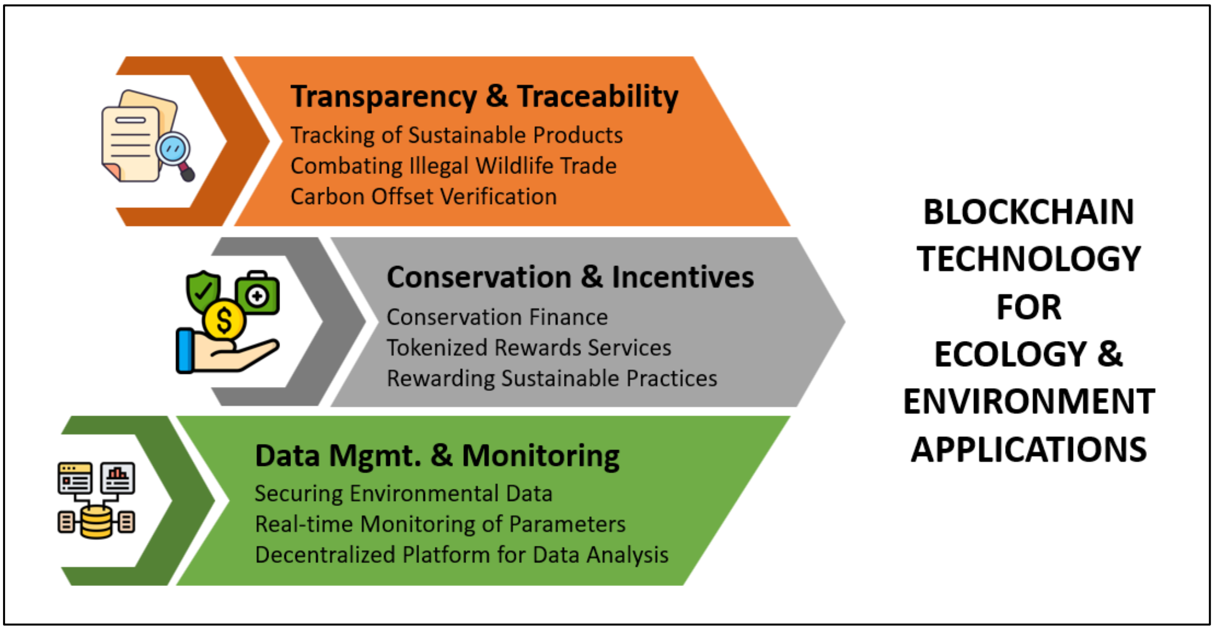

Figure 2. Blockchain Technology for Ecology & Environmental Applications

4.1. Transparency and Traceability

4.1.1. Blockchain-based Tracking of Sustainable Products

Blockchain can be used to track the origin and journey of materials in products, ensuring they meet sustainability standards throughout the supply chain in both marketplace mode and reselling modes (Dou et al., 2023). It can enhance the effectiveness of ecolabelling schemes (eco-labels) and better inform consumers of eco-labeled products' green benefits (Balzarova, 2021).

Several studies dealt with how Blockchain can help maintain a careful eco-balance in the clothing and textiles industry (Fohrer et al., 2024), wood and timber (Komdeur & Ingenbleek, 2021), organic honey (Lukovac et al., 2023), among others, primarily because of its strong global interconnectedness. Nordic fashion and design companies have kept traceability a pivotal consideration to maintain trust and accountability. Companies like BESTSELLER and H&M have incorporated transparent and traceable supply chains. Similarly, Minimum, a Danish fashion brand, created a capsule collection using blockchain-powered fiber-to-fiber recycling. Other companies like COS, Gina Tricot, Filippa K, Houdini, and Fjällräven focused on consumer-facing transparency, while others such as Wehlers, Empower.eco, and Vestre are increasing circularity and rethinking traditional practices. The Digital Product Passport (DPP) serves as a digital record documenting a product's lifecycle from inception to end-of-life. It thus plays a vital role in a product's pre-sale, post-sale, and post-life stages. (Nordic Blockchain Alliance, 2024). Blockchain can help integrate with other Industry 4.0 technologies and promote quality management practices, leading to the excellence of circular economy (Duong Thi Binh et al., 2024).

4.1.2. Combating Illegal Wildlife Trade with Blockchain

Wildlife trade involves trading in living or dead wild plants, animals, or fungi. While the wildlife trade has a long history, considering its endangerment of wildlife, it is either regulated or banned. However, the illegal wildlife trade remains a severe global problem and a challenge to stop (De Boer et al., 2021). Handling illicit wildlife trafficking remains a challenge for three reasons (Keskin et al., 2023):

1. Heterogeneous Products and Supply Chains (Ambiguity and International Cooperation)
2. Data (Hidden, Limited, Fragmented, and Tacit)
3. Limited Resources and Corruption
4. Agile Illicit Supply Chain Networks

Traffickers operate through opaque supply chains that disguise the origins of trafficked wildlife products. However, Blockchain technology offers promising potential to increase transparency and make illegal activities more difficult. As an immutable distributed ledger, Blockchain could provide a tamper-proof system to track wildlife components from source to final sale. All participants in the supply chain, from poachers to retailers, could be recorded on an open yet secure registry. This would allow regulators to identify bottlenecks and problematic actors more quickly.

However, there are also challenges to implementing such a system. Setting up the necessary infrastructure in remote wildlife areas may be technically and financially challenging. Not all communities may have access to computers or stable internet connections needed to participate. There is also the challenge of getting competing governments and organizations to agree on standards for interoperable blockchains. Poachers may also find ways to circumvent tracking by selling “off-grid.” While Blockchain shows potential, overcoming these obstacles would require substantial resources and coordination among multiple stakeholders over many years.

4.1.3. Carbon Offset Verification on a Blockchain

In recent decades, carbon emissions from various industries have received attention (Anwar et al., 2024). Blockchain has become a key technology solution for carbon markets. Often augmented with artificial intelligence and game theory in energy trading, the technology promises to help countries and companies achieve their net zero targets (Parhamfar et al., 2024). The effectiveness of carbon offset markets depends on the credibility of carbon credits, representing verified emission reductions. However, concerns exist regarding double counting and the true impact of offset projects. With its decentralized and immutable ledger, Blockchain technology offers a promising solution for transparent and verifiable carbon offset verification. Decentralization is spreading the authority over the network to multiple computer nodes instead of having a single centralized node (such as a server). This helps the system work democratically without any single point of authority. Such decentralized platforms do not have a single point of failure and are very stable. Immutability is a feature where information, once put on Blockchain, cannot be deleted or tampered with. Distributed Applications (dApps) are software applications and services that are run on a distributed computer system such as a Blockchain network. Several distributed applications (dApps) are now available in the energy sector. These applications make transactions more reliable by applying Blockchain technology to measure carbon emission rights (Kim & Huh, 2020).

The technology can help retailers and manufacturers to collaborate on establishing a Blockchain platform for sharing the manufacturer’s carbon footprint data. The platform plays a significant role in giving confidence to consumers so that they can perceive authentic green information without being influenced by greenwashing (Zhang et al., 2024).

Imagine a Blockchain-based system where project information, including location, methodology, and anticipated emission reductions, are recorded. Independent verification bodies could validate project activities and record the generated carbon credits on the same ledger. This creates a permanent, transparent record that is accessible to all stakeholders. When a public Blockchain is used, this audit process can happen in parallel without disturbing the organization’s routine activities.

Furthermore, Blockchain facilitates the tracking of individual carbon credits. Carbon credits are generated from carbon offset projects and purchased by polluting companies. Each credit could be assigned a unique identifier linked to the project that generated it. This ensures traceability throughout the trading process, preventing double counting and guaranteeing that retired credits represent genuine offsets (Hu et al., 2024). Smart contracts can be used to automate specific processes, such as automatic payment for purchases. Stakeholders can understand when they can expect the payments, and because the system makes the payment, there is enhanced transparency and a lower risk of fraudulent activity. Thus, smart contracts are critical to efficient resource and workflow management, such as in Robotic Process Automation (RPA) (Eggers et al., 2021). Figure 3 explains the steps in the Carbon Credits cycle on Blockchain.

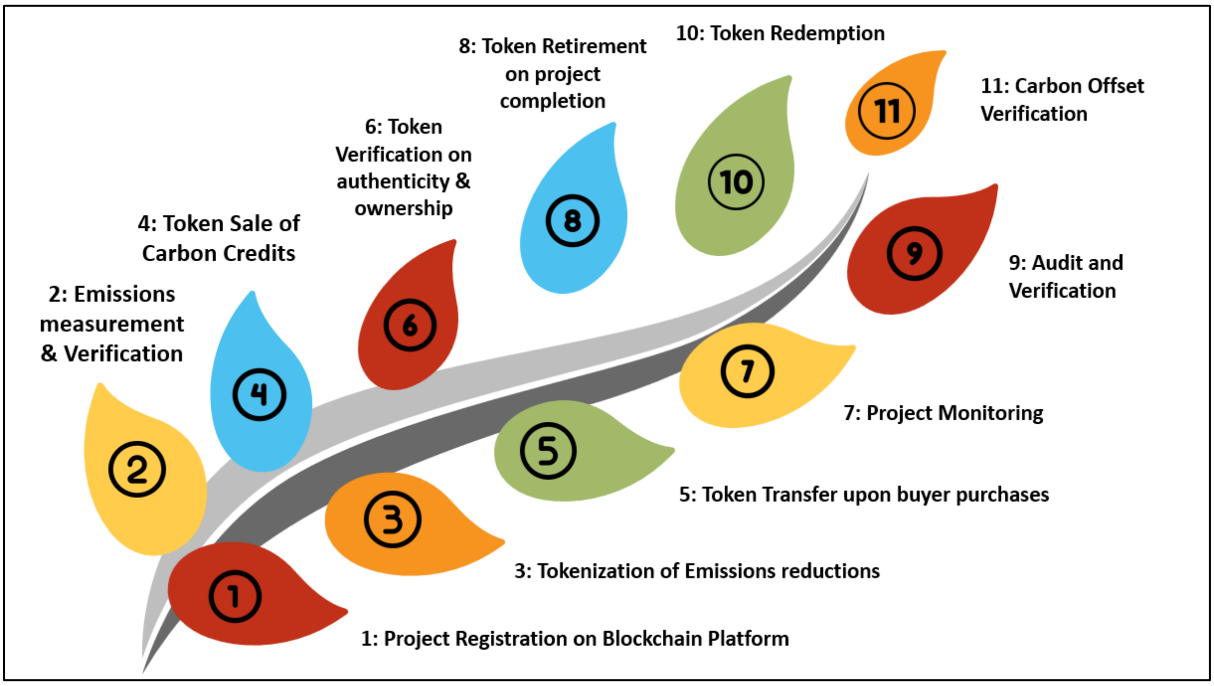

Figure 3. 11 Steps in the Carbon Credits Cycle on Blockchain

With the Industrial Internet of Things (IIoT) and reinforcement AI learning, Blockchain is found to help protect nature and reduce carbon footprint by nearly 5%, while improved algorithms such as Q-learning reduced carbon footprint by 7% (Whig et al., 2022).

However, implementing such a system faces challenges. Integrating existing carbon registries and verification bodies with Blockchain requires careful planning and collaboration. Additionally, ensuring robust data collection methodologies across geographically diverse projects is crucial. Finally, scalability remains a concern, as large-scale adoption necessitates efficient Blockchain infrastructure.

Despite these challenges, Blockchain's potential to revolutionize carbon offset verification is undeniable. By promoting transparency, traceability, and automation, this technology can play a pivotal role in ensuring the integrity of carbon markets and fostering trust in carbon offsetting as a viable climate change mitigation strategy.

4.2. Conservation and Incentives

4.2.1. Blockchain-powered Conservation Finance

Blockchain technology is promising to revolutionize conservation and green finance (Arslan et al., 2024) through decentralized crowdfunding models. By providing an open, transparent ledger, Blockchain allows micro-donations to be pooled towards specific ecosystem restoration or biodiversity protection projects. This broadens the donor base beyond large grants by enabling even small individual contributions to be tracked and allocated in a verifiable manner. Smart contracts further ensure funds are spent in the way they are outlined to supporters. By automating conditional payments, Blockchain supports 'results-based financing' approaches that release installments only after pre-defined impact milestones are achieved and verified. This performance-linked funding structure fosters accountable stewardship of resources. However, challenges remain in educating the public about complex decentralized finance applications and incentivizing smaller non-profits to embrace cryptocurrency platforms. However, superior algorithms with lower consensus delay and higher throughput, which can reduce network communication overhead and save system transmission energy consumption, are now becoming available as part of green technology offerings (Li, 2021).

Further, as a robust technology, the initial technical learning curve is a little high. Perhaps the technology will be accessible to those with a background in computer science, cryptography, and distributed systems. Still, Blockchain represents a good source for trying new funding sources at an accelerated scale.

Various climate finance experiments are envisioned, though there is an unanswered question of whether financial technology is being repositioned as climate technology exists. Various imaginaries share their views from social, technical, and political dimensions. Some recent developments owing to this are the emergence of climate finance Blockchain platforms, real-time accounting of emissions reductions, and decentralization by removing intermediaries (Campbell-Verduyn, 2023).

4.2.2. Tokenized Rewards for Ecosystem Services

Blockchain technologies can help make payments for performance approaches by using tokenized rewards for ecosystem services. Property owners and local stewards could earn cryptographic tokens for quantifiable conservation actions like reforestation, biodiversity protection, or lowering carbon emissions. These crypto credits representing verified natural capital accrual could then be exchanged for income, education, or healthcare benefits to empower communities as long-term sustainability partners. Smart contracts automate token distribution according to independently established environmental baselines and impact milestones. Tokenization thus shows potential to gamify conservation efforts at fine-grained local levels.

The major reason for the success of the Brazilian Amazon Bolsa Floresta Program (Standing Forest Program) is the Payment for Ecosystem Services (PES) model. PES incentivized the retention of standing forests to enhance climate and biodiversity benefits and helped about 9,500 families in the region. PES model was tested in several other geographies including in Australia (Sangha et al., 2024), Czech and Slovak Republic (Báliková & Šálka, 2022; Dobšinská et al., 2024), Vietnam (Gallemore et al., 2024), Ecuador (Joslin, 2023), Namibia (Heydinger et al., 2022), amongst others. It used a native tokenized currency in place of the traditional fiduciary currency. The project is considered a permanent offline Blockchain solution because only a few families have internet connectivity. The project has clear expansion plans to benefit more families and conservation units (Villares, 2021).

Startup projects such as “Single.Blockchain” came up with the idea of saving nature and forests by offering landowner profit for not harvesting the trees and using the forest as CO2 storage. The project successfully built a carbon refund marketplace for consumers interested in nature projection. It brought minting transparency by using the services of GitHub while acknowledging the risks involved in cryptos (Lappalainen, 2024). The system offers landowner profit for not harvesting the trees and using the forest as CO2 storage.

Fashion brands such as Soulland, Carlings, and Rotate, and fashion brands such as Simone Faurscho have used the NFT route to bridge the gap between physical and digital and benefited by opening revenue streams and embracing technology to meet the evolving demands of the digital universe (Nordic Blockchain Alliance, 2024).

4.2.3. Rewarding Sustainable Practices with Blockchain Incentives

Encouraging widespread adoption of sustainable practices remains a challenge. With its ability to create secure, transparent reward systems, Blockchain technology presents a novel approach to incentivizing individuals, businesses, and farmers.

Imagine a system where verifiable data on sustainable practices, such as improving recycling habits (Cervin & Carlsson, 2022), water conservation, or organic farming techniques, is recorded on a Blockchain. This data could be collected through sensors, satellite imagery, or on-site verification. Upon verification, participants would be rewarded with crypto tokens, a digital currency native to the Blockchain platform. Smart contracts can be used to make rewards automatically payable upon reaching targets.

Stakeholders, like farmers, can use the tokens to purchase sustainable equipment or access carbon credits. Businesses could utilize them for discounts on eco-friendly supplies or to offset their carbon footprint. Consumers incentivized to support sustainable practices could use tokens for product discounts with a proven sustainability record.

Implementing such a system necessitates collaboration between governments, Non-Governmental Organizations (NGOs), and private stakeholders to develop standardized data collection methods and ensure token value. Additionally, ensuring accessibility to the technology, particularly in rural areas, remains crucial. Existing research already showed how Blockchain technology can help in sustainability development (Shin et al., 2020), accounting practices (Kuruppu et al., 2022), accounting transparency (Teerlink, 2018), IT infrastructure operating cost and improving efficiency (Lee et al., 2023), data protection practices (Kurzadkar, 2020) and in various activities (Valand, 2019) for NGOs.

4.3. Data Management and Monitoring

Table 1 briefly lists some case studies on environmental projects that are powered by Blockchain technology.

Table 1: Case Studies Environmental projects that are powered by Blockchain

Project Name	**Blockchain Use Case**
Climate Chain Coalition	A global alliance of businesses, non-profits, and governments. Uses Blockchain technology in climate sector. They aim to develop standards, share best practices, and demonstrate the potential of Blockchain in addressing climate change.
Energy Web Foundation	Non-profit organization in energy sector. Blockchain is used to help companies develop projects in renewable energy, energy efficiency, and demand response.
Loom Network	Partnered with several companies to develop projects in the area of environmental monitoring and reporting.
VeChain	Platform for Supply Chain Management. Blockchain is used to help companies develop projects in the area of environmental sustainability.

Provenance	Provenance uses Blockchain in food traceability applications and has partnered with several companies to develop projects in sustainable agriculture.

4.3.1. Securing Environmental Data with Blockchain

Blockchain technology offers a promising solution for securing environmental data by providing a decentralized and transparent platform for storing and sharing information. Studies have already shown how Blockchain can help in data processes and display digital resilience in biodiversity conservation (Chalkias et al., 2024).

The critical feature of Blockchain is its immutability, which ensures that once data is recorded, it cannot be altered or tampered with. This characteristic is precious in environmental data, where accuracy and integrity are paramount. By leveraging Blockchain, stakeholders can have confidence in the authenticity of the information, leading to increased trust and collaboration in environmental initiatives. Blockchain uses advanced encryption techniques (such as AES and other algorithms) to enhance data security, protecting sensitive environmental information from unauthorized access. Organizations such as the World Economic Forum (WEF), the United Nations Environment Programme (UNEP), and journals such as Nature Communications can benefit from such an infrastructure.

With computer vision, machine learning, and IoT sensors, Blockchain can help check and secure natural life creatures like tigers (Vishwas et al., 2022).

Blockchain can help in transparent resourcing for marine conservation, reducing pollution from plastics, reducing slavery at sea, managing sustainable fisheries, and helping in seafood traceability (Yang et al., 2024) and other fishery products (Jaya et al., 2021). It can thus help build trust and equity in marine conservation and fisheries' supply chain management. The technology can help build and maintain trust in conservation charities and related organizations (Howson, 2020). Organizations such as governments and public and private institutions can use blockchain-based systems to disseminate environmental compliance data. The network works like a public register, has improved data management, and allows for faster data-sharing capabilities (Allena, 2020).

4.3.2. Real-time Monitoring of Environmental Parameters using Blockchain

Periodic emergencies (Dolchinkov, 2024), systematic and burst pollution of environmental components (Sawicka et al., 2023; Omoyajowo et al., 2024; Tang et al., 2024), the spread of epidemics (El Morabet et al., 2023; Ali et al., 2024), all this needs careful monitoring for a prompt response. Real-time monitoring of environmental parameters using Blockchain technology presents a promising avenue for enhancing the integrity and reliability of environmental data collection and management. Blockchain, a distributed ledger technology, offers immutable and transparent record-keeping capabilities, making it particularly suitable for ensuring the integrity of environmental data. By leveraging Blockchain, environmental monitoring systems can establish tamper-proof data collection records from various sensors deployed across ecosystems.

One significant application of Blockchain in environmental monitoring is tracking pollution levels. Through blockchain-enabled systems, air and water quality sensor data can be securely recorded and timestamped, preventing unauthorized alterations or manipulations. Similarly, Blockchain technology can aid in monitoring deforestation by creating an auditable trail of data related to forest cover changes captured by satellite imagery or ground-based sensors. The captured data can be stored by encrypting it with superior data security models that can effectively reduce the block nodes' computation, communication, and storage overhead (Zhao et al., 2022). Figure 4 shows the steps involved in using Blockchain technology for environmental monitoring.

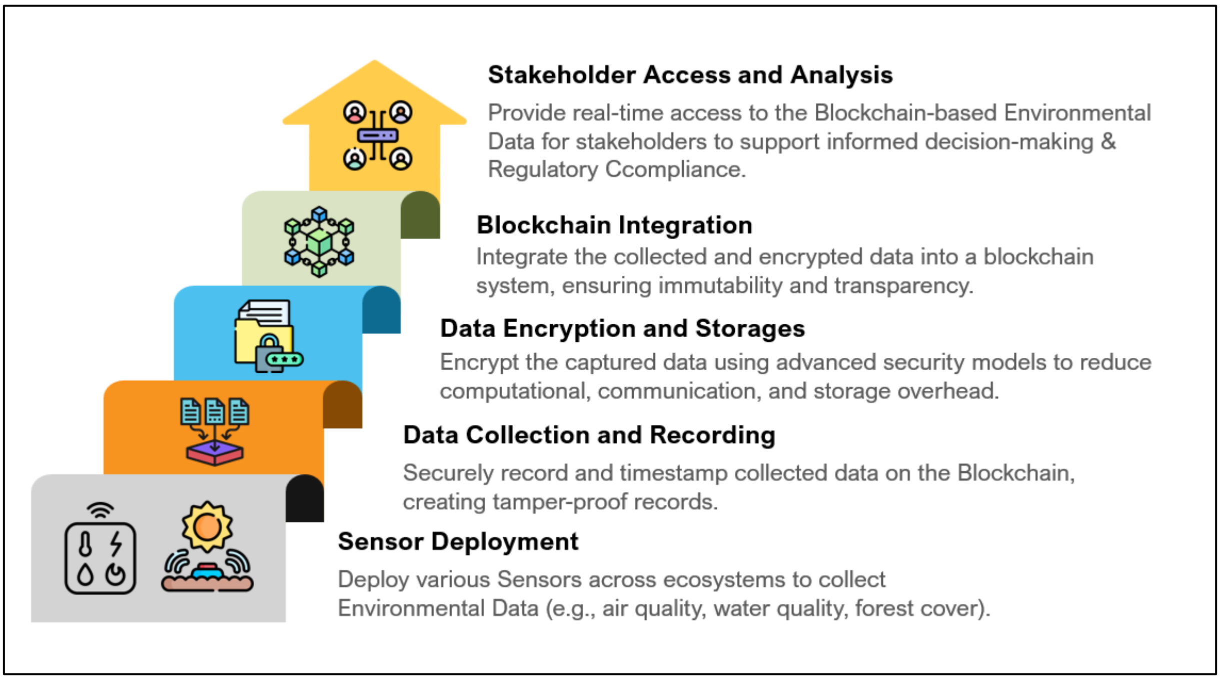

Figure 4. Blockchain technology for environmental monitoring

Blockchain-based environmental monitoring systems can facilitate greater transparency and accountability in regulatory compliance efforts. Stakeholders, including governmental bodies, environmental agencies, and the public, can access real-time, trustworthy information about environmental parameters, fostering more informed decision-making and promoting sustainable practices.

4.3.3. Decentralized Platform for Environmental Data Analysis

Due to siloed data ownership, transparency concerns, and limited collaboration, environmental research and decision-making often face challenges. With its core principles of decentralization, immutability, and traceability, Blockchain technology presents a unique opportunity to address these issues.

A decentralized platform for environmental data analysis powered by Blockchain could revolutionize data sharing and collaborative research. Data collected from various sources, such as sensor networks, satellites, and research institutions, could be securely stored on a distributed ledger. This would ensure transparency and prevent data manipulation.

The platform can use smart contracts to self-execute agreements, govern data access, and incentivize data sharing. Researchers and stakeholders could contribute data sets while maintaining ownership and control over access rights. This would foster collaboration and enable researchers from diverse backgrounds to work on common environmental challenges.

The platform could facilitate real-time data analysis by enabling secure and efficient computation on a distributed network. This would improve the timeliness and accuracy of environmental insights. By democratizing access to environmental data and fostering collaboration, a decentralized platform powered by Blockchain has the potential to enhance environmental research and decision-making significantly.

4.4. Research Implications

The study gains importance considering the importance of using technology to build sustainable practices to protect and conserve the environment and ecology. The study draws practical implications because Blockchain is a technology that can attract practical implementations. The study also draws academic implications for explaining the research themes related to the topic and identifying potential future agendas.

4.5. Limitations of the Study

Based on the study as presented, there are indeed some potential limitations that requires a mention:

1. **Scope limitation**: The study focuses primarily on literature review and conceptual analysis, without including empirical data or case studies. This limits the ability to validate the proposed applications in real-world settings.

2. **Technological focus**: The research emphasizes only on Blockchain technology. There is a potential overlooking other technological solutions or non-technological approaches to environmental challenges.
3. **Limited stakeholder perspective**: The study is limited in capturing inputs from stakeholders. Some potential stakeholders can be environmental practitioners, policymakers, or communities affected by environmental issues. These stakeholders can provide valuable practical insights.
4. **Interdisciplinary gaps**: Environmental studies generally touch on various fields, it may not fully integrate perspectives from environmental science, economics, and policy studies.

5. Future Research Agenda

Although Blockchain technology alone cannot address the core causes of environmental degradation, its potential for promoting a neoliberal approach to environmental governance, characterized by increased commoditization, global accounting, surveillance, and marketization of environmental resources, warrants further investigation within the context of environmental policymaking (Stuit et al., 2022).

Some researchers believe Blockchain is too advanced technology for present mainstream customers and requires Governmental support to be more trustworthy (Lappalainen, 2024). For example, several industries, such as textiles and clothing, report low levels of digitalization and linkages in their ecosystem for technologies like Blockchain to be made applicable (Fohrer et al., 2024). Stakeholders should be made aware of the availability of such a technology to address customers' quality and security concerns, such as in the case of agricultural products.

Technology such as Blockchain is necessary to promote convergence with other technologies, artificial intelligence (AI), robotics, biotechnology, and the Internet of Things, paving the way for the Internet of Everything (IoE) to help build sustainable and precision agriculture called Smart Agriculture. Blockchain can add value to smart agriculture practices by bringing in agriculture finance, supply chain management, livestock management, food safety, farm inventory, and land registration (Babar & Akan, 2024). Several use cases in this regard are already available. European Union policies pair digitalization with sustainability. Firms should introspect their capabilities and vision accordingly (Myshko et al., 2024).

Other technologies like the Metaverse can offer immersive engagement, improve customer experiences, encourage environment-conscious behaviors, and encourage sustainability practices, thereby revolutionizing the food industry (Kulova et al., 2024).

6. Conclusion

In conclusion, this research underscores the transformative potential of Blockchain technology in addressing ecological and environmental challenges. Through enhancing transparency, traceability, and data management, Blockchain offers innovative solutions to combat illegal wildlife trade, verify carbon offsets, and incentivize sustainable practices. Its role in conservation finance, tokenized rewards for ecosystem services, and rewarding sustainable practices with Blockchain incentives demonstrates its capacity to foster a more sustainable and equitable world. Moreover, Blockchain's ability to secure environmental data and facilitate real-time monitoring of environmental parameters presents a robust platform for environmental data analytics. This study's findings contribute to the academic discourse on the intersection of technology and environmental sustainability and provide practical insights for environmental practitioners, researchers, and policymakers. As Blockchain technology continues to evolve, its environmental conservation and management applications are poised to expand, offering a promising avenue for achieving sustainable development goals and preserving our planet for future generations.

References

Ali, N., Kausar, A., Vambol, S., Kozub, P., Kozub, S., & Hrynzovskyi, A.(2024). Environmental retrieval during COVID-19 lockdown in the megacity Karachi, Pakistan. *Ecological Questions*, 35(3), 1-16. https://doi.org/10.12775/EQ.2024.032.

Allena, M. (2020). Blockchain Technology for Environmental Compliance. *Environmental Law / Lewis & Clark Law School*, *50*(4), 1055–1103.

Anwar, M., Tasir Khan, F. M., Zamir Ali, F. A., & Ullah, W. (2024). Analyzing the relationship between energy use for economic development and CO2 emissions, crop, and livestock production in Pakistan by using the extended STIRPAT model. *Trends in Ecological and Indoor Environmental Engineering*, 2(1), 1-10. https://doi.org/10.62622/TEIEE.024.2.1.01-10.

Arslan, M., Faizulayev, A., Abeuova, D., & Kayani, U. N. (2024). Exploring the Risks, Challenges, and Opportunities of Using Digital Financial Technologies for Green Finance: In A. Alqatan, K. Hussainey, M. Hamed, & K. Benameur (Eds.), *Advances in Finance, Accounting, and Economics* (pp. 226–242). IGI Global. https://doi.org/10.4018/979-8-3693-1678-8.ch010

Babar, A. Z., & Akan, O. B. (2024). *Sustainable and Precision Agriculture with the Internet of Everything (IoE)* (arXiv:2404.06341). arXiv. http://arxiv.org/abs/2404.06341

Baimukhanbetova, E., Onaltayev, D., Daumova, G., Amralinova, B., & Amangeldiyev, A. (2020). Improvement of informational technologies in ecology. *E3S Web of Conferences*, *159*, 01008. https://doi.org/10.1051/e3sconf/202015901008

Báliková, K., & Šálka, J. (2022). Are silvicultural subsidies an effective payment for ecosystem services in Slovakia? *Land Use Policy*, *116*, 106056. https://doi.org/10.1016/j.landusepol.2022.106056

Balzarova, M. A. (2021). Blockchain technology – a new era of ecolabelling schemes? *Corporate Governance: The International Journal of Business in Society*, *21*(1), 159–174. https://doi.org/10.1108/CG-08-2020-0328

Camel, A., Belhadi, A., Kamble, S., Tiwari, S., & Touriki, F. E. (2024). Integrating Smart Green Product Platforming for Carbon Footprint Reduction: The Role of Blockchain Technology and Stakeholders Influence within the Agri-Food Supply Chain. *International Journal of Production Economics*, 109251. https://doi.org/10.1016/j.ijpe.2024.109251

Campbell-Verduyn, M. (2023). Conjuring a cooler world? Imaginaries of Improvement in Blockchain Climate Finance Experiments. *Environment and Planning C: Politics and Space*, 239965442311628. https://doi.org/10.1177/23996544231162858

Cervin, W., & Carlsson, L. (2022). *Decentralized Rewards for incentivising recycling using Blockchain Technology* [Bachelor of Science Independent Project, Kristianstad Universit]. https://researchportal.hkr.se/files/63813985/FinalThesis-Carlsson-Cervin-3.pdf

Chalkias, K. K., Kostis, A., Alnuaimi, A., Knez, P., Naulty, J., Salmasi, A., Servatius, R., & Veloso, R. (2024). *Preserving Nature's Ledger: Blockchains in Biodiversity Conservation* (arXiv:2404.12086). arXiv. http://arxiv.org/abs/2404.12086

De Boer, H., Rydmark, M. O., Verstraete, B., & Gravendeel, B. (2021). *Molecular identification of plants: From sequence to species*. Pensoft Publishers. https://doi.org/10.3897/ab.e98875

Dobšinská, Z., Báliková, K., Jarský, V., Hríb, M., Štifil, R., & Šálka, J. (2024). Evaluation analysis of the compensation payments schemes for ecosystem services: The case of Czech and Slovak Republic. *Forest Policy and Economics*, *163*, 103202. https://doi.org/10.1016/j.forpol.2024.103202

Dolchinkov, N. T. (2024). Natural Emergencies and Some Causes of Their Occurrence: a Review. *Trends in Ecological and Indoor Environment Engineering*, 2(1), 18–27. https://doi.org/10.62622/TEIEE.024.2.1.18-27.

Dou, G., Ma, L., Wei, K., & Zhang, Q. (2023). Coordination of a Supply Chain with an Online Platform Considering Green Technology in the Blockchain Era. In G. Dou, L. Ma, K. Wei, & Q. Zhang, *Operations Management for Environmental Sustainability* (pp. 123–148). Springer International Publishing. https://doi.org/10.1007/978-3-031-37600-9_6

Duong Thi Binh, A., Akbari, M., Le Thi Cam, H., Nguyen Canh, L., & Truong Quang, H. (2024). Forging Pathways to Circular Economy Excellence: Integrating Industry 4.0 with Quality Management. *Sustainability*, *16*(7), 3053. https://doi.org/10.3390/su16073053

Eggers, J., Hein, A., Weking, J., Böhm, M., & Krcmar, H. (2021). *Process Automation on the Blockchain: An Exploratory Case Study on Smart Contracts*. Hawaii International Conference on System Sciences. https://doi.org/10.24251/HICSS.2021.681

El Morabet, R., Khan, R. A., Alsubih, M., Khan, N. A., Yusuf, M., Khan, P., ... & Lutsak, O. (2023). Epidemiology study of Diarrhoea, Cholera, Typhoid, Hepatitis A and Hepatitis E in Middle East and North Africa Region. *Ecological Questions*, 34(4), 1-21. https://doi.org/10.12775/EQ.2023.044.

Fohrer, N., Gade, A., & Muschkiet, M. (2024). Digitalization in logistics for textiles – possible fields of application for the Blockchain technology. *Communications in Development and Assembling of Textile Products*, *5*(1), 38–47. https://doi.org/10.25367/cdatp.2024.5.p38-47

Fraga-Lamas, P., & M. Fernández-Caramés, T. (2020). Leveraging Blockchain for Sustainability and Open Innovation: A Cyber-Resilient Approach toward EU Green

Deal and UN Sustainable Development Goals. In C. Thomas, P. Fraga-Lamas, & T. M. Fernández-Caramés (Eds.), *Computer Security Threats*. IntechOpen. https://doi.org/10.5772/intechopen.92371

Frosch, R. A. (1995). Industrial Ecology: Adapting Technology for a Sustainable World. *Environment: Science and Policy for Sustainable Development*, *37*(10), 17–37. https://doi.org/10.1080/00139157.1995.9930966

Gallemore, C., Pham, T. T., Hamilton, M., & Munroe, D. K. (2024). Vietnam's Payments for Forest Ecosystem Services scheme's puzzling role in protecting longstanding forests as deforestation rates rise. *Ecological Economics*, *217*, 108078. https://doi.org/10.1016/j.ecolecon.2023.108078

Heydinger, J., Diggle, R., Stuart-Hill, G., Dierkes, K., & Packer, C. (2022). Differentiated payments for ecosystem services based on estimated prey consumption by lions within communal conservancies in northwest Namibia. *Ecosystem Services*, *53*, 101403. https://doi.org/10.1016/j.ecoser.2021.101403

Howson, P. (2020). Building trust and equity in marine conservation and fisheries supply chain management with Blockchain. *Marine Policy*, *115*, 103873. https://doi.org/10.1016/j.marpol.2020.103873

Hu, Y., McFarlane, A., & Hussain, F. (2024). CarbonApp: Blockchain Enabled Carbon Offset Project Management. In L. Barolli (Ed.), *Advanced Information Networking and Applications* (Vol. 202, pp. 13–25). Springer Nature Switzerland. https://doi.org/10.1007/978-3-031-57916-5_2

Jaya, E. A., Candra, M. Z. C., & Ferindra, T. D. (2021). Development of Blockchain-Based Traceability System for Fishery Products. *2021 International Conference on Data and Software Engineering (ICoDSE)*, 1–6. https://doi.org/10.1109/ICoDSE53690.2021.9648448

Joslin, A. (2023). Struggles for recognitional justice through payments for ecosystem services contracts in Ecuador's Andes. *Geoforum*, *145*, 103832. https://doi.org/10.1016/j.geoforum.2023.103832

Keskin, B. B., Griffin, E. C., Prell, J. O., Dilkina, B., Ferber, A., MacDonald, J., Hilend, R., Griffis, S., & Gore, M. L. (2023). Quantitative Investigation of Wildlife Trafficking Supply Chains: A Review. *Omega*, *115*, 102780. https://doi.org/10.1016/j.omega.2022.102780

Kim, S.-K., & Huh, J.-H. (2020). Blockchain of Carbon Trading for UN Sustainable Development Goals. *Sustainability*, *12*(10), 4021. https://doi.org/10.3390/su12104021

Komdeur, E. F. M., & Ingenbleek, P. T. M. (2021). The potential of blockchain technology in the procurement of sustainable timber products. *International Wood Products Journal*, *12*(4), 249–257. https://doi.org/10.1080/20426445.2021.1967624

Kryvenko, I., Hrynzovskyi, A., & Chalyy, K. (2022, June). The internet of medical things in the patient-centered digital clinic's ecosystem. In International Scientific-Practical Conference" Information Technology for Education, Science and Technics" (pp. 515-529). Cham: *Springer Nature Switzerland*. https://doi.org/10.1007/978-3-031-35467-0_31

Kulova, I., Nikolova-Alexieva, V., & Paskalev, R. (2024). The metaverse and sustainability as drivers revolutionizing customer experience in the food industry. *BIO Web of Conferences*, *102*, 04009. https://doi.org/10.1051/bioconf/202410204009

Kuruppu, S. C., Dissanayake, D., & De Villiers, C. (2022). How can NGO accountability practices be improved with technologies such as Blockchain and triple-entry accounting? *Accounting, Auditing & Accountability Journal*, *35*(7), 1714–1742. https://doi.org/10.1108/AAAJ-10-2020-4972

Kurzadkar, Prof. S. (2020). NGO Data Protection using Ethereum Blockchain Technology. *International Journal for Research in Applied Science and Engineering Technology*, *8*(12), 407–412. https://doi.org/10.22214/ijraset.2020.32492

Lappalainen, J. (2024). *The opportunities intangible assets generate for forest management: A case study of a service company from a disruptive innovation perspective* [Master's Programme in Industrial Management and Innovation, Faculty of Technology, Uppsala Universitet]. https://www.diva-portal.org/smash/get/diva2:1845373/FULLTEXT01.pdf

Lee, M., Lee, S., Lee, H., & Gim, G. (2023). A Study on the Application of Blockchain Technology in Non-governmental Organizations. In R. Lee (Ed.), *Software Engineering, Artificial Intelligence, Networking and Parallel/Distributed Computing* (Vol. 1074, pp. 121–133). Springer International Publishing. https://doi.org/10.1007/978-3-031-19604-1_9

Li, D. (2021). Green technology innovation path based on blockchain algorithm. *Sustainable Computing: Informatics and Systems*, *31*, 100587. https://doi.org/10.1016/j.suscom.2021.100587

Lukovac, P., Miletić, A., & Radenković, B. (2023). A System for Tracking Organic Honey Production Using Blockchain Technologies. In M. Mihić, S. Jednak, & G. Savić (Eds.), *Sustainable Business Management and Digital Transformation: Challenges and Opportunities in the Post-COVID Era* (Vol. 562, pp. 239–254). Springer International Publishing. https://doi.org/10.1007/978-3-031-18645-5_15

Myshko, A., Checchinato, F., Colapinto, C., Finotto, V., & Mauracher, C. (2024). Towards the twin transition in the agri-food sector? Framing the current debate on sustainability and digitalisation. *Journal of Cleaner Production*, *452*, 142063. https://doi.org/10.1016/j.jclepro.2024.142063

Nazarov, D., Sulimin, V., & Shvedov, V. (2023). Blockchain technology: A novel approach to enhance ecology conservation and management. *E3S Web of Conferences*, *419*, 03008. https://doi.org/10.1051/e3sconf/202341903008

Negueroles, S. C., Simón, R. R., Julián, M., Belsa, A., Lacalle, I., S-Julián, R., & Palau, C. E. (2024). A Blockchain-based Digital Twin for IoT deployments in logistics and transportation. *Future Generation Computer Systems*, S0167739X24001407. https://doi.org/10.1016/j.future.2024.04.011

Nordic Blockchain Alliance. (2024). *Nordic Blockchain Guide—For the fashion, furniture and design industries*. Nordic Innovation. https://www.diva-portal.org/smash/get/diva2:1850561/FULLTEXT01.pdf

Omoyajowo, K. O., Adewunmi, M. A., Omoyajowo, K. A., Ogunyebi, A. L., Njoku, K. L., Makengo, B. M., Babalola, O. O., & Ojo-Emmanuel, G. (2024). Transitioning to a Climate-Resilient Society: Empirical Evidence on What Drives the Adoption of Green Computing Policies in Nigerian Organisations. *Trends in Ecological and Indoor Environment Engineering*, 2(1), 28–34. https://doi.org/10.62622/TEIEE.024.2.1.28-34.

Parhamfar, M., Sadeghkhani, I., & Adeli, A. M. (2024). Towards the net zero carbon future: A review of blockchain-enabled peer-to-peer carbon trading. *Energy Science & Engineering*, *12*(3), 1242–1264. https://doi.org/10.1002/ese3.1697

Sangha, K. K., Ahammad, R., Russell-Smith, J., & Costanza, R. (2024). Payments for Ecosystem Services opportunities for emerging Nature-based Solutions: Integrating Indigenous perspectives from Australia. *Ecosystem Services*, *66*, 101600. https://doi.org/10.1016/j.ecoser.2024.101600

Sawicka, B., Krochmal-Marczak, B., Sawicki, J., Skiba, D., Pszczółkowski, P., Barbaś, P., ... & Farhan, A. K. (2023). White Clover (Trifolium repens L.) Cultivation as a Means

of Soil Regeneration and Pursuit of a Sustainable Food System Model. *Land*, 12(4), 838. https://doi.org/10.3390/land12040838.
Shin, E.-J., Kang, H.-G., & Bae, K. (2020). A Study on the Sustainable Development of NPOs with Blockchain Technology. *Sustainability*, *12*(15), 6158. https://doi.org/10.3390/su12156158
Sousa, M. J., Workneh, T. C., & Holtskog, H. (Eds.). (2024). *Blockchain as a technology for environmental sustainability* (First edition). CRC Press.
Stuit, A., Brockington, D., & Corbera, E. (2022). Smart, Commodified and Encoded: Blockchain Technology for Environmental Sustainability and Nature Conservation. *Conservation and Society*, *20*(1), 12. https://doi.org/10.4103/cs.cs_41_21
Tang, B., Zhang, L., Salam, M., Yang, B., He, Q., Yang, Y., & Li, H. (2024). Revealing the environmental hazard posed by biodegradable microplastics in aquatic ecosystems: An investigation of polylactic acid's effects on Microcystis aeruginosa. *Environmental Pollution*, 344, 123347. https://doi.org/10.1016/j.envpol.2024.123347.
Teerlink, M. (2018). *Creating Transparency and Accountability in Non-governmental Organisations Using Blockchain Technology* [Master Business Informatics, Utrecht University]. https://studenttheses.uu.nl/handle/20.500.12932/32674
Valand, R. B. (2019). Block-Chain Technology and its Application in NGO. *International Journal for Research in Applied Science and Engineering Technology*, *7*(12), 822–826. https://doi.org/10.22214/ijraset.2019.12132
Van Klink, R., August, T., Bas, Y., Bodesheim, P., Bonn, A., Fossøy, F., Høye, T. T., Jongejans, E., Menz, M. H. M., Miraldo, A., Roslin, T., Roy, H. E., Ruczyński, I., Schigel, D., Schäffler, L., Sheard, J. K., Svenningsen, C., Tschan, G. F., Wäldchen, J., … Bowler, D. E. (2022). Emerging technologies revolutionise insect ecology and monitoring. *Trends in Ecology & Evolution*, *37*(10), 872–885. https://doi.org/10.1016/j.tree.2022.06.001
Villares, L. (2021). Blockchain and Conservation: Why Does It Matter: Applications in Payments for Ecosystem Services and Bolsa Floresta Program. In L. Pereira, J. R. H. Carvalho, P. Krus, M. Klofsten, & V. J. De Negri (Eds.), *Proceedings of IDEAS 2019* (Vol. 198, pp. 346–355). Springer International Publishing. https://doi.org/10.1007/978-3-030-55374-6_34
Vishwas, D. B., Gowtham, M., Ajay, A. V., Raghavendra, K., Ravi, V., & Goundar, S. (2022). Blockchain-Based Secure Method for Tiger Detection Using Machine Learning. In H. L. Gururaj, V. Ravi Kumar, S. Goundar, A. A. Elngar, & B. H. Swathi (Eds.), *Convergence of Internet of Things and Blockchain Technologies* (pp. 221–242). Springer International Publishing. https://doi.org/10.1007/978-3-030-76216-2_14
Whig, P., Velu, A., & Bhatia, A. B. (2022). Protect Nature and Reduce the Carbon Footprint With an Application of Blockchain for IIoT: In S. Kautish & G. Dhiman (Eds.), *Advances in Computational Intelligence and Robotics* (pp. 123–142). IGI Global. https://doi.org/10.4018/978-1-6684-3733-9.ch007
Yang, H., He, S., Feng, Q., Xia, S., Zhou, Q., Wu, Z., & Zhang, Y. (2024). Navigating the depths of seafood authentication: Technologies, regulations, and future prospects. *Measurement: Food*, *14*, 100165. https://doi.org/10.1016/j.meafoo.2024.100165
Zhang, S., Liu, W., Hou, P., & Haiteng, M. (2024). *Carbon Footprint Information Sharing with Blockchain Technology Implement*. https://doi.org/10.2139/ssrn.4765201
Zhao, M., Liu, W., & He, K. (2022). Research on Data Security Model of Environmental Monitoring Based on Blockchain. *IEEE Access*, *10*, 120168–120180. https://doi.org/10.1109/ACCESS.2022.3221109