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Blockchain-based IoT framework for enhancing sustainability in cyber-physical systems

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Abstract
The integration of blockchain technology with Cyber-Physical Systems (CPS) and the Internet of Things (IoT) has emerged as a transformative solution for advancing sustainability across various industries. This paper explores the potential of combining blockchain's decentralized, secure, and immutable features with the real-time data processing capabilities of IoT in CPS. The application of blockchain in CPS enables enhanced transparency, security, and operational efficiency in sectors such as smart cities, energy management, transportation, healthcare, and manufacturing. By leveraging blockchain, CPS can optimize resource management, reduce waste, and promote the use of renewable energy, while ensuring secure and transparent data exchanges. Despite the benefits, challenges such as scalability, integration with legacy systems, security, and privacy concerns, as well as regulatory issues, must be addressed for blockchain's widespread adoption. The paper concludes by discussing future directions, including advancements in quantum-resistant blockchain algorithms, the potential contribution of blockchain to the United Nations' Sustainable Development Goals (SDGs), and the role of digital twins and collaborative ecosystems in shaping the future of blockchain-enabled CPS.

Keywords: Blockchain, cyber-physical systems, internet of things, smart cities, sustainability, energy management, scalability, digital twins, security, privacy, blockchain algorithms, sustainable development goals.

Introduction

A. Overview of Cyber-Physical Systems (CPS)

Cyber-Physical Systems (CPS) refer to the integration of computational elements, such as sensors and actuators, with physical processes in various industries. These systems are designed to interact with the real world through continuous data collection and real-time monitoring. CPS combines the traditional cyber world of computing and control with the physical world of sensors and machinery, enabling advanced automation, remote control, and optimization in diverse sectors, including manufacturing, healthcare, transportation, and energy (Rahman *et al*., 2021) [1]. The integration of the Internet of Things (IoT) within CPS has further amplified their impact. IoT allows for seamless communication between physical devices and computational systems, enabling CPS to collect massive amounts of data, make data-driven decisions, and automate processes autonomously (Kaur *et al*., 2021) [2].

IoT plays a critical role in making CPS more adaptive and responsive by offering real-time capabilities. The proliferation of IoT devices has led to the creation of complex networks where physical entities, such as machines, vehicles, or sensors, are interconnected to share information and enhance system intelligence (Jiang *et al*., 2021) [7]. These systems provide opportunities for industries to achieve higher levels of automation, efficiency, and safety by transforming raw data into actionable insights. For instance, in manufacturing, CPS allows for predictive maintenance, optimized production schedules, and energy consumption reduction. The role of IoT in CPS makes it a key enabler of Industry 4.0, where machine learning, artificial intelligence, and blockchain work in harmony to optimize operational efficiencies and sustainability (Suhail *et al*., 2022) [4].

B. The Need for Sustainability in CPS

The demand for sustainability in CPS has grown significantly in recent years, as industries face increasing pressure to reduce their environmental footprint while maintaining operational excellence. The global shift towards sustainable practices in manufacturing, energy, and transportation has highlighted the critical need for systems that balance technological advancements with environmental considerations (Saleem *et al*., 2024) [22]. As industries scale, the environmental impact of operations, including energy consumption and waste generation, has become a major concern. At the same time, operational inefficiencies and security risks in legacy CPS systems exacerbate these challenges, creating a need for more resilient and sustainable infrastructures (Kaur *et al*., 2021) [2].

CPS, by their nature, operate on vast amounts of data gathered from interconnected devices and sensors. While this opens doors to innovative solutions, it also creates new environmental and operational challenges, such as energy inefficiency, data security issues, and waste generation. For instance, the energy consumption of data centers used in cloud computing, which is integral to CPS operations, contributes significantly to global carbon emissions (Chen *et al*., 2025) [9]. The environmental impact of these systems, coupled with the challenges of maintaining their security and efficiency, calls for the development of CPS that integrate sustainable principles. The sustainability of CPS involves not just the energy efficiency of the systems themselves but also the lifecycle management of the physical and digital components involved in these systems (Rajawat *et al*., 2023) [3]. Hence, there is an urgent need for CPS that not only maximize performance but also contribute positively to environmental conservation.

C. Blockchain as a Solution

Blockchain technology has emerged as a promising solution to address many of the challenges faced by CPS, particularly in terms of security, transparency, and operational efficiency. Blockchain, by design, is a decentralized and distributed ledger technology that ensures the immutability and transparency of data exchanges across networks. Each transaction or data exchange in a blockchain network is securely encrypted and validated by consensus mechanisms, ensuring the integrity and trustworthiness of the system (Rahman *et al*., 2021) [1]. This makes blockchain particularly valuable for CPS, where the security and reliability of data are paramount.

One of the major challenges facing CPS is ensuring secure communication between IoT devices within the system. Blockchain provides an effective mechanism to protect sensitive data by preventing unauthorized access, manipulation, or tampering. Furthermore, it enables transparent data management, where all participants in a CPS network have access to the same, unalterable data. This transparency ensures that all decisions made within the system are based on verified and trusted data, which is critical for industries such as energy, healthcare, and manufacturing, where system failures or data discrepancies can have catastrophic consequences (Kaur *et al*., 2021) [2].

Blockchain also enhances the operational efficiency of CPS by enabling the automation of processes through the use of smart contracts. These self-executing contracts automatically execute predefined actions based on specific conditions, thus reducing the need for human intervention and increasing system efficiency (Ahmed *et al*., 2022) [5]. In the context of sustainable CPS, blockchain can optimize resource allocation, improve energy management, and facilitate secure data exchange, all of which contribute to sustainability goals. For example, in the smart grid industry, blockchain can enable secure, transparent, and efficient energy trading, ensuring that resources are distributed optimally and that energy consumption is minimized (Rajawat *et al*., 2023) [3].

D. Purpose of the Paper

The purpose of this paper is to propose a framework for integrating blockchain technology with IoT and cyber-physical systems (CPS) to foster sustainability and enhance operational efficiency. This framework aims to leverage the strengths of blockchain in securing IoT communications, ensuring transparency, and automating processes in CPS to create more sustainable outcomes across various industries, including manufacturing, transportation, and energy management. By integrating blockchain into CPS, the proposed framework seeks to address critical challenges such as energy inefficiency, data security risks, and operational inefficiencies, which hinder the sustainability of current CPS infrastructures.

In the following sections, the paper will explore the role of blockchain in enabling secure and efficient data management within CPS, providing specific examples of its application in different industries. Furthermore, it will address the environmental and operational challenges that blockchain-enabled CPS can mitigate, highlighting the potential benefits of this integration for sustainable development. Finally, the paper will discuss the challenges and limitations of adopting blockchain technology in CPS, such as scalability and integration with legacy systems, and propose future directions to overcome these obstacles. Through this framework, this paper aims to contribute to the ongoing efforts to make CPS more resilient, efficient, and sustainable in the face of global environmental and operational challenges (Lu & Wu, 2022) [10].

The Role of Blockchain in Cyber-Physical Systems

A. Security and Trust in CPS

One of the primary challenges in cyber-physical systems (CPS) is ensuring the security and trustworthiness of the vast amount of data exchanged between devices and centralized control systems. Blockchain technology offers a robust solution to this problem, thanks to its decentralized nature and distributed ledger architecture. Unlike traditional centralized systems, blockchain operates on a peer-to-peer network, where no single entity controls the data, making it highly resistant to tampering or manipulation (Rahman *et al*., 2021) [1]. Each transaction or data exchange within the blockchain is cryptographically secured, ensuring that once data is recorded, it cannot be altered or deleted without consensus from the network participants. This immutability is particularly critical in environments like CPS, where even a minor data breach or manipulation could lead to significant operational failures or security vulnerabilities.

Moreover, blockchain enhances trust within CPS by allowing all network participants to independently verify the integrity of data. The distributed ledger ensures that each action is visible and auditable by all stakeholders, making it nearly impossible for malicious actors to alter system

information without detection. This transparency is essential in industries like manufacturing, healthcare, and energy management, where secure, reliable data is needed to make informed decisions. The encryption inherent in blockchain further ensures that only authorized entities can access sensitive data, protecting it from unauthorized tampering. Therefore, blockchain acts as a critical enabler of security and trust in CPS, safeguarding both operational processes and data integrity.

B. Blockchain and IoT Integration

The Internet of Things (IoT) plays a crucial role in the functioning of cyber-physical systems by providing real-time data collection and analysis. CPS, by definition, relies heavily on sensors, actuators, and other IoT devices to gather data from the physical world and make autonomous decisions. However, the sheer volume of data generated by these devices, combined with the interconnectedness of the network, can create significant security and management challenges. Blockchain offers a perfect solution by enabling secure IoT data management through its decentralized nature. By recording IoT data transactions on a blockchain, CPS can ensure the integrity, traceability, and accessibility of data, regardless of how many devices or nodes are involved (Kaur *et al*., 2021) [2].

Blockchain's decentralized approach to data management ensures that IoT data is not stored in a central location, reducing the risk of data breaches or single points of failure. Each IoT device in a CPS can act as a node in the blockchain network, allowing for direct, secure communication between devices without the need for a central authority. This integration of blockchain and IoT allows for real-time, transparent monitoring of processes such as manufacturing production lines, energy consumption in smart buildings, or patient data in healthcare systems. Furthermore, the use of smart contracts—self-executing agreements written into the blockchain—enables automation of processes within CPS without requiring human intervention. This feature greatly enhances efficiency by reducing errors, ensuring compliance, and speeding up decision-making processes in environments where time is critical. Thus, blockchain enhances IoT systems in CPS by providing a secure, scalable, and transparent data management solution, ensuring that the data generated by IoT devices is both reliable and tamper-proof.

C. Blockchain for Smart Grids and Energy Management

In the context of smart grids and energy management, blockchain technology is increasingly being viewed as a transformative solution to secure energy transactions and optimize grid operations. Smart grids are evolving to handle renewable energy sources, distributed energy resources, and a wide range of devices and sensors. As these systems grow in complexity, maintaining the security, efficiency, and transparency of energy transactions becomes more challenging. Blockchain addresses these issues by enabling secure, decentralized transactions without the need for a central authority. In a blockchain-enabled smart grid, every energy transaction—whether it's the sale of surplus energy, the exchange of renewable credits, or data regarding energy usage—is recorded on the blockchain in an immutable ledger, ensuring its integrity and transparency (Rajawat *et al*., 2023) [3].

Applications of Blockchain in Sustainable Cyber-Physical Systems

A. Smart Cities and Urban Sustainability

The concept of smart cities revolves around the integration of advanced technologies to improve the quality of life for citizens while promoting environmental sustainability. One of the key innovations enabling smart cities is the combination of Artificial Intelligence (AI) and blockchain technology, which allows for the seamless management of urban resources and services. AI systems can analyze data collected from various IoT devices deployed throughout the city to optimize resource use, manage traffic, and improve energy efficiency. When combined with blockchain, AI can ensure that data remains secure and transparent, allowing for more accountable decision-making in urban management (Ahmed *et al*., 2022) [5]. Blockchain provides a decentralized and immutable ledger, which means that all transactions related to city operations, such as energy usage, water management, and waste disposal, can be transparently recorded and verified. This not only enhances trust in urban systems but also encourages citizens to engage in sustainable practices, knowing that their contributions will be accurately tracked.

Case studies have demonstrated the transformative potential of blockchain in managing urban environments. In several cities, blockchain has been used to optimize energy distribution through smart grids, which dynamically balance electricity supply and demand, ensuring that renewable energy sources are utilized effectively. Additionally, blockchain facilitates peer-to-peer energy trading, allowing residents to buy and sell excess energy from solar panels without the need for an intermediary, thus reducing costs and encouraging more sustainable energy practices (Suhail *et al*., 2022) [4]. Furthermore, blockchain applications in waste management have been explored, where waste disposal data is recorded on the blockchain, enabling more efficient tracking and recycling processes. This integration of blockchain with AI in urban sustainability initiatives helps reduce the carbon footprint of cities while making urban living more efficient and environmentally friendly.

B. Smart Transportation Systems

Transportation systems are crucial to the functioning of modern cities, but they also contribute significantly to environmental pollution and inefficiency. Blockchain technology has the potential to revolutionize smart transportation systems by enhancing both efficiency and security. One of the primary ways in which blockchain can enhance transportation is through its ability to securely manage data and transactions in real-time. For example, blockchain can be used to secure communications between autonomous vehicles, enabling them to share important information about traffic conditions, accidents, and road closures without compromising privacy or security (Suhail *et al*., 2022) [4]. This would facilitate more efficient traffic management, reducing congestion and lowering carbon emissions.

C. Healthcare and Smart Buildings

Blockchain's potential in healthcare is significant, particularly in improving the security and management of patient data. In today's healthcare systems, patient information is often stored in centralized databases, making it vulnerable to cyberattacks and unauthorized access. By

integrating blockchain into healthcare management, patient data can be securely recorded and shared across various institutions while maintaining patient privacy (Ch *et al*., 2022). Blockchain's decentralized ledger ensures that healthcare data is immutable and accessible only to authorized individuals, thereby preventing data tampering and improving overall security. Additionally, blockchain can enable more efficient billing and insurance processes, reducing fraud and administrative costs.

In the context of smart buildings, blockchain plays a vital role in ensuring sustainability by optimizing energy use and reducing waste. Smart buildings, equipped with IoT devices, collect vast amounts of data on energy consumption, temperature, lighting, and occupancy. Blockchain can securely record and manage this data, allowing building managers to analyze it and make data-driven decisions to optimize energy efficiency (Hakim *et al*., 2023) [18]. Additionally, the integration of blockchain with digital twin technology allows building systems to simulate real-time conditions and predict future performance, enabling proactive maintenance and reducing the environmental impact of energy consumption. For instance, by using blockchain to manage data from HVAC systems, lighting, and electrical grids, buildings can dynamically adjust energy use, minimizing waste and improving sustainability. This combination of blockchain and digital twins in smart buildings not only enhances operational efficiency but also contributes to broader sustainability efforts by reducing energy consumption and carbon emissions.

D. Blockchain in Industrial Automation and Manufacturing

In industrial automation and manufacturing, blockchain technology is increasingly being adopted to enhance security, traceability, and overall efficiency. One of the main challenges in these industries is ensuring the integrity and security of supply chains, where raw materials, parts, and finished goods must be tracked and verified at every stage. Blockchain addresses this challenge by providing an immutable record of all transactions, allowing manufacturers to track the provenance of goods and materials in real time. This level of transparency is crucial in industries such as pharmaceuticals, food production, and electronics, where safety and quality are of utmost importance (Jiang *et al*., 2021) [7]. By using blockchain to monitor supply chain activities, companies can reduce the risk of fraud, ensure compliance with regulations, and increase trust among consumers.

Key Technologies Enhancing Blockchain-Enabled CPS

A. Artificial Intelligence (AI) in CPS

Artificial Intelligence (AI) plays a crucial role in enhancing the capabilities of cyber-physical systems (CPS) by enabling predictive analytics and intelligent decision-making. Machine learning (ML) algorithms, a subset of AI, are particularly useful in CPS as they can analyze vast amounts of data generated by IoT devices and sensors, providing insights that would otherwise be difficult for humans to extract. For instance, in industries like energy, transportation, and manufacturing, AI can forecast trends and behaviors based on historical data, allowing systems to make proactive adjustments in real time. In the energy sector, AI-driven predictive analytics can optimize power generation and distribution, ensuring energy efficiency and minimizing waste (Das *et al*., 2021) [6]. In manufacturing, AI can be used to predict equipment failures before they occur, reducing downtime and ensuring the smooth operation of production lines. By integrating AI with blockchain, CPS can benefit from more efficient decision-making processes, as blockchain ensures that the data used by AI algorithms is transparent, immutable, and trustworthy.

The integration of AI with blockchain enhances decision-making processes by ensuring that the data driving these decisions is reliable and tamper-proof. In traditional systems, decision-making often relies on centralized databases that can be vulnerable to data breaches or manipulation. However, blockchain offers a decentralized solution where data is distributed across multiple nodes, preventing any single party from altering the data. By combining AI's ability to process complex data and make predictions with blockchain's transparency and security, CPS can operate more efficiently and securely. For example, in smart cities, AI can manage traffic flow based on real-time data, and blockchain can ensure that the data used for traffic optimization is accurate and secure, fostering greater trust in the system (Suhail *et al*., 2022) [4]. This synergy between AI and blockchain is vital for creating responsive and secure CPS that can handle the growing complexity of urban and industrial environments.

B. 5G Networks and Blockchain

The emergence of 5G networks has opened up new possibilities for enhancing cyber-physical systems (CPS), particularly in applications that require real-time communication and low latency. The ultra-high-speed data transmission capabilities of 5G are particularly beneficial in the context of smart cities and transportation systems, where immediate and seamless data exchange is essential. With 5G-enabled CPS, smart cities can support millions of connected devices that transmit data at incredible speeds, enabling faster decision-making and more responsive systems. For example, in transportation, 5G can facilitate the real-time communication between autonomous vehicles, traffic management systems, and infrastructure, allowing for more efficient traffic control, reduced congestion, and enhanced safety. 5G's low latency ensures that these systems can react almost instantly to changing conditions, such as traffic flow or weather changes, making them more reliable and adaptive (Rajawat *et al*., 2023) [3].

When combined with blockchain, 5G further strengthens the security and reliability of CPS. Blockchain ensures that the data transmitted across 5G networks remains secure and immutable, preventing unauthorized access or tampering. This is particularly important in applications such as autonomous vehicles, where real-time data exchanges are critical for safe navigation and decision-making. Blockchain can be used to create secure communication channels between vehicles, infrastructure, and control systems, ensuring that data remains intact throughout its journey. Additionally, 5G-enabled CPS can support real-time updates to blockchain ledgers, ensuring that all participants in the system have access to the most current and accurate information. The integration of 5G networks with blockchain enhances the overall performance and security of CPS, making it a promising solution for the smart cities and autonomous transportation of the future.

C. Edge Computing in CPS

Edge computing is another key technology that enhances the performance and efficiency of blockchain-enabled cyber-physical systems (CPS). Edge computing involves processing data closer to the source of data generation—such as IoT devices—rather than sending it to a centralized cloud or data center for processing. This reduces the amount of data that needs to be transmitted over the network, thereby decreasing latency and bandwidth usage. In CPS, where real-time decision-making is essential, edge computing can provide immediate insights and actions based on the data generated by connected devices. For instance, in smart manufacturing, edge computing can enable real-time monitoring of equipment, allowing for instant adjustments to optimize production processes without the need for cloud-based analysis (Thakur & Sehgal, 2022) [14].

Integrating edge computing with blockchain adds an additional layer of security and efficiency to CPS. Blockchain's decentralized nature ensures that the data processed at the edge is securely recorded and cannot be altered or tampered with. This is especially important in environments where data integrity is critical, such as in healthcare or industrial automation.

Challenges and Opportunities in Implementing Blockchain-Based CPS

A. Scalability Issues

One of the most significant challenges in implementing blockchain-based cyber-physical systems (CPS) is scalability. As CPS grows in size and complexity, with numerous interconnected devices generating massive amounts of data, the blockchain network must handle a high volume of transactions in real time. Blockchain's inherent architecture, particularly in traditional proof-of-work systems, can be a bottleneck when it comes to processing large-scale data at high speeds. The need to validate and record every transaction across a decentralized network can lead to latency and reduced throughput, which is particularly problematic in CPS environments where real-time decision-making is crucial (Kaur *et al*., 2021) [2]. This scalability issue becomes even more critical when considering the vast amounts of data produced by IoT devices in industrial applications, healthcare systems, and smart cities, where millions of transactions may need to be processed daily.

Several potential solutions have been proposed to address scalability concerns in blockchain-based CPS. One promising approach is sharding, which involves partitioning the blockchain into smaller, manageable pieces, or "shards." Each shard processes a subset of transactions, which reduces the overall load on the network and increases processing speed. Another solution is the implementation of Layer-2 blockchain solutions, such as the Lightning Network, which operates on top of the main blockchain to enable faster and cheaper transactions without compromising security. By reducing the amount of data that needs to be processed directly on the main blockchain, these solutions can improve the scalability and efficiency of CPS while maintaining the integrity and security of the data. As blockchain technology continues to evolve, these scalability solutions will play a pivotal role in enabling the widespread adoption of blockchain in large-scale CPS applications.

B. Integration with Legacy Systems

Another major challenge when implementing blockchain in CPS is integrating blockchain technology with existing legacy systems. Many industries, such as manufacturing, energy, and healthcare, already rely on well-established CPS infrastructures that may not be compatible with blockchain's decentralized model. Legacy systems often operate on centralized platforms with proprietary software, making it difficult to introduce a new blockchain-based solution without disrupting existing processes and operations (Deng *et al*., 2023) [21]. The integration of blockchain into these systems requires substantial modifications to the underlying infrastructure, which can be both time-consuming and costly. Moreover, legacy systems may not be capable of supporting the complex cryptographic operations needed for blockchain, requiring additional investments in hardware and software.

Incorporating blockchain into existing CPS frameworks also involves overcoming issues related to interoperability. Different industries may use different communication protocols, data formats, and network architectures, which could create friction when attempting to integrate blockchain with legacy systems. However, as blockchain solutions continue to mature, there are emerging tools and frameworks designed to facilitate interoperability between blockchain and traditional systems. These include blockchain gateways, middleware solutions, and cross-chain protocols that can bridge the gap between new blockchain-based technologies and older systems. Despite these challenges, integrating blockchain with legacy systems holds significant potential for enhancing security, transparency, and operational efficiency in CPS, and it remains a critical area of focus for the future development of blockchain-enabled CPS.

C. Security and Privacy Concerns

While blockchain offers enhanced security features compared to traditional centralized systems, implementing it within CPS also introduces new security and privacy challenges. Blockchain's decentralized nature and immutability make it an attractive solution for ensuring data integrity and preventing tampering. However, vulnerabilities can still exist, particularly when it comes to the security of the endpoints in a CPS, such as IoT devices and sensors. These devices are often the entry points for cyberattacks, and if compromised, they can undermine the entire security framework of the blockchain network (Saleem *et al*., 2024) [22]. Additionally, while blockchain guarantees the integrity of stored data, it does not automatically ensure the security of data in transit. This is particularly problematic in CPS, where real-time communication and data exchange between IoT devices are essential for system performance.

Another critical concern is privacy. The immutable nature of blockchain means that once data is recorded on the chain, it cannot be deleted or altered. This presents a challenge when dealing with sensitive information, such as personal health data in healthcare CPS or customer data in smart cities. As blockchain data is publicly accessible to all network participants, there is a risk that privacy could be compromised, especially if confidential data is exposed unintentionally (Ahmed *et al*., 2022) [5]. To mitigate privacy risks, some solutions include incorporating zero-knowledge proofs, which allow data to be verified without revealing the actual content, and off-chain storage of sensitive information, with only references to the data being stored on the blockchain. These approaches aim to strike a balance

between the transparency and immutability of blockchain and the privacy needs of CPS.

D. Regulatory and Standardization Issues

Blockchain's integration into CPS also faces significant regulatory and standardization challenges. While blockchain technology offers significant advantages in terms of transparency, security, and efficiency, its decentralized nature poses challenges for regulators who are accustomed to dealing with centralized entities that are accountable to specific authorities. The lack of global standards for blockchain applications in CPS means that organizations must navigate a fragmented regulatory landscape, which can hinder the adoption and implementation of blockchain solutions (Chen *et al*., 2025) [9]. For example, in industries like healthcare and finance, where data privacy regulations are stringent, blockchain solutions must ensure compliance with local laws such as the General Data Protection Regulation (GDPR) in the European Union or the Health Insurance Portability and Accountability Act (HIPAA) in the United States. Without clear guidelines and frameworks, organizations may hesitate to adopt blockchain technologies due to concerns about compliance and legal risks.

Future Directions and Innovations

A. Next-Generation Blockchain Technologies

As blockchain technology continues to evolve, significant advancements are being explored to enhance its application in cyber-physical systems (CPS). One of the most promising areas of innovation lies in developing quantum-resistant algorithms. Quantum computing, with its potential to solve complex problems exponentially faster than classical computers, poses a significant threat to the cryptographic algorithms that underpin most blockchain networks. Current encryption methods, such as elliptic curve cryptography, could be vulnerable to quantum algorithms, which could potentially break the security of blockchain systems. To address this challenge, researchers are working on developing quantum-resistant algorithms that will ensure the security and resilience of blockchain networks even in the era of quantum computing (Al-Ghuraybi *et al*., 2024) [12]. This advancement is crucial for the long-term viability of blockchain in CPS, especially as the adoption of quantum technologies accelerates.

B. Blockchain and Sustainability Goals

Blockchain's integration into cyber-physical systems offers significant potential for advancing sustainability, particularly in relation to the United Nations' Sustainable Development Goals (SDGs). By providing a transparent and immutable record of data, blockchain can help achieve SDGs related to sustainable cities, affordable and clean energy, and responsible consumption and production. Blockchain can enable sustainable supply chains by tracking the environmental footprint of products from production to end-of-life, ensuring that companies adhere to sustainability practices (Kumar *et al*., 2021) [13-24]. In the energy sector, blockchain can facilitate decentralized energy trading, where users can buy and sell energy generated from renewable sources, thereby promoting the use of clean energy and reducing dependency on non-renewable resources. Additionally, blockchain can support waste reduction by tracking waste streams and enabling more efficient recycling processes through transparent waste management systems.

Blockchain's potential to contribute to circular economy models is particularly promising. By enabling real-time tracking and management of resources, blockchain can help optimize the use of materials, reduce waste, and promote resource reuse in manufacturing and other industries. Through blockchain-enabled transparency, businesses can verify the sustainability of their supply chains and make more informed decisions about resource procurement and waste management. This ability to create transparent, traceable, and verifiable records of resource use and waste helps to reduce inefficiencies and fosters more sustainable production practices. In the future, as more industries embrace blockchain for sustainability, its role in facilitating the transition to a circular economy will be crucial for meeting global environmental targets.

C. Collaborative Ecosystems in Blockchain-Enabled CPS

The power of blockchain in enabling collaborative ecosystems across industries cannot be overstated. By providing a secure, transparent, and decentralized platform for data exchange, blockchain creates opportunities for collaboration between diverse sectors, including energy, transportation, healthcare, and manufacturing. For instance, in the energy sector, blockchain can be used to create decentralized energy grids, where consumers, producers, and distributors of energy can collaborate more effectively through shared blockchain platforms. These platforms can facilitate peer-to-peer energy trading, where excess energy generated by consumers (e.g., through solar panels) can be securely sold to others, reducing the need for centralized control and increasing the efficiency of energy distribution (Kaur *et al*., 2021) [2].

D. The Role of Digital Twins and IoT in Shaping Future CPS

The future of cyber-physical systems is poised to be shaped significantly by the integration of digital twins and IoT devices, with blockchain serving as the enabling technology that secures and authenticates the data exchanged between them. Digital twins, which are virtual replicas of physical entities, can provide real-time monitoring and simulation capabilities for a wide range of applications, from smart buildings to industrial machinery. The integration of blockchain with digital twins allows for the secure storage and management of data generated by IoT devices in real time. This integration ensures that data remains immutable and can be traced back to its source, thus increasing trust in the system and enabling more accurate simulations and predictions (Tanha *et al*., 2022) [8].

Conclusion

A. Summary of Findings

The integration of blockchain technology, the Internet of Things (IoT), and cyber-physical systems (CPS) has emerged as a promising solution for addressing many of the challenges associated with sustainability in industrial applications. Through this integration, various sectors, such as smart cities, energy management, and transportation, stand to benefit significantly. Blockchain enhances the transparency, security, and efficiency of CPS, making data transactions both secure and immutable, thus enabling trust among all stakeholders (Rahman *et al*., 2021) [1]. In the

context of smart cities, this integration allows for more efficient resource management, from optimizing energy use to streamlining waste management and traffic control, while ensuring that these processes are transparent and secure. Blockchain also plays a crucial role in decentralizing energy grids, promoting the use of renewable energy, and reducing carbon footprints by facilitating peer-to-peer energy trading (Suhail *et al*., 2022) [4]. In transportation, the use of blockchain enables secure communication between autonomous vehicles and infrastructure, improving traffic flow and reducing congestion, while enhancing safety. The ability to leverage blockchain for real-time monitoring, decision-making, and optimization within these industries demonstrates its transformative potential for advancing sustainability goals.

The combination of IoT and blockchain in CPS brings about a new level of operational efficiency, where IoT devices collect real-time data that blockchain records and secures, ensuring that this data can be trusted and acted upon swiftly. The impact on sustainability is particularly notable in manufacturing, where blockchain-based CPS can optimize production processes, reduce energy consumption, and prevent resource wastage through smart contracts and automated systems (Das *et al*., 2021) [6]. By ensuring that only verified and transparent data is used, the integration of blockchain with IoT and CPS facilitates better resource management and promotes sustainable practices across industries.

B. Implications for Industry and Research

The proposed blockchain-integrated CPS framework has the potential to drive significant changes in multiple industries. For example, in energy management, the use of blockchain to securely manage energy transactions and optimize grid operations opens the door for more decentralized energy systems, reducing the reliance on centralized infrastructure and promoting the use of renewable energy sources. By enabling secure, transparent, and efficient data exchanges, blockchain can help industries like healthcare, manufacturing, and transportation achieve greater operational efficiencies, reduce costs, and enhance their sustainability profiles (Kaur *et al*., 2021) [2]. Industries can benefit from blockchain's ability to automate transactions, verify data, and ensure that critical information is available in real time, helping companies make more informed decisions that contribute to environmental and operational sustainability.

From a research perspective, this framework paves the way for further exploration into the interoperability of blockchain with legacy systems, the scalability of blockchain in large-scale CPS applications, and the development of new consensus mechanisms that can improve blockchain's performance. As blockchain technology evolves, further research will be needed to address scalability challenges, improve energy efficiency, and explore new solutions for integrating blockchain with other emerging technologies such as artificial intelligence (AI) and edge computing. Additionally, understanding the regulatory landscape and establishing global standards for blockchain applications in CPS will be crucial for ensuring widespread adoption and compliance across industries (Chen *et al*., 2025) [9]. Research into these areas will help refine blockchain solutions for CPS and accelerate their adoption in both existing and emerging markets.

C. Final Thoughts

The future of blockchain-based CPS holds immense promise for transforming industries and driving global sustainability efforts. Blockchain's ability to provide secure, transparent, and immutable records of data, combined with its integration with IoT, AI, and edge computing, creates a robust platform for optimizing resource management, reducing waste, and improving efficiency across a wide range of sectors. By supporting sustainable practices in smart cities, energy management, transportation, healthcare, and manufacturing, blockchain-enabled CPS can contribute significantly to achieving the United Nations' Sustainable Development Goals (SDGs) (Kumar *et al*., 2021) [13-24]. The continued evolution of blockchain technology, particularly with advancements such as quantum-resistant algorithms and scalable consensus mechanisms, will ensure that blockchain remains a key enabler of innovation in CPS.

However, challenges remain, including the integration of blockchain with legacy systems, security and privacy concerns, and the need for regulatory clarity. Addressing these challenges will be essential for unlocking the full potential of blockchain in CPS. In conclusion, blockchain-enabled CPS is poised to be a transformative force in achieving global sustainability goals, and as research continues to address its challenges, the widespread implementation of these systems will help create a more sustainable and efficient future.

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