2025 European Conference on Computing in Construction

CIB W78 Conference on IT in Construction

Porto, Portugal
July 14-17, 2025

A DECENTRALIZED BLOCKCHAIN FRAMEWORK FOR TRACING GREEN/SUSTAINABLE MATERIALS DURING BUILDING LIFE CYCLE

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Abstract

Sustainability awareness stoked the need to trace green/sustainable materials throughout the building life cycle to minimize environmental impacts, optimize resource use, and meet the standards of environmentally responsible construction practices. Traditional material tracing systems harness centralized servers, posing security and transparency issues. Blockchain technologies enable alternatives for achieving decentralized systems, which can resolve the limitations of centralized ones. Few blockchain and smart contract frameworks are presented for supply chain management, yet scarce research focused on tracing green/sustainable materials. This study aims to present a decentralized green/sustainable material tracing system framework for building life cycle with blockchain and smart contract technologies.

Introduction

There has been a significant raise in the awareness for the environment and the importance of sustainability in recent years with the influence of population growth and urbanization, which brings an exponentially increasing demand for the environmentally responsible and green constructions considering the huge role and impact of the construction industry in almost every environmental measure including energy consumption, carbon emission, waste generation, and raw material extraction. So, in order to meet these demands and minimize the environmental side effects of the constructions, numerous construction strategies and methods, which are applicable from the planning and design stages to the final operation and management stages of a building life cycle, have been developed.

One of the most used environmentally responsible methods for combining sustainability with construction projects is to use green or sustainable materials during the entire building life cycle. Although these materials are integral to environmentally responsible construction practices, they encompass distinct principles and objectives. Green materials specifically refer to those that minimize harm to the environment during their production, use, and disposal, while they are often renewable, non-toxic, energy-efficient, and sourced responsibly to reduce their carbon footprint. On the other hand, sustainable materials refer to a more holistic approach by addressing not only environmental concerns but also economic and social benefits. These materials consider the entire lifecycle of a building, aiming to enhance long-term performance and resilience while supporting economic vitality and community well-being. Sustainable materials often include locally sourced products to reduce transportation emissions, materials that are durable and require minimal maintenance, and those that can be easily recycled or repurposed. So, the use of both green and sustainable materials is driven by the growing need to balance the construction industry's demands to mitigate climate change, reduce waste, and promote healthier living environments.

The integration of green or sustainable materials to the construction projects plays a significant role in fostering a more environmentally responsible future, which thus creates an essential need for advanced material tracing systems since the complex processes of the construction projects require high level of coordination and collaboration among the stakeholders of the different stages of the building life cycles. Moreover, tracing green/sustainable materials during the different stages of building life cycles are also crucial for actually achieving the goals of the environmentally responsible construction practices, especially considering the increasing trend in the greenwashing marketing strategies that may mislead the public (Li, J., Niu, J., & Liu, Y. 2023). On the other hand, most of the existing material tracing systems are centralized systems with limitations depending on responsible parties and thus creating possible threats of trust, security, serviceability, traceability, transparency, and integrity.

With the help of the advancement of blockchain and smart contract technologies in recent years, an effective solution for the existing problems can be obtained with a decentralized green/sustainable material tracing system which is designed to provide a secure, transparent, and trustworthy platform for tracing and monitoring the information regarding the green or sustainable materials used depending on the requirements and needs of the construction projects during the stages of the building life cycles (Li et al. 2023, Bułkowska et al. 2023). Therefore,

in this proceeding, a smart contract powered blockchain framework for decentralized green/sustainable material tracing system for building life cycle is presented as an alternative that eliminates the limitations of traditional centralized models by improving the materials' accessible information and secured data flow among various stakeholders, minimizing the possible problems and uncertainties, in addition to providing convenient management of coordination and collaboration.

This proceeding is organized as follows: In Literature Review Section, the existing researches and works in addition to the possible contributions of the proposed framework to the existing systems are discussed. The proposed framework and the used tools for it are given in section three, Proposed Decentralized Blockchain Framework, in detail. In Discussion of the Framework Section, the advantages and possible variations of the proposed framework are discussed in addition to the proposed framework's comparison to the existing solutions, along with its vulnerabilities, potential user risks, limitations, and adoption processes. Finally, in the Conclusions section, concluding remarks are provided for a more efficient green/sustainable material tracing system in construction industry with smart contracts together with the limitations of this paper and the recommendations for the future research directions.

Literature Review

As a result of the new advancements in the technologies, the blockchain and smart contract based systems have been started to be used as a solution for the ongoing problems of many sectors including the construction industry projects. Frisch et al. (2023) proposed blockchain technology using the Ethereum protocol as the optimal trustless, transparent, immutable, and always accessible solution to document forgery problem in the field of higher education compared to the centralized electronic document verification systems which require trust to a third party for verification and bring the risk of single point of failure in addition to data manipulation. As Flanagan et al. (2023) mentioned supply chain management is also one of the industries that benefit from the advancements in the blockchain technologies, so there are several blockchain and smart contract frameworks that have been proposed especially for supply chain management. Considering the limitations of the traditional systems such as the fragmentation, lack of trust among the stakeholders and the restricted information sharing as stated in Basheer et al. (2024), the blockchain and smart contract based systems can be a solution since they improve the traceability and transparency for the supply chain material information and create an environment with high level of accountability and trustworthiness among the stakeholders. Also, Kulkarni et al. (2023) and Turjo et al. (2021) stated that the existing supply chain processes, which may include untrustworthy organizations during the entire process from raw material extraction to the ultimate consumption of a finished product and thus are ineffective and untrustworthy for consumers, can be replaced with the utilization of the smart contracts with trackable, irreversible, and credible performances and decentralized blockchain technologies that protect data from unauthorized access without the involvement of third parties. Moreover, with the abovementioned advantages of the blockchain and smart contract applications can be utilized also in the material quality control processes where the production must meet certain standards that range from quality control to the quality of the used materials (Gaiardelli et al., 2022).

Gayialis et al. (2022) mentioned that there is an increasing need and demand in recent years for effective traceability due to the growing consumer awareness of the quality of products in the wine industry considering the impact of visibility loss of the product origins to the production and distribution processes and the serious fraud risks. A similar perspective can be achieved in the tracing of green/sustainable materials during the different stages of the building life cycle, which requires complex material tracing systems with high level of coordination and collaboration among the stakeholders of the processes; however, there is still scarce research of blockchain and smart contract frameworks that have focused specifically on tracing of green/sustainable materials. Some of the research that combine the sustainability concepts with the blockchain, and smart contract technologies can be reflected as follows. Li et al. (2023) proposed a green supply chain evaluation system based on blockchain and smart contract rules with the characteristics of decentralization, non-tampering, openness and multi-agent transparent participation in the whole process evaluation that improves the efficiency and level of green in the supply chain management, while Bułkowska et al. (2023) implemented the blockchain technology, which provides a secure and transparent system for recording every step in the lifecycle, from waste generation to collection, transportation, recycling, or disposal, in waste management to improve the processes' transparency, traceability, and efficiency since the traditional waste management systems are vulnerable to fraud, mismanagement, and inefficiency and the disposal of waste materials are not transparent due to lack of tracking. Moreover, Xu et al. (2024) introduced a distributed solution for transparent and secure carbon management with the help of the blockchain and smart contract applications stating that the existing carbon management for CMP certification depends on non-transparent, open to manipulation, unreliable and hard to track traditional centralized data management tools. Santhuja & Anbarasu (2023) also proposed an e-waste management solution based on smart contract and blockchain technologies to manage the e-waste collection and transportation process while ensuring that the e-waste is disposed in an environmentally sustainable manner. So, this study aims to contribute to the existing literature by proposing a decentralized blockchain framework for specifically tracing green/sustainable materials during building life

cycle to improve the used sustainable materials' accessible information and secured data flow in addition to the coordination and collaboration among various stakeholders of different stages, together with minimizing the uncertainties related to the materials and possible greenwashing practices.

Proposed Decentralized Blockchain Framework

In this study, a novel smart contract powered blockchain framework for decentralized green/sustainable material tracing system for the entire building life cycle of construction projects is designed and proposed for secure, transparent, and trustworthy tracing and monitoring of the information for production, design, transportation, construction, testing, and operation stages of green/sustainable materials. The proposed tracing framework consists of different modules which are the blockchain integrated decentralized storage system to store related sustainability documents of the materials and the decentralized smart contract to execute the works of accessing, storing and validating the material information throughout the processes, which are used for the coordination between the stakeholders of the different stages as the owner/employer, contractor and suppliers. These different modules together with their interrelations are schematized and summarized in the provided Figure 1.

The material tracing framework starts with the owner's implementation of the smart contract module, which is monitored by the MetaMask system that controls the user access to the module, for the integration of the Ethereum blockchain storage system with the usage of the contractor to upload the related documents of the sustainable materials' information and the supplier to review, confirm and validate these material information in a secure, transparent, and trustworthy platform. The smart contract module is included to execute decentralized codes on the blockchain. The owner determines the required documentation criteria including the certificates, reports,

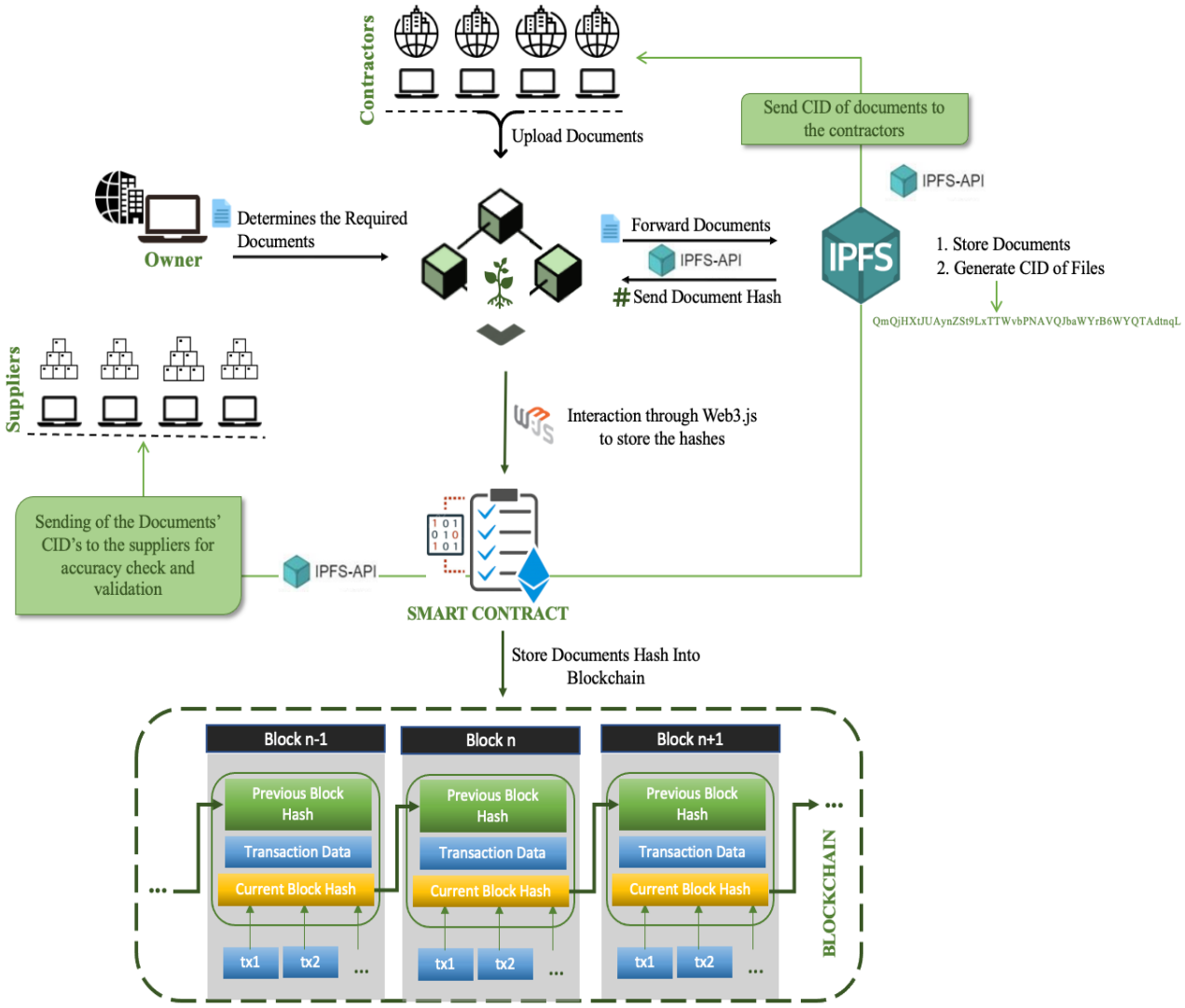

Figure 1: The Proposed Smart Contract Powered Blockchain Framework for Decentralized Green/Sustainable Material Tracing (Ahmadisheykhsarmast et al., 2023)

analysis results, and procurement, supply chain and transportation history of the construction materials decided to be used in each of the specific stages of the building life cycle to prove that these selected materials are actually meet the desired sustainability standards of the project. In the following step, the contractors who can access the smart contract module with their assigned MetaMask profiles upload the related requested documents through the system to prove that they use the required quality and level of standard sustainable materials to perform the project, and then the smart contract system forwards these submitted documents of the contractors to the provided suppliers, who also have the authorized public keys to access the module, of the related materials for the approval of the provided information accuracy in a decentralized manner without the interaction of the owner or any other trusted organization. The framework completes with the smart contract identification of the qualified materials when the suppliers confirm the accuracy of the documents needed for the approval of the required sustainability standards of the materials used by the contractors in the projects, and the information of the contractor as well as all the regarding sustainability qualifications of the approved materials used in the project be disclosed through the system to the other users, which makes the whole process highly transparent (Ahmadisheykhsarmast et al., 2023).

The blockchain integrated decentralized storage module presented in the framework is a result of the incorporation of blockchain with decentralized storage technologies due to the limitations of the direct use of the blockchain technology for storing data such as the storable data size resulted from the block size limit, the high cost of document storage, and the possible network problems; moreover, Ahmadisheykhsarmast et al. (2023) implements the IPFS Cloud data storage system for storing and accessing the uploaded documents instead of the other decentralized storage technologies developed recently since it provides a well-established, transparent, and traceable platform for securely storing and distributing large data with blockchain technology by creating unique irreversible cryptographic identifiers called content identifier (CID) for each and every data uploaded. Since the generated CID's change whenever the content of a document is altered, any malicious attempt to change sensitive information may be tracked down, which improves the data integrity and security of the sustainability documents throughout the process. Additionally, the system provides decentralized storage by using different multiple storage nodes to avoid a single point of failure and works properly even if one or a few nodes fail, unlikely to the traditional systems. So, in the presented decentralized blockchain framework for tracing green/sustainable materials, a hash/hyperlink represented with the unique CID's are created with the help of the IPFS Cloud decentralized storage system for each of the required documents that are uploaded by the contractors in order to increase the transparency of the sustainability tracking process since the created CID's are the content proof of each file in the system that are also used by the users to access the stored files; furthermore, due to the comparatively small digital sizes of these generated CID's than the original document sizes, they provide convenient and cost efficient storage and distribution on the blockchain Ethereum. Ahmadisheykhsarmast et al. (2023) presents the usage of the IPFS-API (IPFS JavaScript implementation) and the ipfs.io gateway for the integration of the IPFS Cloud and the proposed blockchain based smart contract framework to play a crucial role by forwarding the documents uploaded to the system to be stored and turn the generated CID back to the user to access the document, in addition to the usage of the web3.js for enabling the smart contract to retrieve and store the CID of the documents into the blockchain.

For the decentralized smart contract module of the proposed framework on the other hand, the usage of the Ethereum blockchain is considered due to its qualifications as scalability, security, privacy, maturity, throughput, cost, efficiency and data storage, based on the blockchain decision framework for project management applications presented by Sonmez et al. (2023), and the usage of the Solidity 0.8.2 language can be verified to achieve transparent and trustless processes. The smart contract module of the proposed system is needed for the execution of all the processes of document uploading, data storage, generating and recording of the hash of the documents, information validation, information tracking, interactions among the stakeholders, validation and status tracking of the authorized contractors and green/sustainable materials, managing the complex material tracing without the involvement of a trusted or third party but with the help of the MetaMask web wallet system for the authorized account management and access to the Ethereum blockchain.

Discussion of the Framework

The proposed smart contract powered blockchain framework for decentralized green/sustainable material tracing system during the building life cycle creates an effective solution for the existing problems by providing a secure, transparent, and trustworthy platform for tracing and monitoring the required information for different stages of sustainable materials as production, design, transportation, construction, testing, and operation stages. The proposed framework provides a solution to eliminate the limitations of the traditional centralized models by improving the materials' accessible information, securing the data flow among various stakeholders, minimizing the possible problems and uncertainties, and thus providing convenient management of coordination and collaboration, in addition to making improvements in different perspectives including cost and security analysis, data security and integrity, anonymity and privacy with the authentication and access control, and resilience to the cyber-attacks which would also aid management of construction projects.

In terms of the cost analysis, the proposed system enables numerous advantages considering the decrease in the administrative costs and burdens since the proposed system for sustainable material tracing performs all the required processes in a decentralized manner without relying on trusted third parties. Yet, there are still some financial concerns regarding the integration, implementation and maintenance of a blockchain based system's requirements including transaction fees paid to the network, which may vary depending on network congestion and the complexity of smart contract operations, and long-term safe distributed storage fee since blockchain networks require redundant storage across multiple nodes to maintain decentralization and security. Public blockchains, such as Ethereum, may experience high gas fees, especially during peak usage periods, which can impact the cost-effectiveness of executing smart contracts and thus should be considered for the cost analysis of the proposed framework. However, in recent years due to increased activity on Layer-2 networks, Ethereum's transaction fees have dropped in recent years. On the other hand, since the long-term safe distributed storage fee of the large datasets resulted from the requested documents directly on the chain can be prohibitively expensive, the IPFS Cloud module is selected and integrated to the presented framework as a solution to minimize the overall cost of the proposed material tracing framework and to enable decentralized storage of documents. IPFS protocol enables use of numerous decentralized cloud solutions.

On the other hand, in terms of the data security and integrity, the proposed smart contract powered blockchain framework provides a secure, transparent, and trustworthy platform with data integrity throughout the tracing and monitoring processes since the storage documents on the system, which are protected with the implementation of the public key cryptography mechanism, cannot be distorted, altered, or removed without the authorized digital signatures. Moreover, a high level of transparency and traceability are achieved with the help of the proposed system that uses the blockchain integrated IPFS Cloud storage for the secure storage of the required sustainability documents and generates unique CID's, that are sensitive to any modification in the document content they represent and thus traceable in the network, stored in the Ethereum blockchain for each of the documents when they are updated to the system by contractors, and thus reduces the possibility of unfair or unjust practices and data leakage in addition to the data manipulation issue that often arises from centralized cloud service providers (Ahmadisheykhsarmast, S., Senji, S. G., & Sonmez, R. 2023). The presented framework also enhances the anonymity and privacy with the help of the authentication and access control gained with the MetaMask system and public keys provided to the different type of stakeholders depends on their usage of the modules considering the removal of the trusted third parties in the sustainable information validation, material tracing and monitoring processes; furthermore, it also increases the workability and trustworthiness of these processes by providing convenient management of coordination and collaboration among the stakeholders. As a final advantage the decentralized and distributed nature of the blockchain system and IPFS Cloud network make the framework resilient to malicious cyber-attacks since the system can properly work and operate even if one or more nodes are down, and the MetaMask public key system adds another layer of security to the system.

The proposed decentralized blockchain framework for tracing green/sustainable materials during the building life cycle offers significant differences and improvements compared to existing centralized material tracing solutions, addressing many of their inherent limitations. Unlike traditional material tracing systems, which create issues related to security and transparency primarily due to their reliance on centralized servers, the proposed framework utilizes blockchain technology to decentralize data storage and management. This shift enhances security and transparency, reducing the risks associated with data manipulation and unauthorized access. Moreover, the integration of smart contracts provides a secure and trustworthy platform to the stakeholders for validating and tracing information, while the existing centralized systems often face challenges related to trust and integrity, as they depend on a single point of control, which can be vulnerable to breaches, thus the framework's resilience to cyber-attacks and its ability to maintain functionality even if some nodes are down representing significant improvements over traditional systems. The proposed framework achieves a high level of transparency and traceability with the use of blockchain and IPFS Cloud storage, since each document is assigned a unique content identifier (CID) that is sensitive to modifications, which ensures that any changes in the documents are traceable. In contrast, centralized systems may lack such robust tracking mechanisms, leading to potential data leakage and manipulation. Furthermore, the decentralized nature of the proposed system reduces administrative costs by eliminating the need for trusted third parties and streamlines processes although it does involve transaction fees associated with blockchain usage, while the traditional systems often incur high operational costs due to reliance on intermediaries, inefficiencies related to manual processing, administrative overhead, and susceptibility to fraudulent activities. Finally, the proposed framework also enhances stakeholders' accessibility of information and control over data flow with public key cryptography and authentication mechanisms, which contrasts with centralized systems where users may have limited control over their data and its validation processes. In summary, the proposed framework not only addresses the limitations of existing centralized solutions but also offers enhanced security, transparency, and efficiency in tracing green/sustainable materials throughout the building life cycle.

On the other hand, considering the usage of advanced technologies like blockchain, smart contracts, and decentralized storage, and the application area as the construction industry where errors or security flaws can have significant financial and operational consequences, the proposed decentralized blockchain framework for tracing green/sustainable materials during the building life cycle, while innovative, is not without its vulnerabilities and potential user risks. These include the reliance on smart contracts, which, despite their ability to automate processes and enhance transparency, can be susceptible to coding errors and vulnerabilities. If a smart contract is poorly designed or contains bugs, it may lead to unintended consequences which could compromise the integrity of the complex material tracing processes of the construction projects. Moreover, the proposed framework's dependence on the Ethereum blockchain introduces risks associated with network congestion and transaction fees. Users may face delays during the document processing and approvals or increased costs during peak usage times, which could deter participation and undermine the system's efficiency. Additionally, while the use of public key authentication enhances data security, it also places the responsibility of safeguarding private keys on users. If a user loses access to their private key, they may permanently lose access to their data and the ability to interact with the smart contract, leading to potential financial and operational drawbacks. Furthermore, the integration of the MetaMask system for user access management, while beneficial for authentication, may expose users to cybersecurity threats. If users are not adequately educated about secure practices, they may inadvertently compromise their accounts, leading to unauthorized access and manipulation of sensitive information. So, the decentralized nature of the framework, while enhancing resilience against cyber-attacks, does not eliminate the risk of malicious actors exploiting vulnerabilities in the system to manipulate data or disrupt operations. Thus, while the proposed framework offers significant advantages, it is crucial to address these vulnerabilities and risks to ensure a secure and reliable material tracing system. The usage of the advanced technologies may also create some technical barriers which can harden the adoption of the framework, especially for smaller construction firms with limited expertise in blockchain development and cybersecurity. Implementing and maintaining smart contracts requires specialized knowledge, making it difficult for non-technical stakeholders to ensure secure deployment and efficient execution. Integrating decentralized storage and blockchain systems with existing industry workflows including enterprise systems and regulatory compliance requirements may require additional financial investment to mitigate these risks, posing an additional challenge for firms with constrained budgets. So, addressing these challenges necessitates user-friendly interfaces, education on smart contract security, and the development of standardized, industry-specific blockchain frameworks.

Considering the discussed significant differences with the traditional centralized systems, for the successful adoption of the proposed decentralized blockchain framework, some adjustments needed to be made by the stakeholders of the construction projects as the contractors, suppliers, and owners in order to integrate this new system into their existing workflows. The contractors must upload the relevant documentations of the sustainability criteria of the materials previously defined by the owner to the smart contract module monitored by MetaMask, and for this integration process to be successfully completed, contractors are required to be familiar with blockchain technology and the specific requirements of the proposed and adopted smart contract system, which may involve training and adjustments in their operational processes. Moreover, the suppliers also play a crucial role in validating the accuracy of the submitted documents, necessitating their active participation and understanding of the decentralized system. The transparency and traceability offered by the blockchain can enhance trust among stakeholders, but it also demands a shift from traditional centralized practices to a more collaborative approach that emphasizes data sharing and communication. Overall, the transition to this new system will likely require a cultural shift within organizations, emphasizing the importance of sustainability and collaboration in the construction industry.

Finally, the proposed decentralized blockchain solution for tracing green/sustainable materials during building life cycle is a framework and is not a fully developed application with real-world testing. Hence, a cost and scalability analysis are not provided for the framework.

Conclusions

In this study, considering the growing awareness in environment and sustainability, a decentralized green/sustainable material tracing system framework for different stages of the entire building life cycle of construction projects is presented. The proposed framework is integrated with the blockchain and smart contract technologies and designed to provide a secure, transparent, and trustworthy platform for validating and tracing the required information for the approval of meeting the desired sustainability standards of the usage of green/sustainable materials. Since the existing centralized material tracing systems pose trust, security, serviceability, traceability, transparency, and integrity issues with limitations, the presented system provides an efficient alternative by enhancing security, privacy, transparency, and fairness as well as reducing greenwashing campaigns and fraud without requiring a trusted third party with the help of the created benefits and advantages of blockchain, smart contracts, and distributed IPFS Cloud storage modules, which are all discussed in detail, to address these issues of the traditional centralized systems.

However, although the smart contract powered blockchain framework for the decentralized green/sustainable material tracing system is proposed as an alternative solution that eliminates the ongoing problems of the traditional centralized models with many provided advantages, it currently has some limitations. Since this proposal presented as a theoretical framework without case study or real-word testing, the proposed material tracing system lacks demonstration of the practical implementation and effectiveness of the proposed system with quantifiable results, which makes it difficult to present the proposed system's performance, cost reduction benefits and scalability. Thus, further practical implementation analysis including cost and scalability aspects are recommended for the future research works to address these limitations of the proposed material tracing system.

Finally, considering that tracing green/sustainable materials is crucial for achieving accurate sustainability standards, reducing environmental impacts, and meeting the demands for environmentally responsible construction practices, some future research directions can be recommended as focusing on the fully autonomation of the system by eliminating the involvement of the suppliers during the validation processes of the required documentation of sustainable materials by the integration of artificial intelligence to smart contract systems for achieving a more improved decentralized green/sustainable material tracing system in the construction industry.

Acknowledgments

We gratefully acknowledge the financial support provided by the Scientific and Technological Research Council of Turkey (TÜBİTAK), under Application Number 1919B022411606.

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