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Review of Blockchain-Enabled Construction Supply Chains for Transparency and Sustainability Outcomes

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Abstract
The construction industry faces persistent challenges of fragmentation, inefficiency, and opacity in its supply chains, resulting in significant risks related to cost overruns, corruption, waste generation, and unsustainable practices. Ensuring material traceability, accountability, and environmental compliance is increasingly critical as the sector confronts growing pressures to reduce its carbon footprint and align with global sustainability agendas. Blockchain technology, with its features of decentralization, immutability, and automated smart contracts, has emerged as a promising solution to address these challenges by enabling transparent and secure data exchange across diverse stakeholders. This critically examines the application of blockchain-enabled solutions in construction supply chains with a focus on transparency and sustainability outcomes. Drawing on peer-reviewed literature, industry reports, and case studies, the analysis explores blockchain applications in material provenance tracking, automated procurement and payment processes, circular economy facilitation, and carbon monitoring. Comparative insights highlight the effectiveness of blockchain in improving trust, efficiency, and accountability, while also identifying limitations related to scalability, interoperability, energy intensity, and adoption barriers. The findings indicate that blockchain adoption remains concentrated in pilot projects and technologically advanced regions, with limited empirical evidence from large-scale, real-world deployments. Integration with complementary digital tools such as the Internet of Things (IoT), Building Information Modeling (BIM), and artificial intelligence (AI) is emerging as a key trend to strengthen real-time monitoring and sustainability reporting. However, policy gaps, financial constraints, and knowledge shortages continue to hinder widespread adoption. This underscores the potential of blockchain to transform construction supply chains into transparent, efficient, and sustainable systems. It calls for coordinated efforts among policymakers, industry leaders, and researchers to establish global standards, foster collaboration, and develop incentives for blockchain-enabled sustainable construction practices.

Keywords: Blockchain, Construction Supply Chains, Transparency, Sustainability Outcomes, Material Traceability, Smart Contracts, Carbon Accountability, Digital Transformation, Decentralized Platforms, Waste Reduction

1. Introduction

The construction industry is a cornerstone of global economic development, contributing significantly to employment, infrastructure, and urbanization (Onoja and Ajala, 2022; Nicoletti *et al*., 2023) [39, 35]. However, it is also one of the most resource-intensive and environmentally impactful sectors, responsible for a substantial portion of global energy consumption, greenhouse gas emissions, and material waste. Modern construction projects involve highly complex supply chains that span multiple stakeholders, including contractors, subcontractors, suppliers, regulators, and financiers (Chen *et al*., 2021; Koc and Gurgun, 2021) [12, 30]. The coordination of these diverse actors across geographically dispersed networks introduces significant operational complexity, delays, and inefficiencies, often magnifying environmental impacts and undermining sustainability objectives.

Several challenges persist in construction supply chain management that exacerbate these issues. Fragmentation and data silos make it difficult to track materials, monitor project progress, or ensure compliance with sustainability standards (Fasasi *et al*., 2023; Rane and Narvel, 2022) [19, 42]. Lack of transparency in procurement and contract execution increases susceptibility to corruption and mismanagement of resources. Material traceability is often limited, making it challenging to verify the origin, quality, or environmental impact of construction inputs (Davari *et al*., 2023; Xu *et al*., 2023) [14, 52]. Additionally, growing attention to carbon accountability has highlighted the difficulty of accurately monitoring emissions across multi-tier supply chains, hampering efforts to meet environmental targets and reporting requirements. Collectively, these challenges not only affect operational efficiency and cost management but also hinder the sector's transition toward sustainable practices.

Blockchain technology has emerged as a potentially transformative solution for these challenges. As a decentralized digital ledger, blockchain enables secure, immutable, and transparent recording of transactions across multiple parties without reliance on a central authority (Antal *et al*., 2021; Dong *et al*., 2023) [7, 18]. Its smart contract functionality allows automated execution of agreements, improving accountability, efficiency, and compliance in supply chain operations. By providing real-time visibility of material flows and digital verification of sustainability metrics, blockchain has the potential to enhance traceability, reduce disputes, and support circular economy principles within the construction sector (Bacchetta *et al*., 2021; Omisola *et al*., 2023) [8, 38]. Integration with complementary technologies such as the Internet of Things (IoT), Building Information Modeling (BIM), and artificial intelligence (AI) further enhances its capability to optimize resource use, monitor carbon emissions, and improve overall supply chain resilience.

The purpose of this, is to synthesize current research and practice on blockchain-enabled construction supply chains, with a focus on transparency and sustainability outcomes. This seeks to answer the following guiding research questions: How is blockchain currently being applied in construction supply chains to improve transparency, traceability, and sustainability? What are the observed benefits, limitations, and adoption barriers? How do these solutions integrate with other digital technologies and sustainability initiatives? By addressing these questions, this aims to provide insights for policymakers, practitioners, and researchers to advance the development of transparent, efficient, and environmentally responsible construction supply chains.

2. Methodology

The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) methodology was applied to guide a systematic review of blockchain-enabled construction supply chains with a focus on transparency and sustainability outcomes. A comprehensive search was conducted across multiple academic databases, including Scopus, Web of Science, and ScienceDirect, as well as relevant industry reports, conference proceedings, and grey literature to ensure a broad and representative sample of studies. The search strategy combined keywords and Boolean operators such as "blockchain," "construction supply chain," "transparency," "traceability," "sustainability," and "circular construction," to capture both technological and operational aspects of blockchain applications in construction.

The initial search yielded a substantial number of records, which underwent a multi-stage screening process. Duplicate entries were removed, followed by title and abstract screening against predefined inclusion and exclusion criteria. Studies were included if they examined the implementation, benefits, challenges, or outcomes of blockchain technology in construction supply chains, particularly with regard to transparency, traceability, resource efficiency, or sustainability. Excluded studies comprised articles unrelated to blockchain in construction, purely theoretical papers without empirical or applied insights, and works focusing on unrelated sectors or technologies. Full-text reviews were then conducted to confirm relevance, ensuring that only studies providing substantive contributions to understanding blockchain's role in sustainable construction supply chains were retained.

The study selection process was documented using a PRISMA flow diagram to maintain transparency, detailing the number of records identified, screened, excluded, and included in the final synthesis. Data extraction focused on key variables such as blockchain application type, supply chain stage, reported sustainability outcomes, transparency improvements, technological architecture, and implementation challenges. A standardized data extraction template was used to ensure consistency, and cross-validation was conducted to minimize bias and errors.

Synthesis of the findings employed both thematic and comparative analyses to identify recurring trends, innovations, barriers, and regional or sectoral variations. Emphasis was placed on examining how blockchain enables enhanced traceability of materials, reduces information asymmetry, facilitates compliance with environmental regulations, and supports circular construction practices. The PRISMA methodology ensured methodological rigor, transparency, and replicability by maintaining clear records of search strategies, screening decisions, and analytical procedures. This approach provided a systematic foundation for evaluating the potential of blockchain technology to advance transparency and sustainability in construction supply chains.

2.1 Theoretical Background

Blockchain technology, first conceptualized as the underlying infrastructure for cryptocurrencies such as Bitcoin, has rapidly evolved into a transformative tool for managing complex, multi-stakeholder systems. At its core, blockchain is a distributed ledger technology (DLT) that allows digital records of transactions to be stored across multiple nodes in a network, eliminating the need for a central authority. Each transaction or data entry is grouped into a block, which is cryptographically linked to the preceding block, forming a chain that is immutable and verifiable. This architecture ensures data integrity, transparency, and resilience against tampering, making blockchain particularly suitable for environments characterized by fragmented oversight and trust deficits—conditions that are prevalent in global construction supply chains (Teisserenc and Sepasgozar, 2022; Dong *et al*., 2023) [50, 18].

A key feature of blockchain is the smart contract, which is a programmable, self-executing agreement that automatically enforces predefined conditions. In the context of construction supply chains, smart contracts can automate payments, track deliveries, and verify compliance with environmental or quality standards. The combination of immutability, decentralization, and automation not only reduces administrative overhead but also minimizes the potential for fraud, corruption, and disputes among stakeholders. By providing a transparent and auditable record of all transactions, blockchain facilitates real-time traceability, thereby enhancing accountability and enabling data-driven decision-making across the entire supply chain (Zhu *et al*., 2021; Adewale *et al*., 2022) [55, 1].

The integration of blockchain into construction reflects broader trends in digital transformation within the sector. Over the past two decades, construction supply chains have increasingly adopted digital tools to manage project complexity, from Enterprise Resource Planning (ERP) systems to Building Information Modeling (BIM) and IoT-enabled sensors. BIM provides detailed, shared digital models of buildings that facilitate collaboration among architects, engineers, and contractors, while IoT devices capture real-time data on equipment usage, material flows, and energy consumption. Blockchain complements these technologies by serving as a secure, interoperable platform for sharing, validating, and recording this data across all stakeholders (Dodevski *et al*., 2021; Rahman *et al*., 2022) [17, 41]. Together, these digital tools are reshaping traditional supply chain processes, improving efficiency, reducing delays, and enabling performance monitoring with higher accuracy.

From a theoretical perspective, blockchain intersects with supply chain management (SCM) and sustainability frameworks. SCM theory emphasizes coordination, information sharing, and integration among multiple actors to optimize performance, minimize costs, and reduce risks. However, conventional SCM approaches often struggle with transparency, especially in long, multi-tier construction networks. Blockchain directly addresses this gap by providing a tamper-proof, decentralized mechanism for recording all transactions and material flows, thereby enhancing trust and collaboration.

Sustainability theories, particularly those related to environmental and circular economy principles, are also closely aligned with blockchain applications. By enabling material traceability, carbon accounting, and lifecycle monitoring, blockchain supports the implementation of green building practices, responsible sourcing, and waste reduction strategies. For example, tracking the origin of construction materials through blockchain can verify compliance with low-carbon standards or circular economy initiatives, thereby linking operational supply chain activities with broader environmental objectives. Moreover, blockchain facilitates data-driven performance evaluation, allowing stakeholders to assess the environmental impact of each project stage, from procurement and production to transportation and construction (Rane and Narvel, 2022; Liu *et al*., 2023) [42, 31].

The combination of blockchain with other digital technologies represents a paradigm shift in construction supply chain theory and practice. It moves the sector from a largely linear, opaque model—prone to delays, inefficiencies, and sustainability risks—toward an integrated, transparent, and accountable system. The distributed, immutable nature of blockchain ensures that all stakeholders, including contractors, suppliers, regulators, and clients, can access verifiable information, reducing information asymmetry and promoting evidence-based decision-making.

Blockchain technology offers both theoretical and practical value for transforming construction supply chains. Its core principles of distributed ledger, immutability, and smart contracts directly address persistent challenges of fragmentation, opacity, and inefficiency. When integrated with digital transformation tools such as BIM and IoT, blockchain enhances transparency, accountability, and sustainability across multi-tier supply chains. From a theoretical standpoint, it bridges supply chain management and sustainability frameworks by enabling coordinated, traceable, and environmentally responsible operations (Stroumpoulis and Kopanaki, 2022; Centobelli *et al*., 2022) [49, 11]. As construction projects grow in complexity and environmental scrutiny intensifies, blockchain provides a robust foundation for aligning operational efficiency with strategic sustainability goals.

2.2 Blockchain Applications in Construction Supply Chains

Blockchain technology has rapidly emerged as a transformative tool in construction supply chains, offering solutions to long-standing challenges of fragmentation, opacity, and inefficiency as shown in Fig 1. By providing decentralized, secure, and transparent mechanisms for data recording, blockchain enables enhanced trust, coordination, and accountability among multiple stakeholders (Adewale *et al*., 2022; Deng *et al*., 2022) [1, 15]. Its applications span material traceability, procurement automation, waste reduction, and sustainability monitoring, all of which are critical for advancing environmentally responsible and efficient construction practices.

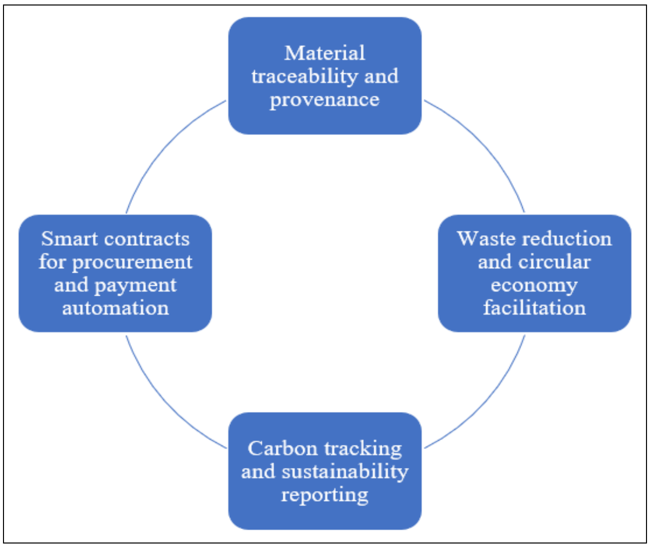

Fig 1: Blockchain Applications in Construction Supply Chains

One of the most compelling applications of blockchain in construction is material traceability and provenance tracking. Construction projects involve multiple tiers of suppliers, subcontractors, and logistics providers, often distributed across regions or even countries. Traditional tracking methods rely on paper documentation or centralized digital systems, which are vulnerable to errors, fraud, and data silos. Blockchain addresses these challenges by creating an immutable record of each material's lifecycle—from production and transport to on-site installation.

For example, timber, steel, or recycled materials can be tagged with digital identifiers recorded on a blockchain ledger. Each transaction or movement is time-stamped and verified by all relevant parties, ensuring that materials meet quality standards, sustainability certifications, and regulatory requirements. This level of transparency not only reduces the risk of counterfeit or low-quality materials entering the supply chain but also facilitates auditing and compliance reporting, thereby enhancing accountability and stakeholder confidence.

Another significant application is the use of smart contracts to automate procurement and payment processes. Smart contracts are self-executing digital agreements embedded with predefined conditions. In construction, these contracts can automatically trigger payments upon verification of material delivery, completion of milestones, or achievement of performance criteria.

This automation reduces administrative overhead, minimizes disputes between contractors and suppliers, and accelerates cash flow management. For instance, a supplier delivering pre-fabricated modules to a construction site can receive instant payment once IoT sensors confirm delivery and installation, with all transactions immutably recorded on the blockchain. Beyond efficiency, smart contracts enhance trust among stakeholders by ensuring impartial enforcement of agreements and reducing opportunities for corruption or manipulation (Howell and Potgieter, 2021; Khan *et al*., 2021) [25, 29].

Blockchain also supports waste reduction and circular economy initiatives within construction supply chains. Material waste and inefficient resource use are major contributors to the sector's environmental footprint. By providing a real-time, transparent view of material flows, blockchain enables stakeholders to track surplus, reuse, or recyclable components across projects.

For example, construction firms can create blockchain-based platforms to exchange surplus materials or repurpose demolition waste, ensuring that resources remain in use rather than being discarded. Smart contracts can automate transactions for reused materials, providing clear provenance and accountability. Such systems align with circular economy principles by promoting resource efficiency, reducing landfill contributions, and extending the lifecycle of construction materials.

Environmental accountability is increasingly central to construction projects, and blockchain facilitates carbon tracking and sustainability reporting. Each stage of a construction project—from material sourcing to transportation, fabrication, and on-site assembly—generates emissions and other environmental impacts. Traditional monitoring systems often rely on fragmented data, leading to incomplete or inaccurate reporting.

Blockchain can integrate with IoT devices, sensors, and BIM models to capture real-time data on energy consumption, emissions, and material use. Each record is stored immutably, providing a verifiable audit trail for sustainability metrics. This enables accurate calculation of embodied carbon, life-cycle emissions, and compliance with environmental standards or green building certifications. Moreover, transparent reporting supported by blockchain enhances stakeholder trust, facilitates regulatory compliance, and informs corporate sustainability strategies.

The combination of material traceability, smart contracts, waste reduction, and carbon tracking demonstrates how blockchain creates synergies across supply chain operations. For instance, tracking materials through blockchain enables not only provenance verification but also informs carbon accounting and circular reuse strategies. Smart contracts can link these processes to financial incentives, such as payments contingent on sustainability compliance, thereby aligning economic and environmental objectives (Groschopf *et al*., 2021; John *et al*., 2023) [21, 27].

Blockchain applications in construction supply chains address critical operational and sustainability challenges by enhancing transparency, automating processes, reducing waste, and improving environmental reporting. Material traceability ensures provenance and compliance, smart contracts streamline procurement and payments, and blockchain-enabled platforms facilitate circular economy practices. Integration with digital sensors and modeling systems further allows for accurate carbon tracking and sustainability verification. Collectively, these applications position blockchain as a powerful enabler of efficient, transparent, and sustainable construction supply chains, offering both operational and environmental benefits across multiple project phases and stakeholder networks.

2.3 Comparative Analysis of Blockchain Approaches

The adoption of blockchain technology in construction supply chains has emerged as a transformative approach to enhancing transparency, accountability, and sustainability outcomes as shown in Fig 2. Different blockchain implementations—ranging from public, permissionless networks to private, permissioned platforms—offer distinct advantages and challenges depending on the context, project scale, and integration with complementary digital technologies. A comparative analysis of these approaches highlights their effectiveness, scalability, interoperability, and limitations, providing insights into optimal deployment strategies for construction stakeholders (Amjad *et al*., 2021; Albouq *et al*., 2022) [6, 3].

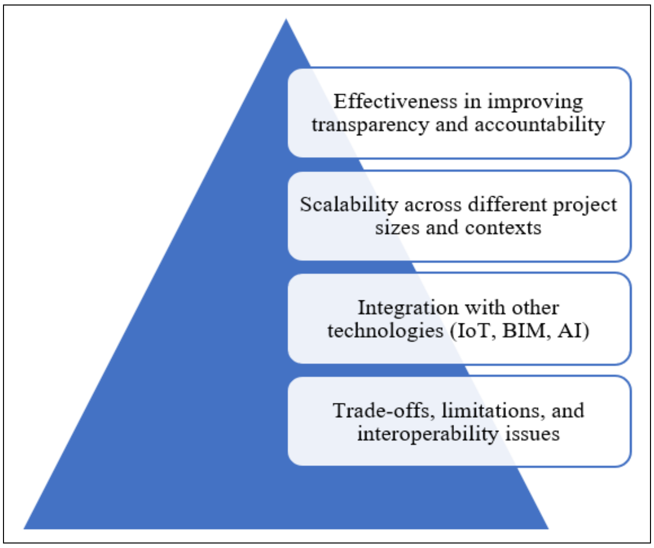

Fig 2: Comparative Analysis of Blockchain Approaches

One of the primary metrics for evaluating blockchain approaches is their effectiveness in improving transparency and accountability. Public blockchains, such as Ethereum, offer fully decentralized and immutable records, ensuring that all stakeholders can access and verify transaction histories. This openness enhances trust and reduces opportunities for fraud, misreporting, or disputes across complex construction supply chains. However, the lack of access control may be problematic in projects that require confidentiality, such as proprietary designs or sensitive financial transactions. Private or consortium blockchains, including Hyperledger Fabric or Corda, provide controlled access while maintaining the immutability of records. These platforms are particularly effective for projects involving multiple contractors and suppliers, as they allow selective visibility, ensuring accountability without exposing sensitive data to all participants. Comparative studies suggest that while public blockchains maximize transparency, permissioned systems often achieve a better balance between transparency, confidentiality, and compliance requirements, especially in commercial construction contexts.

Scalability is another critical factor, as construction projects vary widely in size, complexity, and geographic dispersion. Public blockchains often face limitations in transaction throughput, latency, and energy consumption, which can constrain their applicability in large-scale infrastructure projects requiring real-time updates. Permissioned blockchains, in contrast, offer higher transaction speeds and can be optimized for project-specific requirements, enabling deployment across multiple sites and stakeholders with lower computational overhead. Hybrid approaches, combining elements of both public and private blockchains, have been explored to leverage the benefits of decentralization while maintaining operational efficiency. These models demonstrate that scalability considerations are closely linked to network architecture, consensus mechanisms, and the degree of participant governance, making the choice of blockchain approach context-dependent.

Integration with other technologies significantly enhances the functionality and impact of blockchain in construction supply chains. The combination of blockchain with Internet of Things (IoT) devices enables automated verification of material deliveries, environmental conditions, and equipment usage, with records immutably stored on the blockchain. Similarly, Building Information Modeling (BIM) integration allows 3D design data and construction schedules to be linked with blockchain-based transaction records, improving project coordination and reducing disputes. Artificial intelligence (AI) can further complement blockchain by analyzing supply chain data to detect anomalies, optimize resource allocation, or predict project risks. Comparative evaluations indicate that blockchain alone provides foundational transparency, but its integration with IoT, BIM, and AI amplifies operational efficiency, risk mitigation, and decision-making capabilities across the construction lifecycle (Götz *et al*., 2022; Raval and Sarkar, 2023) [20, 43].

Despite the advantages, blockchain approaches also involve trade-offs, limitations, and interoperability challenges. Public blockchains face issues such as high energy consumption, slower transaction processing, and regulatory uncertainty. Permissioned blockchains require robust governance structures and consensus mechanisms, which can introduce administrative complexity. Interoperability remains a persistent challenge, as different platforms often employ incompatible protocols, data standards, and access controls, complicating collaboration across projects or regions. Moreover, blockchain does not inherently verify the quality or authenticity of input data; errors or falsified inputs at the source can propagate immutably through the system, underscoring the need for complementary verification processes. Cost considerations, stakeholder adoption willingness, and the need for digital literacy among project participants further influence the practicality of implementation.

Comparative analysis of blockchain approaches in construction supply chains reveals a nuanced landscape in which platform choice, integration strategies, and contextual factors determine effectiveness. Public blockchains offer maximum transparency, while private and consortium models provide a balance between accountability and confidentiality. Scalability and performance are enhanced in permissioned systems, particularly for large or complex projects, and integration with IoT, BIM, and AI substantially strengthens operational capabilities. Nevertheless, trade-offs related to interoperability, governance, data integrity, and cost must be carefully managed. Understanding these comparative dimensions enables construction professionals to design blockchain-enabled supply chains that optimize transparency, sustainability, and efficiency while aligning with project-specific requirements.

2.4 Policy, Governance, and Industry Adoption

The integration of blockchain technology into construction supply chains is not purely a technical challenge; it is deeply intertwined with regulatory frameworks, governance structures, industry standards, and adoption dynamics. As blockchain enables transparent, immutable, and decentralized record-keeping, policy and governance mechanisms play a pivotal role in shaping its implementation, ensuring compliance, and promoting sustainable and efficient supply chain practices as shown in Fig 3 (Rozas *et al*., 2021; Ogunwale *et al*., 2023) [45, 36]. Understanding these dimensions is essential for fostering wider adoption and realizing the full potential of blockchain in construction.

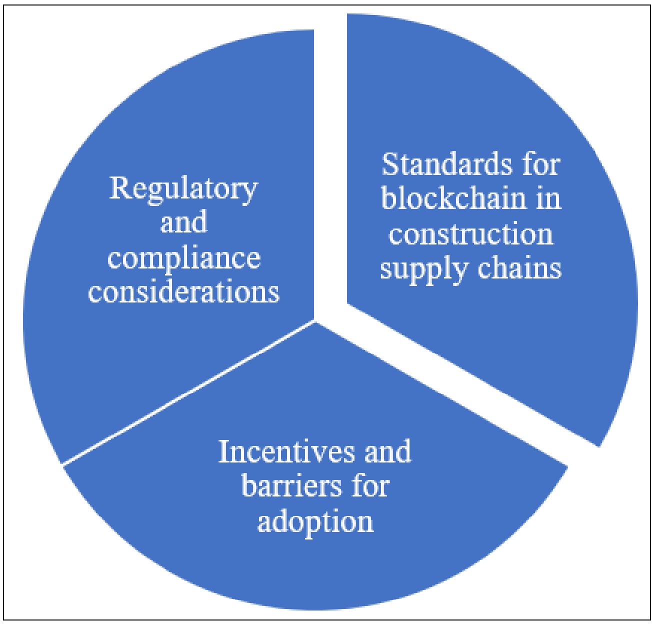

Fig 3: Regulatory frameworks of blockchain

Regulatory and compliance considerations form a foundational aspect of blockchain deployment in construction. Construction supply chains are governed by complex regulations related to material sourcing, environmental impact, labor standards, safety protocols, and financial reporting. Blockchain systems must operate within these regulatory boundaries, ensuring that transactions are auditable and compliant with local and international standards. For instance, immutable ledgers can facilitate adherence to building codes and environmental reporting requirements by automatically recording compliance data at each stage of the supply chain. Conversely, the decentralized and cross-border nature of blockchain raises regulatory challenges, such as jurisdictional ambiguities, data privacy concerns, and conflicts with existing contractual frameworks. Policymakers and industry regulators are therefore tasked with establishing clear legal recognition of blockchain records, defining liability in case of errors, and harmonizing blockchain use with existing construction laws.

The establishment of standards is another critical enabler for effective blockchain adoption in construction supply chains (Amin *et al*., 2022; Okanlawon *et al*., 2023 [37]). Standardization ensures interoperability between different blockchain platforms, consistent data formats, and transparent reporting of transactions. Organizations such as ISO and industry consortia have begun developing frameworks for blockchain application in construction, covering aspects such as data integrity, security protocols, consensus mechanisms, and traceability of materials. Standardized practices allow contractors, suppliers, and regulators to trust blockchain records, reduce disputes, and facilitate cross-project or cross-region collaborations. Without harmonized standards, fragmented implementations may hinder scalability and limit the broader impact of blockchain on supply chain transparency and sustainability.

Incentives and barriers for adoption significantly influence industry uptake. On the incentive side, blockchain offers tangible benefits such as enhanced traceability of materials, reduced administrative overhead, improved coordination among stakeholders, and strengthened compliance reporting. Organizations that adopt blockchain can differentiate themselves in sustainability reporting, achieve higher operational efficiency, and gain reputational advantages in increasingly environmentally conscious markets. Financial incentives, including subsidies, tax breaks, or preferential procurement policies for technology adoption, can further accelerate uptake. However, barriers remain, including high initial investment costs, lack of technical expertise, resistance to change among traditional contractors, and uncertainties regarding return on investment. Cultural factors within the construction industry, which is often risk-averse and project-driven, can also slow adoption despite the potential long-term benefits.

Early adopters across different regions provide valuable insights into blockchain deployment in construction supply chains (Tezel *et al*., 2021; Cheng and Chong, 2022) [51, 13]. In Europe, the Netherlands has pioneered blockchain pilots in circular construction, enabling the tracking of recycled materials from demolition sites to new building projects. In Asia, Singapore has integrated blockchain with Building Information Modeling (BIM) to enhance project coordination and contract management in large-scale urban developments. North American projects have focused on combining blockchain with IoT to monitor supply chain logistics and verify sustainable sourcing of materials. These case studies demonstrate the feasibility of blockchain implementation across varied regulatory environments and project scales, highlighting both successes and challenges in governance, standardization, and stakeholder engagement. Lessons from early adopters emphasize the importance of aligning technology deployment with regulatory frameworks, establishing clear governance structures, and fostering collaboration among contractors, technology providers, and policymakers.

The adoption of blockchain in construction supply chains is shaped by a complex interplay of policy, governance, and industry dynamics (Qian and Papadonikolaki, 2021 [40]; Amin *et al*., 2022). Regulatory frameworks and compliance requirements provide the boundaries within which blockchain systems must operate, while standards ensure interoperability and reliability of data. Incentives can accelerate adoption, whereas technical, financial, and cultural barriers must be carefully managed. Early adopter experiences from Europe, Asia, and North America illustrate the transformative potential of blockchain for supply chain transparency and sustainability, while also revealing the challenges associated with governance, integration, and standardization. Successful scaling of blockchain-enabled construction supply chains will depend on coordinated policy support, robust governance structures, adherence to evolving standards, and the strategic alignment of technology with industry practices.

2.5 Key Findings and Trends

The adoption of blockchain technology in construction supply chains is revealing several important patterns and trends, reflecting both the maturity of the technology and its potential to address systemic challenges in transparency, efficiency, and sustainability. Across the literature and industry reports, emerging applications highlight blockchain's capacity to integrate complex, multi-stakeholder networks into decentralized digital ecosystems, offering operational, environmental, and economic benefits.

A prominent pattern is the increasing focus on end-to-end visibility and traceability. Construction supply chains, characterized by fragmented actors and multiple tiers of suppliers, have historically struggled with information asymmetry, leading to inefficiencies and governance challenges. Blockchain addresses this by providing an immutable record of transactions, enabling real-time monitoring of material flows, procurement, and project milestones. Another trend is the integration of smart contracts for automated enforcement of agreements, which reduces delays in payment processing, mitigates disputes, and aligns incentives across contractors, suppliers, and clients (Hamledari and Fischer, 2021; Xu *et al*., 2021) [24, 53]. Collectively, these mechanisms enhance trust and coordination, transforming traditional linear supply chains into transparent, accountable networks.

Recent innovations emphasize the creation of decentralized digital platforms that link blockchain with complementary technologies such as the Internet of Things (IoT), Building Information Modeling (BIM), and artificial intelligence (AI). IoT sensors provide real-time data on material usage, transportation, and construction progress, while BIM models integrate design and operational information into a shared digital environment. When combined with blockchain, these technologies allow for secure, verified, and automated tracking of materials, costs, and emissions. Emerging ecosystems also include tokenized incentives to encourage sustainable practices, such as rewarding suppliers for using low-carbon materials or participating in circular economy initiatives. These innovations point toward a broader trend of digital convergence, where blockchain serves as the backbone of integrated, data-driven construction supply chains.

Adoption of blockchain varies significantly across regions and construction sectors. In developed economies such as Europe, North America, and parts of Asia, early deployments focus on large-scale commercial and infrastructure projects, often involving high-value materials and complex supply chains. For instance, Amsterdam has implemented blockchain in circular construction initiatives, while Singapore integrates blockchain with digital platforms for procurement and sustainability reporting. By contrast, adoption in developing economies remains nascent, constrained by financial, technological, and regulatory barriers (Nazir and Roomi, 2021; Akang, 2023) [34, 2]. Nonetheless, pilot projects leveraging blockchain for material tracking, waste management, and local supply chain coordination are emerging, particularly in urban infrastructure and public-sector projects. Sectorally, high-value, complex projects—such as large commercial buildings, transport infrastructure, and energy facilities—tend to lead adoption due to their need for enhanced transparency and risk mitigation, whereas smaller-scale residential projects are slower to integrate blockchain.

Empirical and case-based evidence suggests that blockchain-enabled supply chains can generate measurable sustainability benefits. Efficiency gains are observed through automated procurement, reduced delays, and streamlined documentation. Waste reduction is facilitated by better material tracking, verification of surplus utilization, and enabling circular economy practices. Additionally, carbon and emission tracking is enhanced by integrating blockchain with IoT and BIM, allowing accurate monitoring of embodied and operational carbon throughout the project lifecycle. These outcomes indicate that blockchain is not only an operational tool but also a strategic enabler of environmentally responsible construction practices.

Overall, the key findings reveal that blockchain is increasingly being embedded as a core component of digitalized construction supply chains, enabling greater transparency, trust, and sustainability. The convergence of blockchain with IoT, BIM, and AI is driving the development of decentralized digital ecosystems capable of real-time monitoring, automated enforcement, and lifecycle tracking (Sepasgozar *et al*., 2023; Zhong *et al*., 2023) [47, 54]. While adoption is concentrated in technologically advanced regions and complex project types, there is growing interest in applying blockchain across diverse geographies and scales. Importantly, early evidence indicates tangible sustainability outcomes in terms of efficiency, waste reduction, and emissions accountability. These trends highlight the potential for blockchain to transform traditional construction supply chains into resilient, transparent, and environmentally responsible networks, paving the way for broader integration with global sustainability agendas.

2.6 Research Gaps and Challenges

The application of blockchain technology in construction supply chains has garnered significant academic and industry interest, promising enhanced transparency, accountability, and sustainability. However, despite its potential, the field remains characterized by substantial research gaps and practical challenges that constrain widespread adoption. A critical examination of these gaps reveals limitations in empirical evidence, technical maturity, economic viability, organizational readiness, and human capital, all of which must be addressed to advance blockchain deployment in construction (Singh *et al*., 2022; Gupta *et al*., 2022) [48, 22].

One of the most prominent research gaps is the lack of empirical data from large-scale deployments. While numerous pilot projects and case studies exist, they are often limited to single buildings, small construction sites, or experimental frameworks that do not reflect the complexities of extensive urban infrastructure projects. Consequently, there is insufficient evidence on the scalability, operational performance, and long-term sustainability impacts of blockchain-enabled supply chains (Jabbar *et al*., 2021; Kamble *et al*., 2023) [26, 28]. Metrics related to cost savings, reduction in material waste, transaction efficiency, and stakeholder coordination remain underreported, hindering the ability to generalize findings or develop predictive models. The scarcity of longitudinal studies further constrains understanding of lifecycle outcomes, regulatory compliance, and systemic risks associated with blockchain implementation. Filling this empirical gap is essential for validating theoretical benefits, guiding policy frameworks, and informing investment decisions in the construction sector.

Technical challenges also present significant barriers. Interoperability among heterogeneous blockchain platforms remains limited, with differing protocols, consensus mechanisms, and data structures preventing seamless integration across multiple projects, suppliers, or geographic regions. Scalability is another concern, particularly for public blockchain networks, where transaction throughput, latency, and energy consumption may be inadequate for large-scale construction operations. Energy-intensive consensus mechanisms, such as proof-of-work, exacerbate environmental concerns and may offset some sustainability gains intended through blockchain deployment. Moreover, integration with complementary technologies—such as Building Information Modeling (BIM), Internet of Things (IoT) sensors, and artificial intelligence (AI)—requires standardized interfaces and robust data management frameworks, which are still evolving. Addressing these technical hurdles is critical to ensure reliable, efficient, and environmentally responsible blockchain operations in complex construction supply chains.

Economic and organizational barriers further complicate adoption. The upfront costs associated with blockchain infrastructure, including software development, hardware deployment, and ongoing maintenance, can be substantial, particularly for small and medium-sized contractors (Royo *et al*., 2021; Habib *et al*., 2022) [44, 23]. Return on investment remains uncertain due to limited empirical evidence, deterring firms from committing resources to adoption. Organizationally, construction supply chains are traditionally fragmented and project-focused, with multiple stakeholders operating under different contractual, financial, and operational models. Implementing blockchain requires alignment across these actors, which can be challenging in environments with weak collaboration mechanisms or entrenched practices. Resistance may arise due to perceived risks, disruption of established workflows, or concerns about exposing sensitive data to external parties. Overcoming these economic and organizational constraints is essential for scaling blockchain solutions beyond isolated pilots.

Human capital and cultural factors also play a critical role. Effective blockchain adoption requires skilled personnel capable of managing digital ledgers, coding smart contracts, and integrating blockchain with existing enterprise systems. Current workforce capabilities in the construction sector are often limited in these areas, leading to knowledge gaps that impede implementation. Cultural resistance is equally significant, as construction professionals may perceive blockchain as complex, opaque, or unnecessary compared to conventional processes. Overcoming skepticism and fostering trust among stakeholders—including contractors, suppliers, regulators, and clients—is essential for widespread adoption. Training, capacity-building initiatives, and participatory change management approaches can mitigate these barriers, but systematic research on effective strategies remains sparse (Gupta *et al*., 2022; Loper *et al*., 2022) [22, 32].

The adoption of blockchain in construction supply chains is constrained by multiple interrelated research gaps and practical challenges. Empirical evidence from large-scale projects is scarce, limiting confidence in claimed benefits and lifecycle impacts. Technical issues such as interoperability, scalability, and energy consumption require innovative solutions and standardization. Economic and organizational factors, including high upfront costs and fragmented supply chains, hinder investment and collaborative deployment. Finally, workforce skills and cultural resistance present additional obstacles that must be addressed through education, training, and participatory approaches. Addressing these gaps is critical to enabling blockchain to fulfill its potential in enhancing transparency, sustainability, and efficiency in construction supply chains, and represents a key agenda for both researchers and industry practitioners.

2.7 Future Directions

Blockchain technology has demonstrated significant potential for transforming construction supply chains, yet its full impact is still emerging. Future directions center on deeper integration with digital infrastructure, fostering global collaboration, advancing lifecycle-based sustainability monitoring, and implementing policy and industry incentives to accelerate adoption. These avenues collectively point toward the development of more transparent, efficient, and environmentally responsible construction systems.

One of the most promising directions is the integration of blockchain with digital twins—virtual replicas of physical assets that provide real-time monitoring and simulation capabilities. Digital twins enable continuous tracking of construction materials, energy consumption, and structural performance. When combined with blockchain, all data generated by the digital twin can be securely recorded and verified, ensuring immutability, traceability, and transparency. This integration supports automated decision-making through smart contracts, enabling actions such as automatic reordering of materials, verification of sustainability compliance, and predictive maintenance scheduling. In smart infrastructure contexts, blockchain can link real-time operational data with procurement and maintenance records, creating a fully integrated ecosystem that enhances resource efficiency and supports long-term asset sustainability (Brandín and Abrishami, 2021; Omisola *et al*., 2023) [10, 38].

The decentralized nature of blockchain presents opportunities for global collaboration and standardization. Construction supply chains often span multiple countries, with varying regulatory frameworks, quality standards, and reporting requirements. Blockchain can serve as a common platform for exchanging verified data across borders, facilitating interoperability and harmonization of standards. International organizations, industry consortia, and research networks could leverage blockchain to establish common protocols for material certification, carbon accounting, and compliance reporting, thereby enabling comparability and benchmarking across regions. Such harmonization would reduce transaction costs, enhance trust between international partners, and accelerate adoption in both developed and developing economies.

A key future direction involves developing lifecycle-based sustainability monitoring frameworks. Current applications of blockchain often focus on discrete processes, such as material tracking or procurement. Future systems could integrate data across the entire lifecycle of a construction project—from raw material extraction and fabrication to transportation, on-site assembly, operation, and end-of-life decommissioning. By embedding environmental metrics such as embodied carbon, energy consumption, and waste generation into blockchain records, stakeholders can conduct comprehensive sustainability assessments and implement data-driven improvement measures. Integration with IoT sensors, BIM models, and AI analytics will enhance the precision of these assessments, enabling dynamic adjustment of supply chain decisions to reduce environmental impacts.

The acceleration of blockchain adoption in construction will require supportive policy frameworks and industry incentives (Balasubramanian *et al*., 2021; Ding *et al*., 2023) [9, 16]. Governments can introduce regulatory mandates or certifications that encourage the use of blockchain for supply chain transparency, sustainability reporting, and risk mitigation. Financial incentives, including tax credits, subsidies, or preferential procurement for blockchain-enabled projects, can reduce adoption costs and encourage innovation. Industry-led initiatives, such as collaborative platforms or consortia, can provide shared resources, training, and governance structures to lower entry barriers for small and medium-sized enterprises. Additionally, targeted capacity-building programs can address knowledge gaps among professionals, ensuring that designers, contractors, and suppliers are equipped to leverage blockchain effectively.

The future of blockchain-enabled construction supply chains lies in integrated digital ecosystems, global standardization, comprehensive lifecycle sustainability monitoring, and a supportive policy and incentive environment. By linking blockchain with digital twins and smart infrastructure, construction projects can achieve unparalleled transparency, operational efficiency, and environmental accountability (Lv *et al*., 2022; Sadri *et al*., 2023) [33, 46]. Global collaboration and standard-setting will facilitate interoperability across international supply chains, while lifecycle-based monitoring will provide holistic insights into environmental performance. Finally, coordinated policy and industry measures will lower adoption barriers, foster innovation, and ensure that blockchain solutions contribute meaningfully to sustainable construction practices. Collectively, these directions point toward a future where blockchain not only improves operational efficiency but also underpins resilient, low-carbon, and circular construction supply chains, aligning with global sustainability agendas and urban development goals.

3. Conclusion

The systematic review of blockchain-enabled construction supply chains highlights several key insights that underscore both the potential and the current limitations of the technology. Blockchain demonstrates significant promise in enhancing transparency, accountability, and sustainability outcomes across construction supply chains. Empirical evidence, although limited, suggests that blockchain can improve traceability of materials, streamline coordination among stakeholders, and support compliance with environmental and regulatory standards. Emerging innovations, including integration with IoT, Building Information Modeling (BIM), and artificial intelligence, further expand the capacity of blockchain to optimize resource flows, reduce waste, and strengthen operational efficiency. However, adoption remains uneven across regions and sectors, influenced by technological, economic, organizational, and cultural factors.

These findings carry important implications for policymakers, industry practitioners, and researchers. Policymakers should consider establishing clear regulatory frameworks, standardization protocols, and incentive mechanisms to facilitate blockchain adoption while ensuring data security, interoperability, and compliance with environmental and safety regulations. Industry practitioners can leverage blockchain to enhance operational efficiency, supply chain visibility, and sustainability performance, but must also address organizational readiness, workforce skills, and integration with existing digital systems. Researchers are called to generate robust empirical evidence from large-scale deployments, assess long-term impacts, and explore solutions to technical and socio-economic challenges, including scalability, energy efficiency, and stakeholder engagement.

The scaling of blockchain solutions in construction requires coordinated action across multiple stakeholders, including governments, contractors, technology providers, and academic institutions. Collaborative initiatives can accelerate knowledge sharing, standard development, and the deployment of interoperable platforms, ensuring that blockchain contributes to more sustainable, transparent, and resilient construction supply chains. Ultimately, the convergence of technological innovation, policy support, and multi-stakeholder collaboration will determine the extent to which blockchain can fulfill its transformative potential in creating circular, efficient, and accountable urban infrastructure systems.

4. References

1. Adewale TT, Olorunyomi TD, Odonkor TN. Blockchain-enhanced financial transparency: A conceptual approach to reporting and compliance. International Journal of Frontiers in Science and Technology Research. 2022; 2(1):24-45.
2. Akang AU. Regulatory compliance and access to finance: Implications for business growth in developing economies. Sciental Journal of Education Humanities and Social Sciences. 2023; 1(2):8-23.
3. Albouq SS, Abi Sen AA, Almashf N, Yamin M, Alshanqiti A, Bahbouh NM. A survey of interoperability challenges and solutions for dealing with them in IoT environment. IEEE Access. 2022; 10:36416-36428.
4. Amin F, Khan KIA, Ullah F, Alqurashi M, Alsulami BT. Key adoption factors for collaborative technologies and barriers to information management in construction supply chains: A system dynamics approach. Buildings. 2022; 12(6):p766.
5. Amin F, Khan KIA, Ullah F, Alqurashi M, Alsulami BT. Key adoption factors for collaborative technologies and barriers to information management in construction supply chains: A system dynamics approach. Buildings. 2022; 12(6):p766.
6. Amjad A, Azam F, Anwar MW, Butt WH. A systematic review on the data interoperability of application layer protocols in industrial IoT. Ieee Access. 2021; 9:96528-96545.
7. Antal C, Cioara T, Anghel I, Antal M, Salomie I. Distributed ledger technology review and decentralized applications development guidelines. Future Internet. 2021; 13(3):p62.
8. Bacchetta AVB, Krümpel V, Cullen E. Transparency with blockchain and physical tracking technologies: Enabling traceability in raw material supply chains. Materials Proceedings. 2021; 5(1):p1.
9. Balasubramanian S, Shukla V, Islam N, Manghat S. Construction industry 4.0 and sustainability: An enabling framework. IEEE Transactions on Engineering Management. 2021; 71:1-19.
10. Brandín R, Abrishami S. Information traceability platforms for asset data lifecycle: Blockchain-based technologies. Smart and Sustainable Built Environment. 2021; 10(3):364-386.
11. Centobelli P, Cerchione R, Oropallo E, El-Garaihy WH, Farag T, Al Shehri KH. Towards a sustainable development assessment framework to bridge supply chain practices and technologies. Sustainable Development. 2022; 30(4):647-663.
12. Chen Q, Hall DM, Adey BT, Haas CT. Identifying enablers for coordination across construction supply chain processes: A systematic literature review. Engineering, Construction and Architectural Management. 2021; 28(4):1083-1113.
13. Cheng M, Chong HY. Understanding the determinants of blockchain adoption in the engineering-construction industry: Multi-stakeholders' analyses. IEEE Access. 2022; 10:108307-108319.
14. Davari S, Jaberi M, Yousfi A, Poirier E. A traceability framework to enable circularity in the built environment. Sustainability. 2023; 15(10):p8278.
15. Deng W, Huang T, Wang H. A review of the key technology in a blockchain building decentralized trust platform. Mathematics. 2022; 11(1):p101.
16. Ding S, Hu H, Dai L, Wang W. Blockchain adoption among multi-stakeholders under government subsidy: From the technology diffusion perspective. Journal of Construction Engineering and Management. 2023; 149(5):p04023016.
17. Dodevski Z, Filiposka S, Mishev A, Trajkovik V. Real time availability and consistency of health-related information across multiple stakeholders: A blockchain

based approach. Computer Science and Information Systems. 2021; 18(3):927-955.
18. Dong S, Abbas K, Li M, Kamruzzaman J. Blockchain technology and application: An overview. PeerJ Computer Science. 2023; 9:p.e1705.
19. Fasasi ST, Nwokediegwu ZS, Adebowale OJ. New Concepts in Cross-Functional Compliance Integration for Emissions Monitoring in Regulatory Mechanical Engineering Projects, 2023.
20. Götz CS, Karlsson P, Yitmen I. Exploring applicability, interoperability and integrability of Blockchain-based digital twins for asset life cycle management. Smart and Sustainable Built Environment. 2022; 11(3):532-558.
21. Groschopf W, Dobrovnik M, Herneth C. Smart contracts for sustainable supply chain management: Conceptual frameworks for supply chain maturity evaluation and smart contract sustainability assessment. Frontiers in Blockchain. 2021; 4:p506436.
22. Gupta A, Singh RK, Gupta S. Developing human resource for the digitization of logistics operations: readiness index framework. International Journal of Manpower. 2022; 43(2):355-379.
23. Habib G, Sharma S, Ibrahim S, Ahmad I, Qureshi S, Ishfaq M. Blockchain technology: Benefits, challenges, applications, and integration of blockchain technology with cloud computing. Future Internet. 2022; 14(11):p341.
24. Hamledari H, Fischer M. Role of blockchain-enabled smart contracts in automating construction progress payments. Journal of Legal Affairs and Dispute Resolution in Engineering and Construction. 2021; 13(1):p04520038.
25. Howell BE, Potgieter PH. Uncertainty and dispute resolution for blockchain and smart contract institutions. Journal of Institutional Economics. 2021; 17(4):545-559.
26. Jabbar S, Lloyd H, Hammoudeh M, Adebisi B, Raza U. Blockchain-enabled supply chain: Analysis, challenges, and future directions. Multimedia Systems. 2021; 27(4):787-806.
27. John K, Kogan L, Saleh F. Smart contracts and decentralized finance. Annual Review of Financial Economics. 2023; 15(1):523-542.
28. Kamble SS, Gunasekaran A, Subramanian N, Ghadge A, Belhadi A, Venkatesh M. Blockchain technology's impact on supply chain integration and sustainable supply chain performance: Evidence from the automotive industry. Annals of Operations Research. 2023; 327(1):575-600.
29. Khan SN, Loukil F, Ghedira-Guegan C, Benkhelifa E, Bani-Hani A. Blockchain smart contracts: Applications, challenges, and future trends. Peer-to-peer Networking and Applications. 2021; 14(5):2901-2925.
30. Koc K, Gurgun AP. Stakeholder-associated life cycle risks in construction supply chain. Journal of Management in Engineering. 2021; 37(1):p04020107.
31. Liu X, Yang Y, Jiang Y, Fu Y, Zhong RY, Li M, *et al.* Data-driven ESG assessment for blockchain services: A comparative study in textiles and apparel industry. Resources, Conservation and Recycling. 2023; 190:p.106837.
32. Loper AC, Jensen TM, Farley AB, Morgan JD, Metz AJ. A systematic review of approaches for continuous quality improvement capacity-building. Journal of Public Health Management and Practice. 2022; 28(2):E354-E361.
33. Lv Z, Chen D, Lv H. Smart city construction and management by digital twins and BIM big data in COVID-19 scenario. ACM Transactions on Multimedia Computing, Communications, and Applications (TOMM). 2022; 18(2S):1-21.
34. Nazir MA, Roomi MA. Barriers to adopting electronic commerce for small and medium-sized enterprises in emerging economies. Emerging Markets Journal (EMAJ). 2021; 10(2):44-55.
35. Nicoletti L, Sirenko M, Verma T. Disadvantaged communities have lower access to urban infrastructure. Environment and Planning B: Urban Analytics and City Science. 2023; 50(3):831-849.
36. Ogunwale B, Oboyi N, Sobowale A, Alabi OA, Gobile S, Ojonugwa BM. Investigating the Evolution and Impact of Blockchain Beyond Cryptocurrencies into Decentralized Applications, 2023.
37. Okanlawon TT, Oyewobi LO, Jimoh RA. Evaluation of the drivers to the implementation of blockchain technology in the construction supply chain management in Nigeria. Journal of Financial Management of Property and Construction. 2023; 28(3):459-476.
38. Omisola JO, Bihani D, Daraojimba AI, Osho GO, Ubamadu BC, Etukudoh EA. Blockchain in supply chain transparency: A conceptual framework for real-time data tracking and reporting using blockchain and AI. International Journal of Multidisciplinary Research and Growth Evaluation. 2023; 4.
39. Onoja JP, Ajala OA. Innovative telecommunications strategies for bridging digital inequities: A framework for empowering underserved communities. GSC Advanced Research and Reviews. 2022; 13(1):210-217.
40. Qian X, Papadonikolaki E. Shifting trust in construction supply chains through blockchain technology. Engineering, Construction and Architectural Management. 2021; 28(2):584-602.
41. Rahman MS, Chamikara MAP, Khalil I, Bouras A. Blockchain-of-blockchains: An interoperable blockchain platform for ensuring IoT data integrity in smart city. Journal of Industrial Information Integration. 2022; 30:p100408.
42. Rane SB, Narvel YAM. Data-driven decision making with Blockchain-IoT integrated architecture: A project resource management agility perspective of industry 4.0. International Journal of System Assurance Engineering and Management. 2022; 13(2):1005-1023.
43. Raval P, Sarkar D. Enhancing Construction Project Interoperability with Blockchain and BIM: A Fuzzy TOPSIS Evaluation Approach. In International Conference on Computational Modeling and Sustainable Energy. Singapore: Springer Nature Singapore, December 2023, 651-666.
44. Royo PM, Rodríguez-Molina J, Garbajosa J, Castillejo P. Towards blockchain-based internet of things systems for energy smart contracts with constrained hardware devices and cloud infrastructure. IEEE Access. 2021; 9:77742-77757.
45. Rozas D, Tenorio-Fornés A, Díaz-Molina S, Hassan S. When ostrom meets blockchain: Exploring the potentials of blockchain for commons governance. Sage Open. 2021; 11(1):p.21582440211002526.

46. Sadri H, Yitmen I, Tagliabue LC, Westphal F, Tezel A, Taheri A, Sibenik G. Integration of blockchain and digital twins in the smart built environment adopting disruptive technologies-A systematic review. Sustainability. 2023; 15(4):p3713.
47. Sepasgozar SM, Khan AA, Smith K, Romero JG, Shen X, Shirowzhan S, *et al*. BIM and digital twin for developing convergence technologies as future of digital construction. Buildings. 2023; 13(2):p441.
48. Singh RK, Agrawal S, Modgil S. Developing human capital 4.0 in emerging economies: An industry 4.0 perspective. International Journal of Manpower. 2022; 43(2):286-309.
49. Stroumpoulis A, Kopanaki E. Theoretical perspectives on sustainable supply chain management and digital transformation: A literature review and a conceptual framework. Sustainability. 2022; 14(8):p4862.
50. Teisserenc B, Sepasgozar SM. Software architecture and non-fungible tokens for digital twin decentralized applications in the built environment. Buildings. 2022; 12(9):p1447.
51. Tezel A, Febrero P, Papadonikolaki E, Yitmen I. Insights into blockchain implementation in construction: Models for supply chain management. Journal of Management in Engineering. 2021; 37(4):p.04021038.
52. Xu J, Lou J, Lu W, Wu L, Chen C. Ensuring construction material provenance using Internet of Things and blockchain: Learning from the food industry. Journal of Industrial Information Integration. 2023; 33:p.100455.
53. Xu Y, Chong HY, Chi M. A review of smart contracts applications in various industries: a procurement perspective. Advances in Civil Engineering. 2021; 1:p.5530755.
54. Zhong B, Pan X, Ding L, Chen Q, Hu X. Blockchain-driven integration technology for the AEC industry. Automation in Construction. 2023; 150:p.104791.
55. Zhu P, Hu J, Li X, Zhu Q. Using blockchain technology to enhance the traceability of original achievements. IEEE Transactions on Engineering Management. 2021; 70(5):1693-1707.