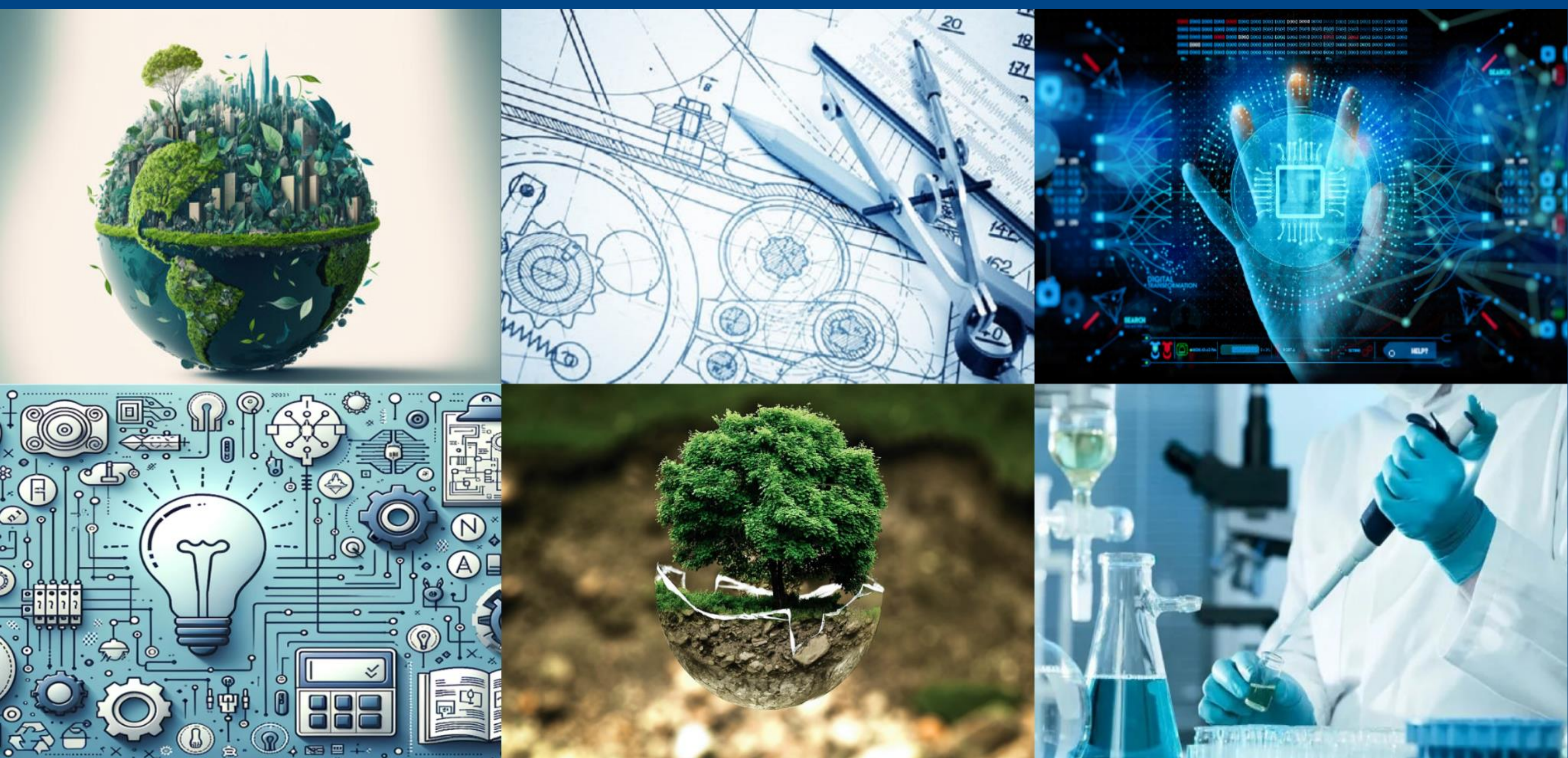
ISSN: 2582-7219

International Journal of Multidisciplinary Research in Science, Engineering and Technology

(A Monthly, Peer Reviewed, Refereed, Scholarly Indexed, Open Access Journal)



Impact Factor: 8.206

Volume 8, Issue 4, April 2025

www.ijmrset.com ijmrset@gmail.com +91 6381 907 438 +91 63819 07438

© 2025 IJMRSET | Volume 8, Issue 4, April 2025 | DOI:10.15680/IJMRSET.2025.0804381

ISSN: 2582-7219 | www.ijmrset.com | Impact Factor: 8.206| ESTD Year: 2018|

International Journal of Multidisciplinary Research in Science, Engineering and Technology (IJMRSET)

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Green Block chain: Sustainable Practices for a Decentralized Future

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ABSTRACT: The growing global imperative for sustainable development necessitates the exploration of innovative technological solutions. This review paper delves into the burgeoning field of "Green Blockchain," investigating its potential to foster sustainable practices within decentralized systems. By synthesizing insights from recent literature, this paper examines how blockchain technology can be adapted and implemented to minimize its environmental impact and actively contribute to ecological and social sustainability. We explore the core tenets of green blockchain, analyze its diverse applications in areas such as renewable energy trading, carbon emissions management and sustainable supply chains, discuss the methodologies employed in current research and outline future research directions for this critical area.

KEYWORDS: Green Blockchain, Sustainability, Decentralization, Renewable Energy, Carbon Trading, Sustainable Supply Chains, Environmental Impact.

I. INTRODUCTION

The pressing need to address climate change and achieve the Sustainable Development Goals (SDGs) has spurred significant research into the role of emerging technologies [1]. Among these, blockchain technology has emerged as a powerful tool with the potential to transform various industries through its decentralized, transparent and immutable nature. However, the high energy consumption associated with certain blockchain consensus mechanisms has raised concerns regarding its environmental sustainability, necessitating the development of more eco-friendly approaches [5]. This has led to the rise of "Green Blockchain," a paradigm focused on deploying blockchain technologies in a manner that minimizes their ecological footprint and actively supports sustainability objectives [3]. This review aims to provide a comprehensive analysis of the current research landscape on green blockchain, exploring its fundamental principles, diverse applications across sustainability domains, methodological approaches employed in the literature and its potential to shape a decentralized and sustainable future [6]. By integrating findings from recent studies [2], this paper seeks to consolidate existing knowledge and identify key avenues for future research and development.

II. LITERATURE REVIEW

The intersection of blockchain technology and sustainability has garnered increasing attention in academic literature [6]. One study [2] specifically investigated the application of blockchain in facilitating transparent and efficient trading within green energy systems. Another study [5] offers a broader definition of "Green Blockchain" as the adoption of environmentally conscious blockchain protocols and practices to support sustainability goals. One paper [1] highlights the synergistic role of AI, blockchain and IoT in achieving sustainable development, implicitly positioning green blockchain as a vital enabler. Another study [4]

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focused on blockchain's potential as a decentralized communication tool to enhance transparency and trust in sustainable development initiatives. One paper [3] proposes a vision of a "Green Web 3.0," where sustainable blockchain infrastructure underpins decentralized AI and edge intelligence for industrial sustainability. Another study [7] specifically reviewed the use of blockchain in peer-to-peer carbon trading mechanisms, emphasizing its contribution to a net-zero carbon future. A bibliometric analysis [6] of blockchain in climate action identified key research trends and future directions, underscoring the growing significance of sustainable blockchain applications. These studies collectively illustrate the growing recognition of blockchain's potential to drive sustainability [5].

III. METHODOLOGY

This review paper employs a systematic literature review methodology to synthesize existing research on green blockchain and its applications in the context of sustainable development. The primary sources of data for this review are peer-reviewed journal articles and conference proceedings published between 2021 and 2025, identified through comprehensive searches in relevant academic databases using keywords such as "green blockchain," "sustainable blockchain," "blockchain and sustainability," "blockchain in renewable energy," and "blockchain for carbon markets." The inclusion criteria prioritized studies that explicitly addressed the intersection of blockchain technology and environmental or social sustainability, with a specific focus on solutions and applications aimed at minimizing the environmental footprint of blockchain technology itself or leveraging blockchain to advance broader sustainability objectives. The selected literature [6] was then subjected to thematic analysis to identify key concepts, application areas [2], methodological approaches, challenges and emerging trends within the field of green blockchain [6]. Figure 1: Conceptual Framework of Green Blockchain Applications This figure would visually represent the key application areas of green blockchain discussed in the literature review (renewable energy, carbon trading, sustainable supply chains) and their relationship to broader sustainability goals.

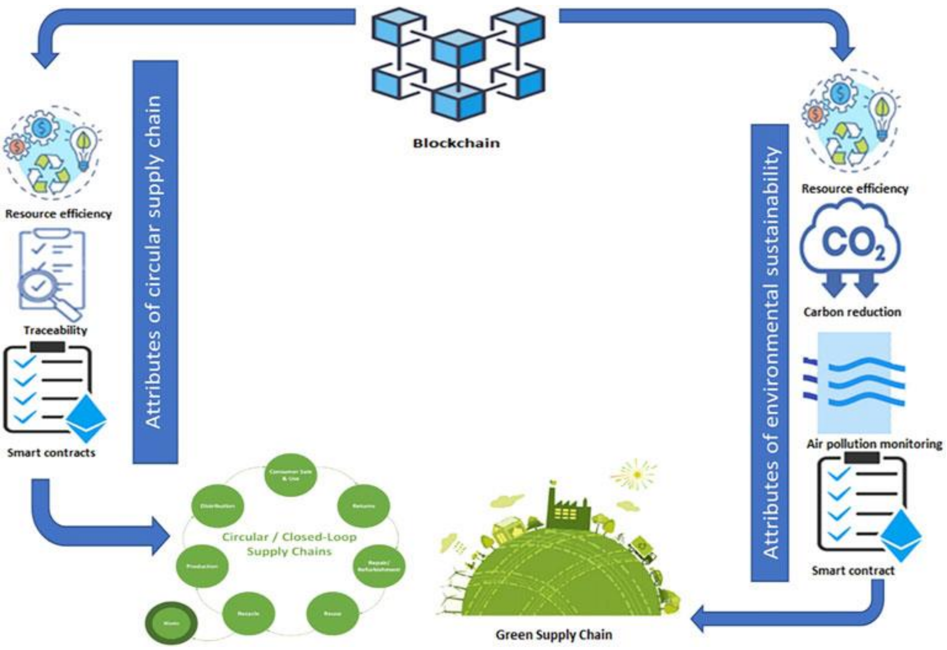

Figure 1

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1. **Energy-Efficient Consensus Mechanisms:**

- **Proof of Stake (PoS):** Instead of energy-intensive mining, PoS selects validators to create new blocks based on the number of coins they "stake" or lock up as collateral .This significantly reduces energy consumption (The Block; Rapid Innovation). Examples of blockchains using or transitioning to PoS include Ethereum, Cardano and Tezos (Tezos).
- **Delegated Proof of Stake (DPoS):** Token holders delegate their staking power to a smaller group of representatives who validate transactions. This further enhances energy efficiency and scalability (Calibraint).
- **Proof of Authority (PoA):** Validators are pre-selected based on their reputation or identity, drastically reducing energy usage as the consensus process doesn't require extensive computation (Clock b Business Technology).
- **Proof of Space and Time (PoST):** Participants prove they are storing a certain amount of data for a specific duration, using available hard drive space instead of processing power (Clock b Business Technology; Blackdown). Chia Network utilizes this mechanism (Blackdown).
- **Practical Byzantine Fault Tolerance (PBFT):** Reaches consensus through voting rounds among network nodes, known for its low energy consumption and speed .
- **Directed Acyclic Graph (DAG):** Enables parallel transactions, reducing reliance on energy-consuming mining by forming a web-like structure where new transactions confirm previous ones .

2. Renewable Energy Integration:

- Powering blockchain networks and mining operations with renewable energy sources like solar, wind and hydro power to reduce their carbon footprint (The Block; Rapid Innovation). The Crypto Climate Accord promotes powering crypto projects with 100% renewable energy by 2030 (Hedera). Some mining companies are also investing in renewable energy and carbon offsetting projects (The Block).

3. Layer 2 Solutions:

- Protocols built on top of a main blockchain to increase transaction speed and reduce energy costs per transaction by processing transactions off-chain. Examples include the Lightning Network for Bitcoin and Polygon for Ethereum (Clock b Business Technology; Blackdown).

4. Carbon Offsetting:

- Investing in environmental projects that mitigate the carbon footprint generated by blockchain operations (The Block). Platforms like KlimaDAO and Toucan tokenize carbon credits for easier trading (Blackdown). Some projects use blockchain to track and verify carbon offset programs (Hedera; Blackdown).

5. Energy-Efficient Hardware and Software:

- Optimizing hardware (e.g., specialized mining rigs, processors) and software used in blockchain networks to minimize energy consumption (Rapid Innovation).

6. Pre-mining:

- Creating a set number of tokens before the initial coin offering to reduce the energy expended on continuous minting of new coins. XRP is an example of a cryptocurrency that pre-mined its coins (Hedera). However, this method can lead to centralization risks.

7. Sustainable Applications of Blockchain:

Utilizing blockchain technology to support sustainability in other sectors, such as:

- **Renewable energy trading:** Facilitating peer-to-peer energy exchange and tracking renewable energy certificates (The Block; Debut Infotech). Platforms like Power Ledger and Grid+ enable decentralized energy marketplaces (The Block; Debut Infotech).
- **Carbon footprint tracking:** Providing transparent tracking of carbon emissions throughout supply chains (Binance Blog).
- **Supply chain management:** Ensuring ethical sourcing and tracking environmental impact of products (Debut Infotech).
- **Environmental conservation:** Incentivizing eco-friendly actions through token rewards (Binance Blog).
- **Carbon credit markets:** Developing transparent and efficient markets for carbon offsets (Blackdown; Debut Infotech).

IV. APPLICATIONS

The reviewed literature highlights several key application areas where green blockchain can significantly contribute to sustainable practices. One prominent application is in renewable energy trading, where blockchain platforms can facilitate decentralized peer-to-peer energy exchange, improve the efficiency and transparency of renewable energy certificate (REC) markets and enhance grid management [2]. Another critical application lies in carbon emissions tracking and trading, where blockchain's immutability and transparency can create more reliable and efficient carbon markets, enabling peer-to-peer carbon credit exchange and contributing towards achieving net-zero emission targets [7]. Sustainable supply chain management is another significant area, where green blockchain can provide enhanced traceability and transparency regarding the origin, ethical sourcing and environmental impact of products throughout their lifecycle [1]. Furthermore, blockchain can serve as a decentralized communication tool to foster trust and collaboration among diverse stakeholders involved in sustainable development initiatives [4]. The vision of a Green Web 3.0, potentially built upon environmentally sustainable blockchain infrastructure, promises a more ecologically conscious and decentralized digital ecosystem [3]. These diverse applications underscore the transformative potential of green blockchain in driving a more sustainable future [6].

V. CONCLUSION

This review has explored the burgeoning field of green blockchain and its potential to integrate decentralized technologies with sustainable practices [1]. The analyzed literature highlights the increasing recognition of blockchain's role in addressing sustainability challenges, particularly in sectors like renewable energy [2], carbon markets [7] and supply chain management [1]. While the energy intensity of traditional blockchain remains a concern [5], the development and adoption of more sustainable consensus mechanisms and application-specific adaptations are paving the way for a greener decentralized future [3]. Future research should focus on addressing the scalability, interoperability and real-world implementation challenges of green blockchain solutions. Nevertheless, the current body of work suggests that green blockchain holds

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significant promise for fostering a more transparent, efficient and environmentally responsible digital economy [6].

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