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BLOCKCHAIN-BASED APPROACH TO IMPROVE ENVIRONMENTAL, SOCIAL, AND GOVERNANCE (ESG) REPORTING IN CONSTRUCTION ORGANIZATIONS

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Atul Kumar Singh (corresponding author)
NICMAR Institute of Construction Management and Research, Delhi-NCR, Bahadurgarh, 124507, India
ORCID: https://orcid.org/0000-0003-3092-2041
atulkumarsingh22031996@gmail.com

Nishanth Rao Dugyala
Depatent of Data Science and Business Systems, College of Engineering and Technology, SRM Institute of Science and Technology, Kattankulathur – 603203, Tamil Nadu, India
ORCID: https://orcid.org/0009-0008-9360-3287
dugyalanishanthrao@gmail.com

Farzad Rahimian
School of Computing, Engineering & Digital Technologies, Teesside University, Middlesbrough, UK
ORCID: https://orcid.org/0000-0001-7443-4723
f.rahimian@tees.ac.uk

Faris Elghaish
School of Natural and Built Environment, Queen's University Belfast, Belfast, UK
ORCID: https://orcid.org/0000-0002-7558-6291
F.Elghaish@qub.ac.uk

Saeed Reza Mohandes
Department of Civil Engineering and Management, School of Engineering, The University of Manchester, Manchester, UK
ORCID: https://orcid.org/0000-0001-9149-3928
saeedreza.mohandes@manchester.ac.uk

SUMMARY*: Existing ESG reporting tools in construction organizations often lack transparency and accountability, presenting significant challenges in effectively managing and reporting ESG data. This research addresses the gap in current reporting practices by proposing and validating a hybrid blockchain solution aimed at enhancing ESG reporting in the Architecture, Engineering, and Construction (AEC) industry. The primary objective is to develop a blockchain-based solution that automates ESG reporting, addressing issues such as data fragmentation, lack of verification, and inefficiencies. Adopting a design science approach, the study develops a conceptual framework that combines Ethereum and Hyperledger Fabric to create a hybrid blockchain model for the prototype. The comprehensive literature review highlights key challenges in ESG practices and emphasizes the potential of blockchain technology to overcome these barriers. The findings show that the hybrid blockchain model successfully automates the ESG reporting process, ensuring transparency, immutability, and accountability. The prototype, validated through a case study involving two construction organizations, demonstrates the feasibility of combining Ethereum and Hyperledger Fabric to manage ESG data, reducing errors, preventing manipulation, and enabling real-time reporting. This research enriches the theoretical understanding of blockchain applications in ESG practices. It provides practical implications by offering a tangible, blockchain-based solution that ensures transparent, reliable, and accountable ESG reporting in the construction industry, ultimately contributing to more sustainable practices.*

KEYWORDS*: environmental, social, and governance (ESG), blockchain, smart contract, internet of things (IoT), construction organization.*

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1. INTRODUCTION

Environmental, social, and governance (ESG) indices have gained increased significance in assessing a company's non-financial performance in recent years (Wang *et al.*, 2023). Topics such as energy, waste, stakeholder rights, gender equality, climate change, and product safety fall under the purview of ESG (Hatayama, 2022). Historically, these aspects evolved due to a small number of investors placing a high value on a company's environmental and social standards (Svanberg *et al.*, 2022).

According to Agnese et al. (2023), ESG is progressively crucial as a measure of management effectiveness, business sustainability, and social responsibility. Buller (2020) argues that integrating the public interest into corporate value systems can foster sustainable development, real economic growth, and the transformation of the capital market economy. Zhou et al. (2023) note that ESG is fundamentally gaining popularity as both a concept and an investment strategy. As the industry demands detailed and accurate ESG reports, they can assist investors in making informed decisions. Additionally, a publicly traded company discloses its ESG performance to enhance its brand and attract potential investors (Qi *et al.*, 2024). Reliable ESG data is also imperative for regulatory agencies to conduct an objective evaluation (Lian and Weng, 2024).

ESG reporting today faces three significant challenges. Firstly, most ESG data is collected manually, making it a labor-intensive process prone to errors (Lin and Guan, 2024). For instance, environmental data collection often requires individuals to manually record readings from measuring instruments (Jin *et al.*, 2024), and insufficient data further complicates analytics. Secondly, the lack of transparency in the reporting process erodes confidence, as ESG professional service providers typically rely on data submitted by corporations, raising concerns about the accuracy of these reports (Naeem *et al.*, 2022). Conflicts of interest may compromise the objectivity of reporting, leading to distorted findings. Publicly traded companies are often reluctant to share data with other parties, treating it as trade secrets or private information, a hesitation exacerbated by the absence of reliable procedures for secure and private data sharing (Babkin *et al.*, 2023). Thirdly, there is a lack of standardization in ESG reporting frameworks, as different organizations use varying methodologies and metrics, leading to inconsistencies that make it challenging to compare ESG performance across companies or industries (Zhao et al., 2024). This fragmentation confuses stakeholders and hinders the adoption of universally accepted best practices, ultimately impacting the credibility and utility of ESG reports.

The construction industry increasingly acknowledges blockchain as a disruptive technology within the context of Industry 4.0. Notable attention has been focused on blockchain applications in supply chain management, payment management, and quality management (Benzidia *et al.*, 2021). As a decentralized database, blockchain allows for the establishment of immutable information records (Shah *et al.*, 2021). The integration of smart contracts within a blockchain system has shown potential in automating various business processes, enhancing efficiency and reliability (Zhong *et al.*, 2020). These inherent features position blockchain as a promising avenue for improving ESG assessment within construction organizations (Xue and Chen, 2025). Despite this potential, there is a lack of systematic exploration of how blockchain can effectively contribute to ESG assessment in the construction industry. Addressing this research gap is crucial for advancing ESG assessment practices in construction, driven by real industry challenges rather than mere curiosity about emerging technologies. Additionally, the study is guided by the design science approach and is framed within the ESG reporting guidelines published by the Ministry of Corporate Affairs (MCA), the Securities and Exchange Board of India (SEBI), and the National Stock Exchange (NSE), specifically focusing on ESG reporting in India.

Despite extensive literature examining the relationship between ESG investment and financial performance, there remains a critical gap in addressing how ESG reporting challenges can be systematically resolved within the construction industry. Existing studies have largely emphasized financial outcomes, while issues such as fragmented data collection, transparency concerns, and the absence of standardized reporting practices in construction remain underexplored. To bridge this gap, this paper proposes two complementary solutions: (i) a blockchain-based incentive system for corporate crowdsourcing, and (ii) an Internet of Things (IoT)-enabled platform for ESG reporting (BI-ESG) (Luque-Vílchez *et al.*, 2023). In the proposed framework, IoT establishes a network of interconnected smart devices equipped with sensing, processing, and communication capabilities. These devices replace manual reporting, enabling automated and instantaneous data aggregation from diverse construction sites (Sun and Wang, 2025). The collected data and ESG reports are transferred to a consortium blockchain, where decentralization, authorization, traceability, and immutability ensure secure, transparent, and tamper-proof reporting (Suta, 2023). This architecture supports the reliable creation, evaluation, and distribution of ESG reports (Li *et al.*, 2024).

Additionally, to encourage active participation from firms, the concept of corporate crowdsensing is introduced. Companies that contribute ESG data through blockchain and IoT networks receive cryptocurrency tokens, serving as a reputation score for transparency and accountability (Tian *et al.*, 2025). These tokens can be reviewed by stakeholders without involving financial transactions in report submissions, enhancing trust in the reporting process. The incentive mechanism is modeled as a coalition game, where benefits are allocated based on each company's contribution to ESG key performance indicators (KPIs). To ensure fairness, the Shapley value is applied to determine the maximum token distribution for each KPI (Quayson *et al.*, 2023a).

With the design science approach as its guide, this study aims to address the identified knowledge gap and evaluate the effectiveness of blockchain in tackling two specific challenges within the construction industry. The first challenge involves summarizing existing issues within ESG practices, while the second pertains to assessing the potential of blockchain technology. A thorough literature review was conducted to outline challenges in ESG practices and emphasize the potential of blockchain. Following this, a blockchain-enabled conceptual framework was proposed to enhance ESG assessment in construction organizations. To validate the proposed framework, a prototype system was developed using a hybrid blockchain, combining both Ethereum and Hyperledger Fabric (HLF, version 2.0), providing a tangible demonstration of the conceptual framework in action.

The rest of the paper follows this structure: Section 2 presents the literature review, providing a foundation for the study's theoretical framework. Section 3 outlines the research methodology, detailing the approach and methods used to explore the research questions. Section 4 covers the proof of concept and evaluation, demonstrating the application and effectiveness of the proposed framework. Section 5 discusses the findings, implications, and significance of the research, offering insights into its broader impact. Finally, Section 6 concludes the paper, summarizing the key contributions and suggesting directions for future research.

2. LITERATURE REVIEW

2.1 ESG reporting

The ESG project, initiated in 2004 by the International Finance Corporation and the United Nations Global Compact to promote sustainable development, has significantly influenced the evaluation of non-financial performance (Huarng and Yu, 2024). Over the years, ESG considerations have gained prominence, particularly in urging businesses to reduce their environmental impact. Social responsibility, encompassing moral and legal rectitude, as well as meaningful engagement with society, is highly valued (Bagh *et al.*, 2024). The governance aspect underscores the importance of having an effective management system that addresses all facets of business operations, including strategy (Quayson *et al.*, 2023b).

As sustainable investment gains traction, numerous nations and organizations have enacted legislation mandating listed companies to disclose not only their financial data but also their ESG performance. For instance, the European Union has formulated norms and criteria for environmental information disclosure, resulting in comprehensive and beneficial environmental reporting. This includes adherence to ISO14001 environmental management systems and environmental auditing recommendations (Chen *et al.*, 2023). The United States has also passed legislation relevant to environmental data disclosure, contributing to the creation of government laws (Tan *et al.*, 2024). Since 2017, the Singapore Stock Exchange has mandated all listed companies to comply with specific guidelines for submitting annual sustainability reports (Fu *et al.*, 2024). The ESG guide, first published in 2015 and subsequently updated by HKEX in 2016, requires listed companies to submit annual ESG reports, adhering to the "comply or explain" provisions (Svanberg *et al.*, 2022). It is anticipated that as the capital market evolves, ESG factors will play an increasingly significant role in investment assessments.

Academic publications on ESG reporting are scarce, with current research predominantly focused on analyzing the relationship between financial returns and ESG disclosure, yielding varied findings (Lin and Guan, 2024; Sahin *et al.*, 2022). Some perspectives suggest a direct relationship between revenues and ESG performance. (Ariff and Majid, 2023), Utilizing regression analysis and correlation studies on the German Prime Standard, ESG progress positively affected return on assets but had a negative impact on Tobin's Q. Governance performance demonstrated a higher effect than the other two. Drawing from stakeholder theory, Yu et al. (2024) showcased a favorable correlation between company innovation and ESG initiatives through hierarchical regression analysis. However, conflicting studies (Qi *et al.*, 2024) found insufficient evidence supporting the notion that enhanced ESG practices boost financial returns.

Despite these conflicts, investors, credit rating agencies (CRAs), and regulators express deep concern about the veracity and authenticity of ESG reports due to information asymmetry among stakeholders. Greenwashing, the act of providing false information or creating a false appearance of environmental conscientiousness, poses a significant challenge in ESG reporting (Mishra *et al.*, 2024). Greenwashing behaviors include exaggerating managerial achievements, misrepresenting greenhouse gas (GHG) emissions, and overstating social impacts. Studies on preventing such deceptive practices open new avenues for ESG research. Nguyen et al. (2023) emphasized the importance of thorough analysis and provided evidence of the effectiveness of two firm-level governance components in reducing greenwashing. However, the current process, marked by secrecy and substantial human input, raises skepticism and questions about credibility. In this context, the integration of blockchain and IoT technology is proposed to address these challenges.

2.2 Blockchain in construction and its potential in ESG

Blockchain technology has garnered significant attention in the construction industry, offering solutions to enduring challenges like inefficiencies, lack of transparency, and environmental impact. Operating as a decentralized and transparent ledger system, blockchain strengthens supply chain management by verifying the authenticity of construction materials and mitigating the risk of fraud (Espinoza Pérez *et al.*, 2022). The implementation of smart contracts, driven by blockchain, automates contract execution, streamlines processes, and reduces disputes, thereby enhancing overall project efficiency (Zhong *et al.*, 2022). Additionally, blockchain's role in asset management ensures secure and transparent tracking of construction assets throughout their lifecycle, aiding in maintenance and minimizing the risk of theft (Rejeb *et al.*, 2023).

An essential facet of blockchain in construction is its contribution to environmental sustainability. By enabling the tracking and verification of sustainable practices, blockchain helps reduce the construction industry's carbon footprint (Jalaei *et al.*, 2022). Transparent documentation of construction processes and materials on the blockchain streamlines the certification process for green buildings, fostering a more sustainable built environment (Kiu *et al.*, 2022). This aligns with the increasing emphasis on environmental considerations in construction practices, supporting global sustainability goals.

Blockchain also holds significant potential for addressing social and governance issues in the construction sector. Transparent and tamper-proof records of worker credentials on the blockchain ensure compliance with labor regulations, promote fair wages, and guarantee safe working conditions (Zhong *et al.*, 2020). Furthermore, blockchain-based platforms facilitate real-time information access for stakeholders, enhancing communication and collaboration among project participants, including local communities and investors (Sigalov *et al.*, 2021). By improving project governance and automating risk management processes, blockchain contributes to enhanced accountability and better overall project outcomes (Ahmadisheykhsarmast *et al.*, 2023).

However, challenges such as scalability, interoperability, and regulatory considerations need attention for the widespread and effective implementation of blockchain in construction (Elghaish *et al.*, 2021; Perera *et al.*, 2020). Ongoing research and development efforts are crucial to overcoming these challenges and unlocking the full potential of blockchain for a more sustainable and socially responsible construction industry. Table 1 illustrates how the fundamental properties of blockchains have the potential to bring transformative changes to ESG reporting in construction organizations. For instance, blockchain facilitates more accurate and reliable tracking of environmental impacts by recording every step in the construction process, from material sourcing to the implementation of sustainable practices. This ensures that ESG reports are grounded in a complete and transparent record of activities, fostering trust among stakeholders.

Additionally, inspection records can be securely documented in a decentralized blockchain system to ensure their authenticity for future accountability. Each inspection event, compliance check, or audit can be time-stamped and linked to specific construction phases, providing a verifiable and unalterable record. This not only enhances the reliability of ESG reporting but also assists construction organizations in meeting regulatory requirements and demonstrating adherence to industry standards (Ma *et al.*, 2023).

However, limited attempts have been made to investigate the full potential of blockchain in ESG reporting within construction organizations. Further research is needed to explore how blockchain technology can be effectively integrated into existing reporting frameworks, overcome implementation challenges, and maximize its impact on enhancing transparency, accountability, and sustainability in the construction sector (Centobelli *et al.*, 2022; Hader *et al.*, 2022; Varavallo *et al.*, 2022; Wang *et al.*, 2020). This exploration is crucial for realizing the full transformative potential of blockchain in the context of ESG reporting for construction organizations.

Table 1: Fundamental Properties of Blockchains and their Potential in ESG Reporting in Construction Organizations.

Property	Description	References
Decentralization	The blockchain operates on a decentralized network, reducing the risk of manipulation and centralized control in ESG reporting.	(Pólvora *et al.*, 2020; Wu *et al.*, 2021; Wu, Zhong, *et al.*, 2022)
Transparency	All transactions on the blockchain are transparent and verifiable, enhancing the reliability of reported ESG data in construction organizations.	(Bai *et al.*, 2022; Centobelli *et al.*, 2022; Hoang *et al.*, 2023)
Immutability	Once information is recorded on the blockchain, it becomes immutable, ensuring the integrity of historical ESG data and preventing tampering or fraud.	(Hader *et al.*, 2022; Kumar Singh *et al.*, 2023; Sadawi *et al.*, 2021)
Smart Contracts	The use of smart contracts automates and enforces ESG-related agreements, enhancing efficiency and accuracy in reporting practices.	(Gatteschi *et al.*, 2018; Kumar *et al.*, 2021; Li and Kassem, 2021)
Traceability	Blockchain allows for the traceability of every transaction and data point, enabling a comprehensive audit trail for ESG reporting purposes in construction.	(Centobelli *et al.*, 2022; Hader *et al.*, 2022; Varavallo *et al.*, 2022; Wang *et al.*, 2020)

2.3 Blockchain for sustainability

Blockchain serves as a distributed, time-stamped, and immutable data system, creating a peer-to-peer network without relying on a central authority. This structure enables users to establish verifiable connections through transactions, with all details recorded in a public ledger duplicated across each network node (Sadeghi *et al.*, 2022). Transactions are encrypted and adhere to predefined rules outlined in smart contracts, ensuring information security and traceability (Teisserenc and Sepasgozar, 2021).

The integration of blockchain with other advanced technologies like IoT, digital twin (DT), cyber-physical system (CPS), cloud/fog/edge computing, and big data is anticipated to support the Fourth Industrial Revolution, emphasizing the convergence of physical and digital realms (Akram *et al.*, 2022; Happy *et al.*, 2023; Mulligan *et al.*, 2023). In this context, data plays a crucial role in achieving system robustness, cost-effectiveness, resilience, adaptability, and efficiency (Shishehgarkhaneh *et al.*, 2023). However, challenges in dependability and data security persist. Blockchain's unique features make it a viable solution, ensuring data traceability and immutability. Its successful application across various sectors, including energy management, healthcare, industry, agriculture, and smart cities, attests to its versatility (Kumar Singh *et al.*, 2023).

Blockchain's potential to enhance supply chain sustainability across economic, ecological, and societal dimensions has been acknowledged (Yadav et al., 2022), and it has been demonstrated that blockchain fosters trust and offers real-time financial transparency, potentially improving profitability and competitiveness in the industry. Varavallo et al. (2022) utilized distributed ledger technology to measure and monitor wastewater discharge from commercial ships, ensuring environmental sustainability by preventing illegal manipulations. The use of less paper for recordkeeping contributes to eco-friendly practices. (Parmentola *et al.*, 2022) proposed a system architecture combining blockchain, IoT, and big data analytics for tracing social interactions in supply chains. This system facilitates compliance tracking, enhances security for digital assets, and improves audit efficacy and legitimacy. Leveraging blockchain and IoT technologies to enhance the efficiency, security, and legitimacy of ESG reporting aligns with these advantages.

Smart contracts play a crucial role in blockchain technology, providing a sophisticated layer of programmability and automation within decentralized systems. These self-executing contracts, often scripted in programming languages like Solidity for Ethereum, enable trustless and secure execution of predefined agreements (Zhong *et al.*, 2022). Deployed onto blockchain platforms, smart contracts reside on the blockchain nodes and autonomously execute when triggered by predefined conditions. Their deterministic nature ensures consistent outcomes across all nodes, contributing to the immutability of blockchain data. Smart contracts interact with blockchain data through state variables, allowing them to store and manage information on the blockchain. They employ cryptographic techniques to ensure transaction integrity and security, enhancing the overall resilience of the blockchain network (Song *et al.*, 2019).

Additionally, smart contracts capture events, enabling external systems to react to changes in the blockchain state. Leveraging consensus mechanisms, smart contracts reach agreement on transaction execution, eliminating the need for intermediaries, reducing transaction costs, and minimizing potential points of failure (Kumar Singh *et al.*, 2023). Advanced features like oracles enable smart contracts to interact with external data sources, enhancing their versatility and real-world applicability. The technical foundation of smart contracts lies in their code execution, data management, cryptographic security, and seamless integration with blockchain protocols, making them powerful tools for automating complex processes and enforcing trust within decentralized systems (Kumar *et al.*, 2021). A summary of the key papers is shown in Table 2.

Table:2 Summary of key papers.

S.No	Title	Aim	Methodology	Findings	Limitations	References
1	Event-based data authenticity analytics for IoT and blockchain-enabled ESG disclosure	This paper aims to address the authenticity concerns in ESG disclosure by proposing a novel solution that integrates IoT and blockchain technologies. It focuses on ensuring data authenticity, consistency, and transparency in ESG disclosures.	It designs an ESG information disclosure system (IBESG) enabled by IoT and blockchain. It develops a Local and Global Authenticity Verification Flow (LGA) using edge and cloud computing to verify data authenticity. Additionally, it creates data authenticity analytics algorithms for event-based spatial-temporal analytics and authenticity index computation.	The experimental simulation in this work demonstrates the implementation and effectiveness of the IBESG system and the LGA verification solution. It also conducts a sensitivity analysis to evaluate the performance of the proposed solution.	The scalability and integration of the IBESG system with diverse ESG reporting frameworks across industries may pose challenges. Technical, financial, and infrastructural barriers might hinder the adoption of IoT and blockchain technologies. Additionally, further refinement of the data authenticity analytics algorithms is needed to handle large-scale, heterogeneous data sets effectively.	(Chen *et al.*, 2024)
2	ESG and Industry 5.0: The role of technologies in enhancing ESG disclosure	This paper aims to explore the application of Industry 5.0 (I5.0) in enhancing ESG disclosure by aligning its values with those of ESG. It seeks to understand how emerging technologies can improve ESG disclosure and address its limitations through various management theories.	The work explains ESG from the perspectives of management theories such as stakeholder theory, legitimacy theory, transaction cost economics theory, institutional theory, signaling theory, network economics theory, and the decoupling view. It then examines how I5.0 technologies can enhance the authenticity, scope, and efficacy of ESG disclosures.	The study finds that I5.0 can significantly enhance ESG disclosure by ensuring authenticity, enabling real-time and prospective reporting, customizing reports, and extending the scope to multi-tier supply chains. I5.0 also reduces the cost and improves the overall effectiveness of ESG disclosure.	The work highlights potential challenges and risks in employing I5.0 for ESG, such as governance issues and the need for further refinement of technologies. Additionally, the conceptual nature of the study indicates the need for empirical research to validate its findings in real-world scenarios.	(Asif et al., 2023b)
3	Blockchain for sustainability: A systematic literature review for policy impact	This paper aims to provide policymakers with insights into how blockchain technology can achieve sustainable development by assisting in ESG and environmental sustainability goals. It seeks to fill the gap in the existing literature regarding a structured approach to this topic.	The study conducts a systematic literature review (SLR) using PRISMA guidelines, analyzing 10,188 technical and policy papers sourced from Scopus and IEEE databases. It also reviews the relevant regulatory environment related to ESG, including various international standards and frameworks.	The work finds that most existing literature lacks a structured approach to applying blockchain in the emerging regulatory environment. It identifies the potential of blockchain to assist policymakers in achieving net-zero goals and outlines recommendations to guide the blockchain research community toward valuable and practical solutions.	The study highlights the need for more empirical research to validate the theoretical insights provided. Additionally, the rapidly evolving regulatory environment may require continuous updates to the findings and recommendations to remain relevant and practical.	(Mulligan *et al.*, 2024)
4	Consortium blockchain-enabled smart ESG reporting platform with token-based incentives for	This paper aims to address the issues of overstatement and lack of transparency in ESG reporting by proposing a smart ESG reporting platform. Leveraging IoT and blockchain technologies, the platform	The proposed architecture utilizes corporate crowdsensing for environmental data and incorporates an incentive mechanism that rewards firms with crypto tokens for high-quality ESG data disclosure. The maximum token settlement for each environmental KPI is modeled as a cooperative game, with the	The experimental simulation illustrates that the proposed platform architecture and token allocation approach effectively enhance the credibility and transparency of ESG reporting. The study demonstrates the potential of advanced technologies to mitigate	The work acknowledges that the proposed platform's effectiveness needs validation through real-world implementation. Additionally, the incentive mechanism and token allocation approach might require adjustments to cater to different	(Wu, Fu, *et al.*, 2022)

	corporate crowdsensing.	seeks to enhance the security, transparency, and credibility of the ESG reporting process.	Shapley value applied for fair distribution based on the significance of disclosure, as scored by experienced investors. The study uses the ESG reporting guide from the Hong Kong Exchange (HKEX) and the Hong Kong apparel industry as a context and conducts an experimental simulation to demonstrate feasibility and effectiveness.	greenwashing and promote intelligent and trustworthy ESG reporting.	industries and regulatory environments. Further research is necessary to refine the model and ensure its broad applicability.	
5	Blockchain-enabled digital asset tokenization for crowdsensing in environmental, social, and governance disclosure	This study aims to investigate a novel digital asset tokenization mechanism for mobile crowdsensing to facilitate ESG disclosure in supply chain networks. It seeks to address the challenges of cost-sharing, information ownership, and the limitations of monetary incentives in traditional crowdsensing.	The study models the interaction between information providers and users as a two-stage Stackelberg game to analyze usage levels and optimal technology investments. It incorporates various factors, such as technology adoption costs and cost-sharing levels, into the incentive mechanism and evaluates the influence of these factors on participant benefits. The cost-sharing aspect is endogenized to determine the ideal level of cost-sharing for digital asset consumers.	The findings reveal that increasing the reputation incentive per token stimulates token consumption, leading to higher payoffs for participants. Conversely, rising technology adoption costs reduce token consumption and profits. The study identifies a unique level of cost-sharing that optimally balances utility for digital asset consumers, indicating that an endogenous cost-sharing mechanism has a competitive advantage over exogenous approaches.	While the proposed tokenization mechanism shows promise, its effectiveness requires empirical validation in real-world scenarios. Additionally, the study focuses primarily on the modeling aspect, and further research is needed to explore practical implementations and the adaptability of the mechanism across different supply chain contexts.	(Rachana Harish *et al.*, 2023)
6	Data-driven ESG assessment for blockchain services: A comparative study in the textiles and apparel industry	This research aims to address data opaqueness and assessment subjectivity in ESG performance evaluation by integrating blockchain technology with multicriteria acceptability analysis (SMAA-2). The goal is to provide a transparent and robust method for assessing the sustainability performances of listed companies.	The study utilizes blockchain to create a transparent ledger for storing and sharing ESG data among listed companies, investors, and stakeholders. It employs SMAA-2, which does not require subjective weight preferences, to assess the ESG data of 71 textiles and apparel companies listed in Hong Kong. Sensitivity analyses are conducted to examine the stability of the approach concerning varying weight preferences for environmental criteria such as water consumption, energy consumption, and greenhouse gas emissions.	The results demonstrate that the proposed data-driven ESG assessment approach effectively analyzes the sustainability performances of the companies and benchmarks their sustainability levels against peers in the industry. The integration of blockchain and SMAA-2 enhances the robustness and transparency of ESG evaluations.	While the proposed approach shows promise, it relies on the availability and accuracy of ESG data, which can vary across companies. Additionally, the study primarily focuses on the textiles and apparel sector in Hong Kong, necessitating further research to validate the approach across different industries and regions.	(Liu *et al.*, 2023)
7	Is there any market state-dependent contribution from Blockchain-enabled solutions to ESG	This study aims to examine the relationship between three blockchain-based platforms (Advanced Internet Blocks (AIB), Blocktix (TIX), and BlockCDN (BCDN)) and prominent global ESG-based indexes (S&P Global 1200 ESG Index and its Shariah-	The research analyzes data from March 5, 2018, to March 30, 2022, to compare the coherence of the blockchain platforms with ESG and SESG investments. It employs pairwise directional connectedness analysis to evaluate the contributions of blockchain innovations to ESG-screened businesses under different market conditions. The study also examines the	The results indicate that BCDN demonstrates a stronger coherence with ESG and SESG investments compared to AIB and TIX, particularly under normal and bullish market conditions. The analysis reveals that only BCDN and AIB provide significant network-transmitting functions in specific market states. The findings suggest that	The study highlights that expecting BCDN or AIB to significantly contribute to ESG markets without considering market conditions may be unrealistic. Additionally, the analysis is limited to a specific timeframe and a small set of blockchain platforms, suggesting the need for further research to explore other platforms	(Shahzad *et al.*, 2023)

	investments? Evidence from conventional and Islamic ESG stocks	screened counterpart). The objective is to assess the coherence of these platforms with ESG investments and their contributions to sustainable objectives.	network-transmitting functions of BCDN and AIB in various market states.	the effectiveness of blockchain platforms in contributing to ESG markets is highly dependent on market conditions.	and longer time horizons for a more comprehensive understanding of their impacts on ESG objectives.	
8	Event-based data authenticity analytics for IoT and blockchain-enabled ESG disclosure	This study aims to address concerns regarding data authenticity in ESG disclosure by proposing a novel ESG information disclosure system (IBESG) that integrates IoT and blockchain technologies. The goal is to enhance the authenticity, consistency, and transparency of ESG data.	The proposed IBESG system facilitates the collection and transmission of ESG data through the integration of IoT and blockchain. A Local and Global Authenticity Verification Flow (LGA) is designed to utilize edge and cloud computing for authenticity verification. Additionally, data authenticity analytics algorithms, including event-based spatial-temporal analytics and authenticity index computation, are developed. The study conducts an experimental simulation to demonstrate the implementation and performance of the IBESG system, along with sensitivity analysis.	The findings illustrate that the IBESG effectively enhances the authenticity and transparency of ESG disclosures. The verification solution provides reliable assessments of data authenticity, and the sensitivity analysis offers insights into the system's robustness. The study also includes deployment suggestions based on experimental findings.	While the proposed solution shows promise, its practical implementation in field manufacturing factories needs further investigation. Additionally, the algorithms developed may require refinement to accommodate diverse ESG data types and ensure broader applicability across different industries. Future research is necessary to explore these aspects and validate the findings in real-world scenarios.	(Chen *et al.*, 2024)
9	ESG disclosure and corporate cost stickiness: Evidence from supply-chain relationships	This study aims to investigate the effect of ESG disclosures by customer firms on suppliers' cost stickiness within a supply-chain context. The objective is to understand how ESG disclosures influence suppliers' cost behaviors.	The research analyzes the relationship between ESG disclosures and suppliers' cost stickiness, focusing on how reduced optimistic expectations from suppliers' management contribute to this effect. It examines variations in the relationship based on geographical and social distance between suppliers and customers, as well as industry differences.	The findings indicate that ESG disclosures effectively mitigate suppliers' cost stickiness. The negative relationship between ESG disclosures and cost stickiness is found to intensify with increased geographical and social distance between suppliers and customers, and when they operate in different industries.	While the study provides valuable insights into the impact of ESG disclosures on cost stickiness, it may be limited by its focus on specific industries and geographical regions. Further research is needed to explore the effects in different contexts and to validate the findings across a broader range of supply-chain settings.	(Jiang and Yang, 2024)
10.	Trust in ESG reporting: The intelligent Veri-Green solution for incentivized verification	This study aims to enhance the ESG data verification process by introducing "Veri-Green," an innovative blockchain-based incentive mechanism designed to improve the authenticity, credibility, and fairness of ESG reports. The goal is to develop a strategic selection process for verifiers that strengthens the overall verification framework.	The research employs advanced machine learning algorithms to identify potential verification candidates, followed by the deployment of the Vickrey Clarke Groves (VCG) auction mechanism for the strategic selection of verifiers. This approach focuses on addressing risks related to reputational damage and data security while promoting a transparent and efficient verification process.	The findings suggest that the Veri-Green mechanism fosters an ecosystem characterized by truthfulness, rationality, and computational efficiency in the ESG data verification process. By incentivizing verifiers appropriately, the framework aims to improve the validity and trustworthiness of ESG disclosures, ultimately supporting corporate responsibility and sustainability efforts.	While the proposed mechanism shows promise, its practical implementation may face challenges related to the integration of machine learning algorithms and the auction mechanism within existing verification systems. Further research is needed to validate the approach in real-world scenarios and to explore its applicability across different industries and regulatory environments.	(Liu *et al.*, 2024)

2.4 Research gap

The construction industry is increasingly acknowledging blockchain as a disruptive force within the framework of the 4th industrial revolution (Industry 4.0). Significant attention has been directed towards blockchain applications in various domains, such as supply chain management (Kumar Singh *et al.*, 2023), payment management (Sigalov *et al.*, 2021), and quality management (Zhong *et al.*, 2020). As a decentralized database, blockchain ensures immutable information records, while the integration of smart contracts enables automation of diverse business processes, thereby improving efficiency and reliability (Pólvora *et al.*, 2020).

Traditional tools in the construction industry often fall short of addressing the complexities of modern project management, particularly regarding transparency, data integrity, and process automation. Conventional methods for managing supply chains, payments, and quality control are often fragmented and susceptible to errors, fraud, and inefficiencies (Chen and Hammad, 2023). These systems rely heavily on centralized databases and manual interventions, which can lead to delays, miscommunication, and increased costs (Ghadge *et al.*, 2021). Additionally, the lack of real-time data sharing and the potential for data tampering further undermine the reliability of these traditional approaches (Viswanadham and Kameshwaran, 2013). Blockchain, with its decentralized ledger and tamper-proof records, presents a promising alternative to overcome these challenges by offering secure, transparent, and automated solutions for construction management (Kumar *et al.*, 2023). Smart contracts, in particular, have demonstrated potential in automating agreements and reducing dependency on intermediaries (Yoon and Pishdad-Bozorgi, 2022).

Recent studies, such as Gong et al. (2024), have advanced this field by introducing the Blockchain-ESG Integrated (BESGI) framework, which enhances ESG data management through secure and traceable reporting, delivering better integrity and cost efficiency. However, a critical gap persists: transparent and accountable ESG reporting for stakeholders in construction has not been fully realized. While blockchain's characteristics align naturally with the principles of ESG, its role in practical ESG assessment and reporting remains underexplored, with limited systematic efforts to address real-world industry challenges. This study seeks to fill this gap by proposing a hybrid blockchain-based framework designed to automate and enhance the transparency, accountability, and reliability of ESG reporting in the construction sector.

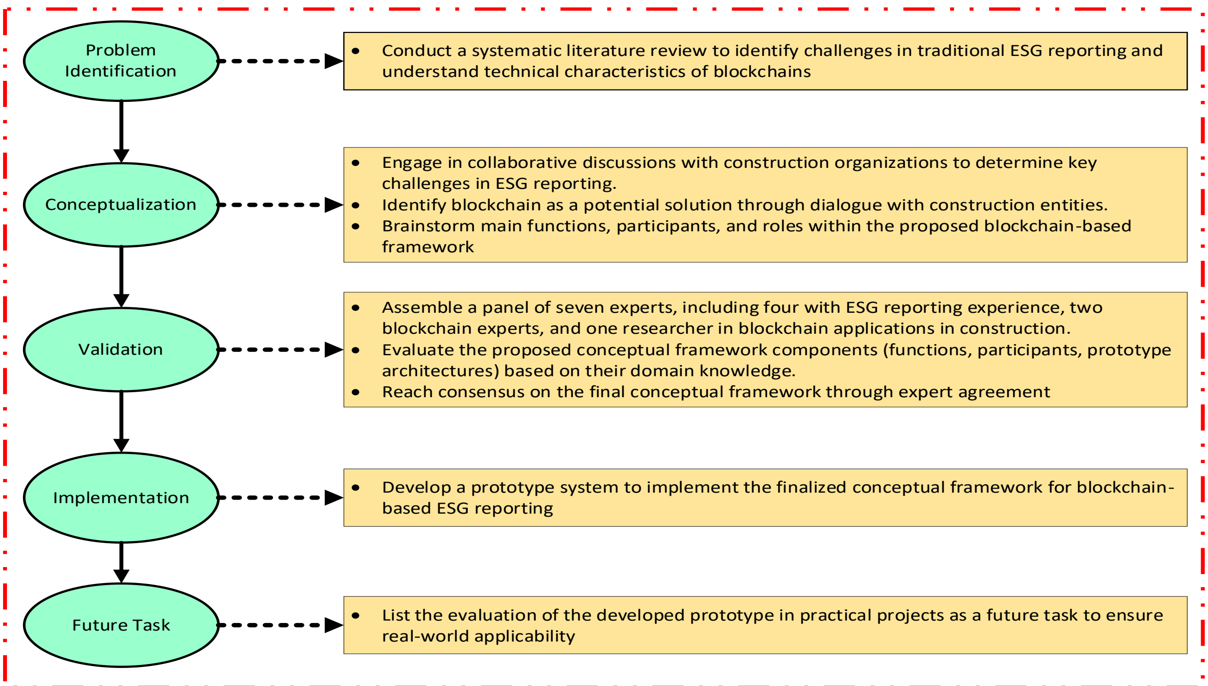

Figure 1: Research framework.

3. RESEARCH METHODOLOGY

The design science approach, advocated by Wiegmann *et al.* (2023), forms the cornerstone of the entire research methodology employed in this study. This approach is adept at comprehending and addressing intricate issues associated with technology and information systems (Fig. 1). Design science, marked by its iterative and problem-solving characteristics, harmonizes effectively with the study's goal of improving ESG reporting in the construction industry through the implementation of blockchain technology. The approach facilitates a methodical journey from problem identification to conceptualization and implementation, ensuring a systematic exploration of the research domain (von Klinggraeff *et al.*, 2023).

To facilitate the design science process, the initial identification of challenges in traditional ESG reporting and the technical characteristics of blockchains was undertaken through a systematic literature review. Subsequently, a collaborative development of a blockchain-based conceptual framework occurred through discussions with construction organizations. The design science approach underscores the importance of stakeholder and expert involvement throughout the research process. In this study, a validation process engaged seven experts, comprising four with extensive experience in ESG reporting, two blockchain experts with development experience, and one researcher in blockchain applications in construction. Together, they evaluated the proposed conceptual framework for its functions, participants, and prototype architectures. This expert review ensured the robustness and applicability of the final conceptual framework, reflecting a commitment to real-world effectiveness and stakeholder engagement in enhancing ESG reporting in the construction sector. The experts were selected based on their role, expertise, and a minimum of three years of professional or research experience relevant to ESG reporting or blockchain. They were engaged through semi-structured interviews, and their feedback was analyzed thematically to identify recurring insights and refine the framework. The experts involved in the validation process included four individuals with rich experience in ESG reporting, two blockchain experts with development experience, and one researcher specializing in blockchain applications in construction who has published related articles in reputable academic journals. Their diverse expertise ensured a comprehensive evaluation of the proposed conceptual framework, enhancing its usability and feasibility in practical construction contexts. The hybrid blockchain architecture seamlessly integrates elements of both public and private blockchains, creating a versatile solution applicable across various industries (Ghosh *et al.*, 2021). By design, it incorporates distinct public and private zones, leveraging the transparency and decentralization of public blockchains along with the privacy and control provided by private blockchains (Nodehi *et al.*, 2022). This hybrid model effectively addresses scalability concerns, ensuring optimal performance without compromising data security (Toufaily *et al.*, 2021). The implementation of smart contracts automates processes and enhances operational efficiency. Use cases for hybrid blockchains span diverse industries, from ensuring transparent and accountable recordkeeping to enabling secure collaboration and adherence to regulatory requirements (Kopyto *et al.*, 2020).

3.1 Tools of development

The configuration of the departments can be made by using the CA (Certificate Authority) issued to the department. In the prototype system, each participant can receive certificates from the CA module of the HLF. CA provides services to authenticate, issue, and revoke the identities of participants through public-private key technology. Once the participant receives the CA, they can establish connections and store public-private keys to sign and manage the digital signatures.

Smart contracts are encoded with the programming language of Go and then deployed in the prototype system (Triana Casallas *et al.*, 2020). The smart contracts are deployed by installing the chain code on every peer using Hyperledger Fabric CLI or SDK. The instantiate the chain code for the specific channel in the network. Then, the chain code can be invoked and queried, which would ensure the publication of data on social and governance for every organization shown in the framework. The smart contracts for environmental data are encoded using either Go or Solidity. The IOT sensors periodically fill the smart contract with the prescribed data, after which the smart contract triggers the IOT sensors, thus getting the required data. The data of these organizations would be collected in the form of different KPIs for every particular ESG field.

4. SOLUTION DEVELOPMENT

4.1 Hybrid Blockchain potential in ESG data management

In Figure 2, the illustrated hybrid blockchain flow demonstrates its application in ESG data management. The architecture hosts a decentralized distributed ledger for storing transactions related to the Environment, Social, and Governance of each company. Smart contracts are designed to support hybrid blockchain functionality with different KPIs for ESG related to various companies. Participating entities in data collection for environments, social aspects, and governance differ based on scenarios, enhancing data diversity and accountability. The government ensures KPI standards for company reporting and establishes a bridge to connect third-party services, verifying and certifying reports more openly and transparently, instilling confidence in investors to choose environmentally sustainable companies. In addition, the framework incorporates mechanisms for enforcement and dispute resolution, such as consensus-based conflict checks and government-mandated audits, to address cases of non-compliance or rating conflicts, thereby strengthening system credibility.

The collection of environmental data employs a public blockchain, and social and governance data are collected through a private blockchain, involving different entities, including working staff and the management board. This process allows for surveys and open feedback, aiding third-party services in efficiently rating companies. Government involvement ensures a comprehensive understanding of fundamental economic development and employee growth in companies through these data. However, since the system assumes government-managed platforms and individual key registration, feasibility and regulatory capacity challenges are acknowledged. Furthermore, safeguards for protecting sensitive ESG data, including encryption and restricted access protocols, are emphasized to address privacy concerns. Thus, the hybrid blockchain plays a pivotal role in connecting all entities in the ESG data management ecosystem.

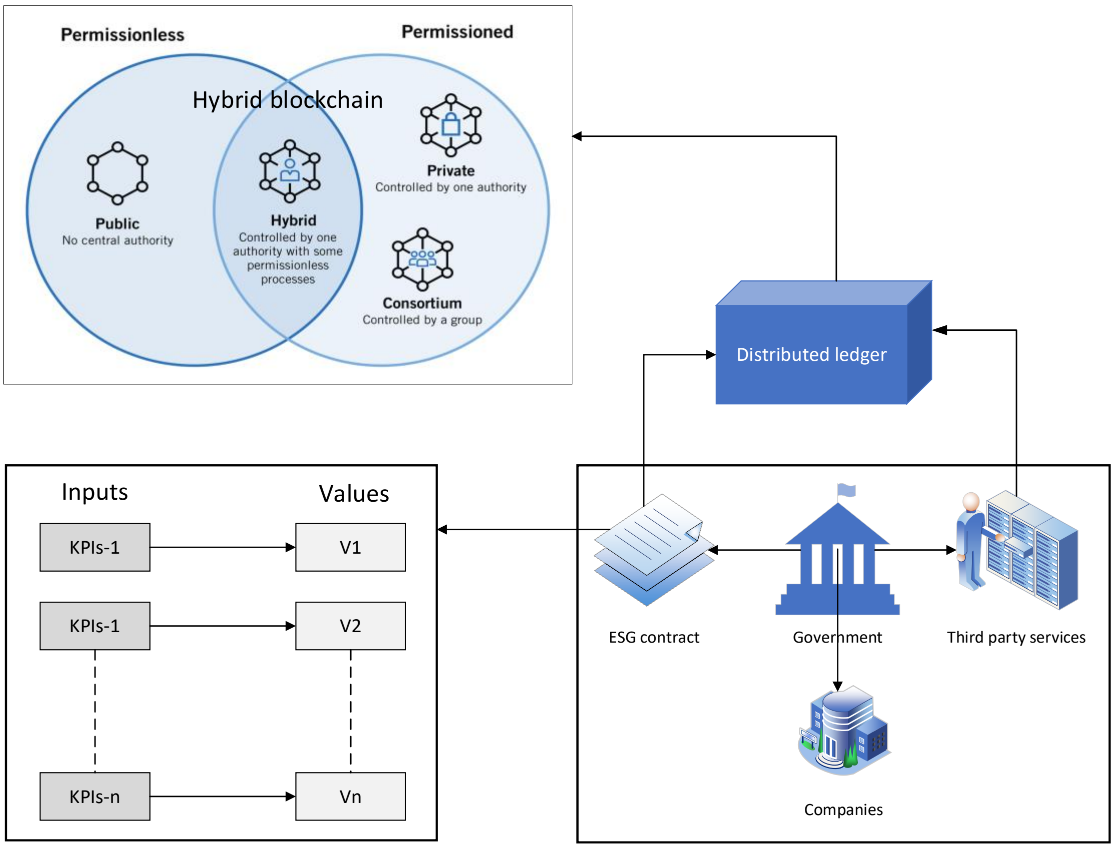

Figure 2: Blockchain flow for ESG reporting.

4.2 Hybrid Blockchain-based conceptual framework for ESG

In this study, a hybrid blockchain framework was proposed to improve ESG reporting in the construction industry by integrating Ethereum (public blockchain) and Hyperledger Fabric (private blockchain). Environmental data is captured via IoT devices and stored on Ethereum to ensure transparency, immutability, and traceability, while social and governance data is recorded on Hyperledger Fabric to maintain privacy, controlled access, and regulatory compliance. The two blockchains interact through interoperability protocols and smart contracts, enabling aggregated ESG data to be combined and verified across both networks before being published to stakeholders.

As shown in figure 3, The conceptual framework consists of four layers: (1) Authorization layer, (2) Data collection layer, (3) Blockchain layer, (4) Application layer (as shown in Fig. 3). Traditional ESG reporting often lacks common laws and regulations, which can lead to the concealment of essential factors and overshadow negative aspects. The Authorization layer addresses this issue by involving the government in the establishment of standard laws and regulations through blockchain technology. This approach enhances transparency and accountability by mandating large companies to report ESG data periodically. Additionally, the government can introduce regulations, conduct ESG audits, provide certifications, and offer incentives for high-performing companies. Furthermore, it may categorize industries, introduce sector-specific Key Performance Indicators (KPIs), and utilize ESG reporting frameworks with mandatory key KPIs, thereby improving data quality and facilitating a realistic situational analysis.

The proposed functions of each layer in the framework are as follows:

The Application layer includes third-party services, independent researchers, stock exchanges, and the public. It hosts a combined platform for ESG information of various companies, which is used by third-party services to evaluate ESG performances. The ESG tracker service, designed for external stakeholders, enables confident investment decisions based on companies adhering to ESG norms, promoting sustainable development, environmental responsibility, and good governance. This approach mitigates misinformation risks associated with traditional data collection methods. The Data collection layer facilitates the filling of KPIs by industries and companies. Different KPIs for Environment, Social, and Governance are collected through various methods. Environment data gathered by IoT devices is automatically published on a website for government, companies, and third-party services to monitor. IoT devices, paired with the company's signature, capture data transparently, minimizing manipulation. This method ensures accountability and transparency, instilling confidence in investors and the public. Social and governance KPIs are collected via a private blockchain, involving employees, managers, and the management board in surveys and questionnaires. The collected data is then published on a central interface, ensuring a more reliable data collection process.

The Blockchain layer is the technical core, integrating Ethereum and Hyperledger through interoperable smart contracts and cross-chain data anchors. Five key techniques are employed: (1) hashing algorithms, (2) peer-to-peer (P2P) networking, (3) public–private key encryption, (4) consensus mechanisms, and (5) smart contracts. In this hybrid model, P2P networks are separated into Ethereum for environmental data, Hyperledger for social and governance data, but both feed into central smart contracts that consolidate and validate ESG KPIs across chains. This integration ensures that final ESG reports are transparent (via Ethereum), secure and permissioned (via Hyperledger), and tamper-proof.

4.3 Peer-to-peer networks and Smart Contract

In the context of ESG data management, environmental sensor data can be immutably recorded on the blockchain using IoT sensors, while social and governance reports can be transparently shared. Independent nodes, operated by company personnel, can participate in questionnaires and feedback, verifying data accuracy and compliance with ESG standards. This integration fosters innovative applications that support sustainability initiatives, promoting a transparent and responsible approach to ESG data management.

Figure 4 illustrates the involvement of various entities in the collection and publication of information, acting as nodes in this distributed ledger. Unlike traditional peer-to-peer networks, the prescribed hybrid blockchain model limits access for entities involved in collecting environmental data. The system integrates with the main website, where sensors automatically gather data, allowing respective companies to verify the data before publication. A precautionary measure ensures that the data is only readable and not editable, mitigating the risk of incorrect information. Regular maintenance checks for sensors and IoT devices guarantee accurate data production over time. Providing companies priority access to environmental data ensures accountability, as the public address of designated officials signs the data. The proposed smart contracts facilitate automatic data field filling and the publication of IoT data.

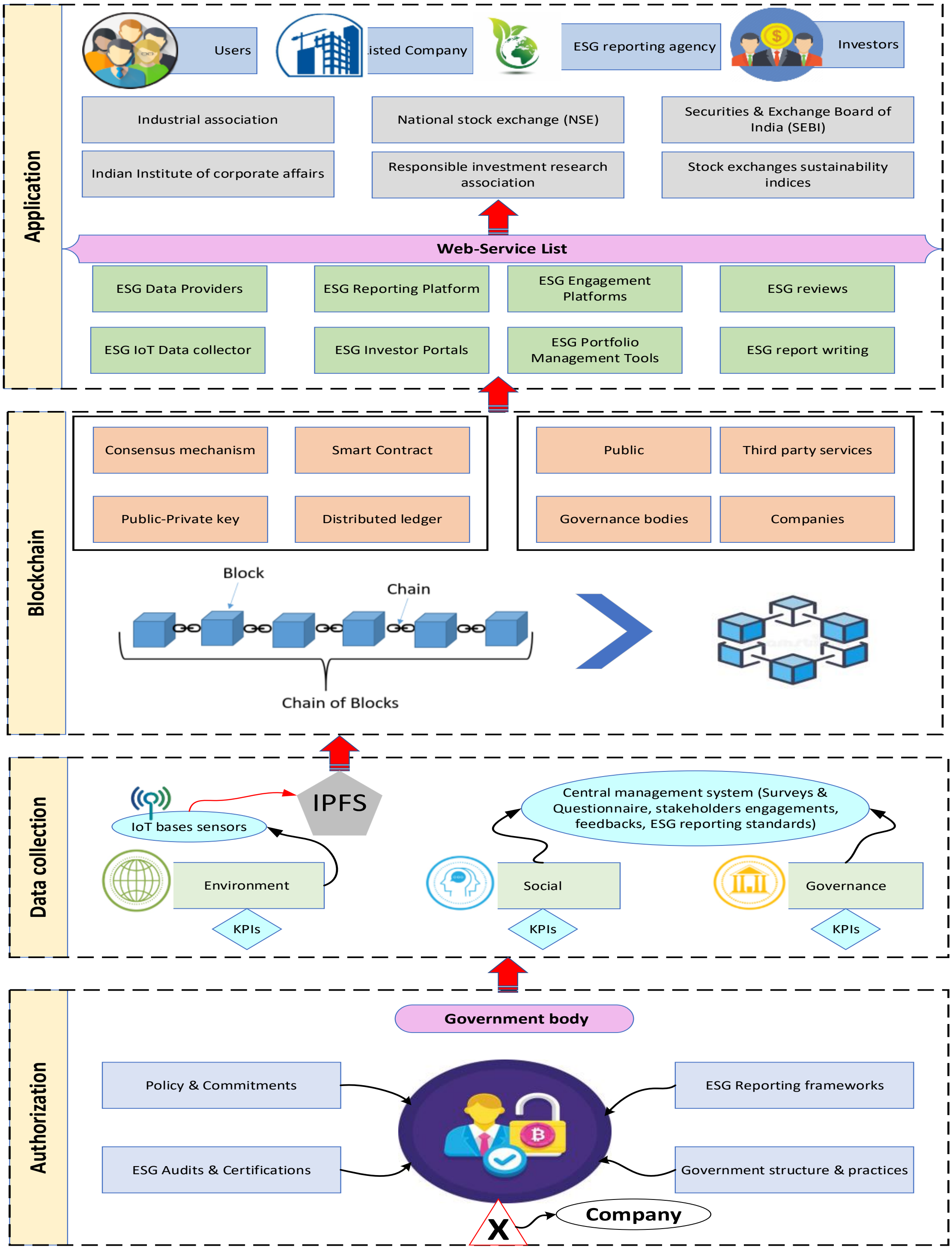

Figure 3: Conceptual framework.

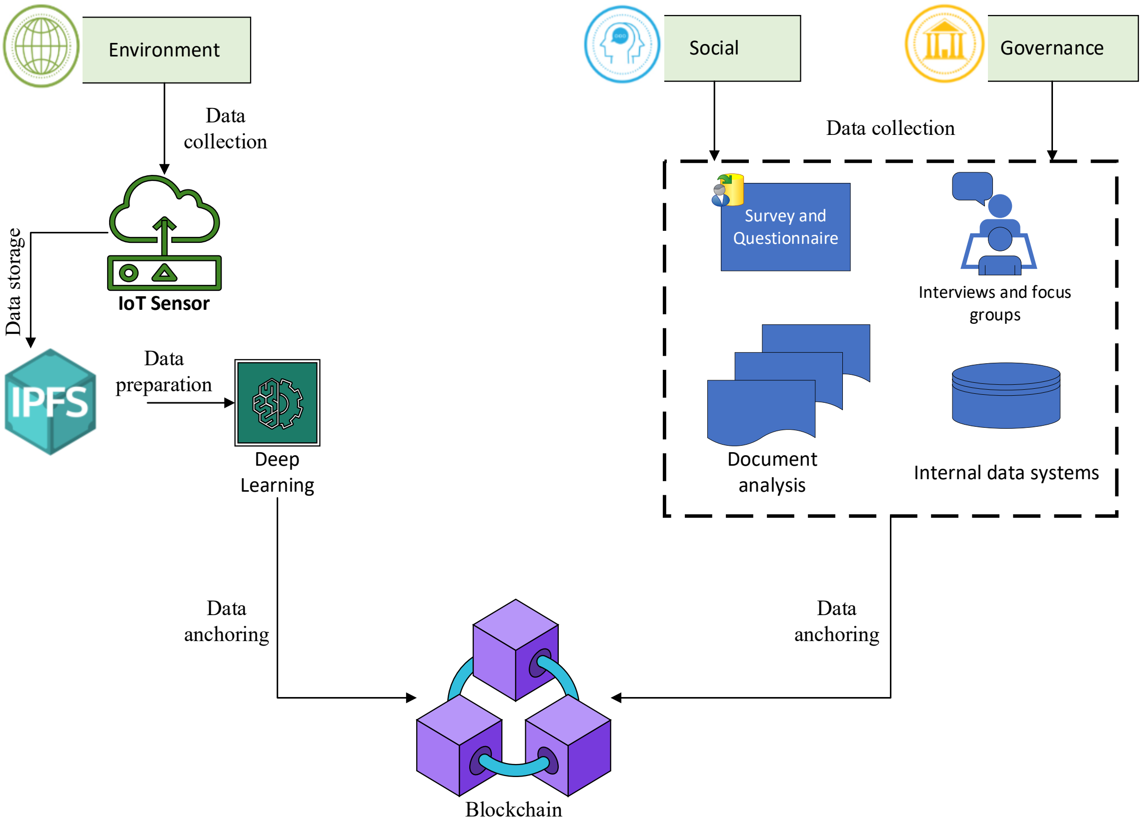

Figure 4: Data collection.

On the other hand, the collection of social and governance data involves a more extensive system, encompassing employees, managers, the Chief Management Board, and the President's board. Utilizing a private blockchain platform initiated by the government, companies can register their personnel with public-private addresses. This platform facilitates data collection through surveys, questionnaires, interviews, focus groups, document analysis, and internal data systems. The private blockchain ensures privacy, builds confidence between organizations, and enhances overall security. In the private blockchain, every peer functions as a node, participating in surveys and providing feedback through predefined smart contracts. This inclusive approach enhances confidence and accountability, enabling third-party services to rate organizations based on collected data. The complete social and governance data can then be published in the public blockchain using the organization's main public address. The peer-to-peer system thus plays a significant role in ensuring data collection verifiability and inherently increasing transparency, immutability, and security through hashing algorithms, smart contracts, and security consensus.

Figure 4 illustrates the utilization of smart contracts within the hybrid blockchain model, highlighting their distinctive roles in collecting environmental, social, and governance data. In the proposed ESG model, smart contracts differ for environmental and social governance due to the hybrid model used and the different data collection methods employing various KPIs. The life cycle of smart contracts involves four stages: negotiation and development, deployment, execution, and completion. Initially, smart contract developers gather necessary KPIs for inspection and publication across organizations. Government intervention can guide the formulation of uniform KPIs, aligning the interests of various organizations. Notably, KPIs may differ, especially in manufacturing or carbon-intensive industries, requiring additional parameters for comprehensive environmental data understanding. Immutable once deployed, smart contracts can be re-deployed with modifications to accommodate data from specific organizations. For social and governance aspects, smart contracts are deployed in a private blockchain. Participating organizations utilize smart contracts to enlist employees as peers and generate necessary data. The private blockchain, government-operated yet accessible to organizations, ensures verifiable data publication. This approach enhances investor confidence by providing transparent data verification mechanisms without disrupting organizational workflows.

4.4 Consensus-based ESG management

4.4.1 Data structure of ESG blocks

Blockchains protect inspection data in blocks, benefiting ESG data managers (Aboelazm, 2018). Each block has a header and body (Li *et al.*, 2021). The index number, timestamp, Merkle root, two hash values, and digital signatures from stakeholders like IOT sensors for environmental data and employees, managers, and the top management board for social and governance data are in the block header (Zhong *et al.*, 2020). The Merkle root links the header and body, hashing ESG information into transactions (Xiong *et al.*, 2019). These transactions construct a binary tree Merkle root through numerous hash operations (Wei *et al.*, 2018). The hashing function has two essential properties: the encrypted content is complex to infer from the hash value, and even small input changes result in different hash values for each block (Biswas and Gupta, 2019). The current and previous block hashes connect blocks. This interconnectedness means that an attacker must change all hashes in the chain between the altered block and the latest block to modify one hash. Thus, ESG data in these blocks is tamper-proof.

4.4.2 Consensus process of ESG blocks

In a centralized network, where trust in a central authority is absolute, consensus is achieved by the central party disseminating information, and participants acknowledge this information as the mutually agreed-upon truth. Blockchain, on the other hand, operates on a decentralized model where all participants hold equal standing. The consensus mechanism facilitates agreement on ESG reporting within the system, preventing any single entity from bypassing the consensus mechanism to control or tamper with the data. This diminishes the risk of data manipulation by intermediaries, and the absence of a singular central database reduces vulnerability to hacking.

The consensus model in this hybrid blockchain proposal involves various entities and peers situated at different points of data publication. In this environment, data consensus is acquired through the signing peer of the organization before being published on the main ledger. The organization's signing address is used for verification. The consensus for both environmental and social aspects is obtained from employees and the management board during the data publication process. Once the data is published in the integrated ESG format on the main ledger, third-party services and the government can function as endorsing peers. Figure 5 depicts the contractual relationship among various peers involved in ESG data publication, namely, the Company or organization, Third-party services, government, and the public. These entities participate as endorsing peers in the consensus model, demonstrated in the architecture, primarily including three stages: proposal request, data transaction, and verification process.

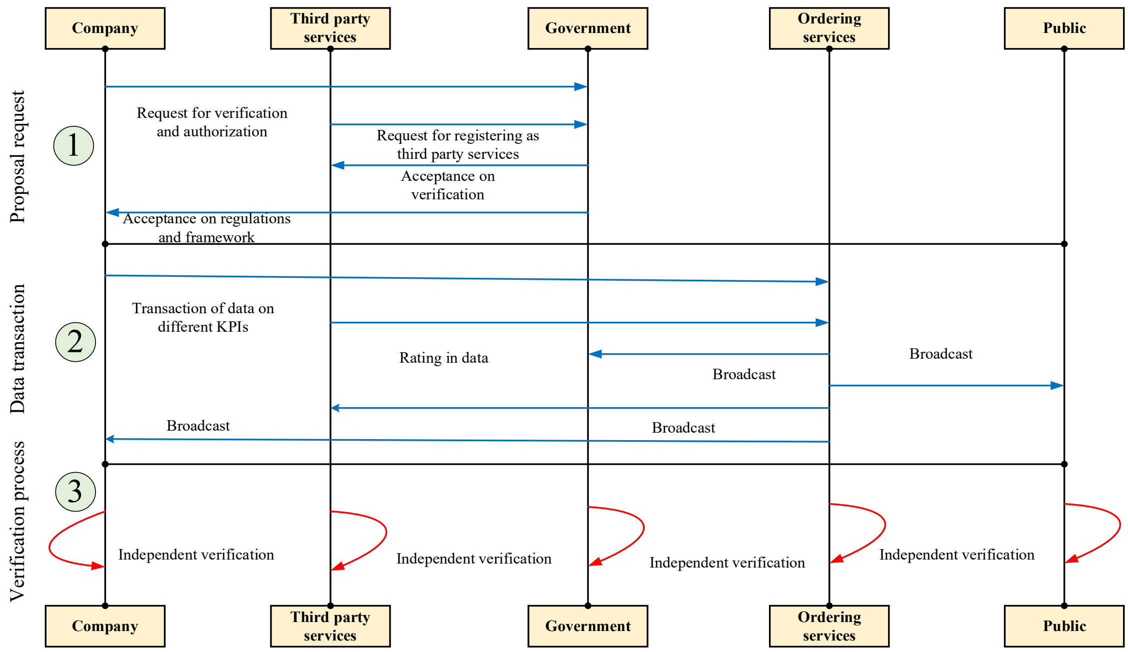

Figure 5: Consensus process of ESG blocks.

In the first stage, the company publishing ESG data periodically registers with the government, submitting legal documents and prescribed data. This registration ensures the prevention of malpractice, avoiding the registration of false companies or shadowing under false names. Once the government verifies the details, the company is granted permission to use the main interface for linking IOT sensors and becoming part of the private blockchain to produce social and governance data. In the second stage, third-party services also register with the government, providing the required details for a license to verify company data and provide ratings influencing investor decisions. Third-party services' registration is crucial to prevent illegal organizations from affecting investor confidence with misleading ratings. Once the government accepts the validity of companies and third-party services, they are registered and published in the blockchain ledger.

In the third stage, data transaction, companies use government-developed software to publish data in the prescribed format using smart contracts and the consensus model. The company transmits the data to the ordering service, which broadcasts it to all peers. Authorized persons sign and verify, ensuring correct information publication and accountability. In the verification process, the information in the ledger is accessible to everyone in the network, including the public, allowing independent verification. Third-party services use the published data to rate companies and conduct field checks. If found guilty of providing incorrect information, companies can be held accountable, contributing to fast decision-making and building investor confidence in the economy.

5. PROOF OF CONCEPT AND EVALUATION WITH CASE STUDY

Typically, the ESG data of any company is collected and published using the same process in the centralized databases. The proposed conceptual framework deals with the publishing of environment and social governance data collected and published through various methods to decrease the human factor and include all participants as nodes in the network, where everyone can contribute and verify, thus increasing the transparency of ESG data management. A case study of ESG data collection is presented using the proposed software to illustrate the conceptual framework. The two organizations were selected based on their active ESG reporting practices, their willingness to share operational data for research validation, and their representation of medium-to-large construction firms in the Indian context, which makes them suitable for testing scalability and applicability. Two organizations, Organization 1 and Organization 2, with departments (D1 to D7), are considered for publishing their ESG data. IoT sensors collect environmental data, while employees, managers, and top management contribute to social and governance data authenticated via digital signatures. The framework enhances transparency and accountability in ESG management, as detailed in Table 3. These organizations use the private blockchain consensus, i.e., Hyperledger Fabric, to collect information related to social and governance, and all the departments are involved in collecting the data.

In addition, the environment data are directly collected by IoT sensors using the company's public address and verified by the employees of that company. The environment data is published by directly linking the IoT sensors using the public blockchain consensus to the main website, where ESG data is aggregated for a particular company. For evaluation, the study applied a structured assessment framework with three key criteria: (i) transparency (measured by the proportion of verifiable records available to all stakeholders), (ii) data integrity (assessed by the number of tamper-proof entries and cross-verifications), and (iii) reporting efficiency (measured by the reduction in manual interventions and time taken to compile ESG reports). The outcomes indicated improvements in transparency and accountability, reduced redundancies in data handling, and enhanced trust among stakeholders. However, limitations remain, including the restricted sample size of two organizations, reliance on simulated IoT data for certain parameters, and the absence of long-term performance tracking. These limitations highlight the need for broader pilot testing across multiple firms and longitudinal validation.

A prototype system is developed using Hyperledger Fabric (HLF, version 2.2) architecture, aiming to implement the proposed conceptual framework in a laboratory environment (Zhong *et al.*, 2020). The development tools are shown in Table 4. Figure 6 shows the connections between various departments in the company using the private blockchain prototype. Once the data is collected from multiple departments, the data gets propagated to all the peers in the network, who can individually verify and publish it. The information collected for the Environment would be by IoT sensors, after which the data is processed by deep learning (e.g., convolutional neural networks), which takes the data and images and further processes them into clear images using the trained data regularly. Once the data is processed using deep learning, it is sent to on-chain data by connecting to the primary blockchain ledger, where the IoT sensors are connected to publish the data. The Social governance data collected using the private blockchain model with Hyperledger Fabric would include the KPIs related to internal records, employee surveys, HR records, training programs, and other specified KPIs as per the norms and regulations set by the government. Figure 6 illustrates the ESG report manager interface developed using the private blockchain through the proposed framework. Once the data is collected and recorded as transactions in the blockchain using smart contracts into blocks, then the data is aggregated for every organization using the company's signed public address.

Table 3: Stakeholder-Driven ESG Data Collection Framework with IoT Integration in the Indian Construction Industry.

Organization	Department	Description	Type of IoT Sensors/Methods	Stakeholders Providing Digital Signatures	ESG Data Collected
Organization 1	D1: Project Management	Oversees project schedules and resource allocation	GPS Trackers, Resource Monitors	Employees, Project Managers	Carbon Footprint, Energy Usage
	D2: Safety	Ensures compliance with safety regulations	Wearable Sensors, Noise Monitors	Employees, Safety Officers	Worker Safety, Incident Reports
	D3: Sustainability	Develops strategies for reducing environmental impact	Smart Meters, Air Quality Sensors	IoT Sensors, Sustainability Team	Emissions, Renewable Energy Usage
	D4: Operations	Manages daily construction activities	Equipment Trackers, Fuel Sensors	Employees, Operations Managers	Resource Utilization, Operational Efficiency
	D5: Quality Control	Ensures adherence to construction standards	Material Testing Sensors	Quality Inspectors, IoT Sensors	Material Wastage, Compliance Metrics
	D6: Procurement	Handles material sourcing and vendor management	Supply Chain Monitoring Tools	Procurement Managers, Vendor Representatives	Supplier ESG Compliance
	D7: Logistics	Coordinates material and equipment movement	GPS and RFID Trackers	Logistics Team, Transport Supervisors	Transport Emissions, Delivery Efficiency
Organization 2	D1: Design	Focuses on sustainable and efficient designs	BIM Tools, Thermal Imaging Sensors	Architects, Designers, IoT Sensors	Sustainable Material Usage, Design Emissions
	D2: Site Monitoring	Tracks on-site progress and compliance	Structural Health Sensors, Cameras	Site Engineers, IoT Sensors	Real-time Safety Metrics, Dust Levels
	D3: Human Resources	Manages workforce well-being and training	Wearables, Attendance Trackers	HR Managers, Employees	Workforce Diversity, Well-being Metrics
	D4: Safety	Ensures adherence to safety protocols	Noise Sensors, Vibration Monitors	Employees, Safety Officers	Noise Pollution, Accident Reports
	D5: R&D	Develops new techniques and technologies	Advanced Sensors, Simulation Tools	R&D Team, IoT Sensors	Innovation Metrics, ESG Technology Adoption
	D6: Sustainability	Implements sustainable practices	Renewable Energy Monitors	IoT Sensors, Sustainability Team	Energy Savings, Water Conservation
	D7: Quality Control	Maintains the quality of construction materials	Material Scanners	Quality Inspectors, IoT Sensors	Recyclability, Material Durability

The collected ESG data will then be uploaded to the blockchain system through the web interface manager. This data will be published in the public blockchain consensus, making up the entire lifecycle of the hybrid blockchain system. This data can be used by third-party services to verify and give ranking information to individual companies. Investors can also use this data to gain a deeper understanding of the data and make a confident investment. Hybrid Blockchain can guarantee the execution of ESG data and record information in blocks, which enhances the information by bringing transparency, accountability, and fault-tolerant mechanisms (Qian *et al.*, 2023).

Table 4: Implementation tools for the proposed blockchain prototype system.

System Component	**Description**
Hyperledger Fabric	Version 2.2
Development System	Linux (Ubuntu 18.04.2 LTS)
CPU	Intel® Core™ i9-9900 k CPUs @ 3.6 GHz processors
Memory	32 GB
Docker Engine	20.10.12
Docker compose	1.29.2
Smart contract programming language	Go

This research is the first attempt to develop a hybrid-based blockchain platform by implementing Ethereum for the public blockchain and Hyperledger Fabric for the private blockchain for ESG data collection and management. The results validated the theoretical feasibility of the proposed framework. More specifically, this prototype guarantees the execution of ESG management in this hybrid model through smart contracts. Additionally, the ESG information collected was recorded into blocks where the data is immutable, transparent, and traceable among the stakeholders and the investors. This model also depicted the combination of data on one single website, combining the data from both private and public blockchains, thus increasing the feasibility of analyzing the information.

Investors and any third-party service involved in the ranking framework for the companies can trust the record and quickly discover the complete information retrospectively by retrieving historical records. Currently, the majority of blockchain systems in ESG management are tested in a laboratory environment based on several metrics, such as latency, storage cost, and throughput. These studies have deepened the understanding of blockchains; however, the performance of these metrics may vary between the laboratory environment and the actual project due to differences in configurable networks. As the network of blockchain peers is distributed across many corners, the throughput performance is affected by the increased processing time. The lack of empirical evidence from ESG practices reveals that industries and governments are cautious about adopting blockchains due to concerns about investor safety. Several barriers from different dimensions (e.g., technology, organization, environment, etc.) may hamper blockchain adoption and implementation. As a result, the field evaluation of the proposed prototype system is regarded as the future task of this research.

Figure 7 describes a conceptual framework for future studies, which illustrates the potential of blockchain in ESG data management. Currently, the majority of blockchain studies in ESG management focus on the project level. However, considering the development process, these projects should not be limited at the project level. As indicated in Fig 7 (1), the data for the environment is collected using the IoT sensors equipped at the company site, which uses the Ethereum blockchain. The data collected includes the category of the information, KPI, IoT data, the units in which the data is calculated, and the period for data submission. This data is then stored using the IPFS (Inter planetary Filesharing system) to enable it to be retrieved even in the future. The data, once uploaded to IPFS, undergoes data filtration using machine learning algorithms so that the images and data captured by IoT are analyzed for better format and picture clarity based on the pre-trained data (Kumar *et al.*, 2021). CNN (Convolutional Neural Network) algorithms are used for data filtration by training the model previously with similar pictures and data (Chen and Zhang, 2022). Once the data is filtered in the required format, it executes a transaction using the public address of the respective company, which is published with the inherent signature of the assigned official of that company, ensuring the company is aware of the information. Fig (2) This would contain the questionnaire and the survey used to collect the data on social and governance from the employees and management board of the company. This employs Hyperledger Fabric blockchain, which is jointly developed by the government and can be used by individual organizations to fill up the required KPIs where all the employees participate in the data sourcing through their private and public addresses, after which they will also be transacted using the company's public address to the main blockchain ledger. Fig (3) This shows the created blocks with the transactions of the data and added to the blockchain. The blocks are transmitted to all the peers on the blockchain and stored publicly, holding all the information on the environment, social media, and governance of every respective company. Fig (4) This depicts the contents of the blocks with the approved transactions and the block address that the block producers successfully created. Thus, this whole process of data collection and data publishing happens through blockchain and is secured using cryptographic hashes, ensuring the trust, transparency, and accountability of the information. In this research, we mainly concentrated on proving the effectiveness of blockchain in ESG management.

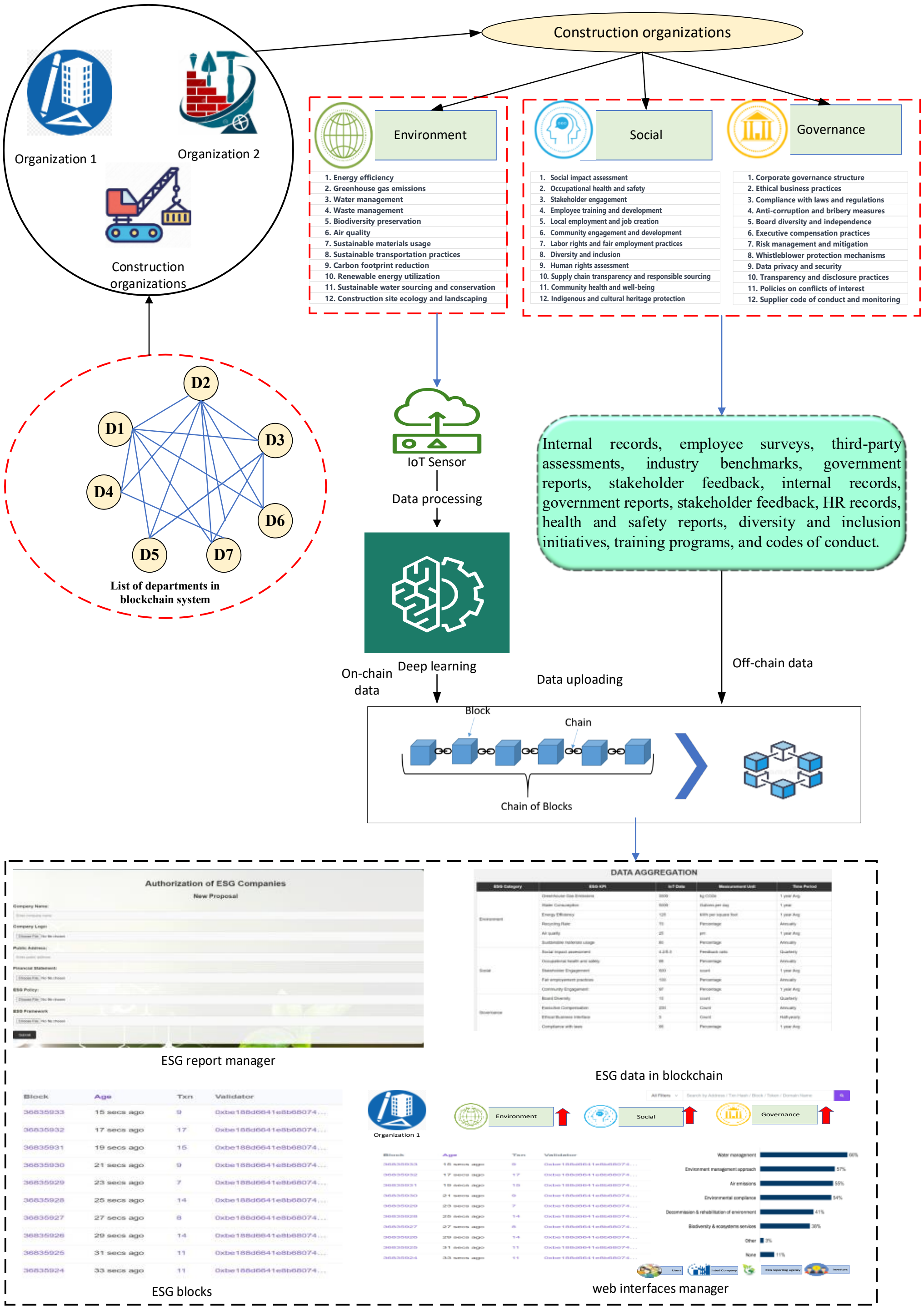

Figure 6: Interfaces and workflow of blockchain services for ESG assessment.

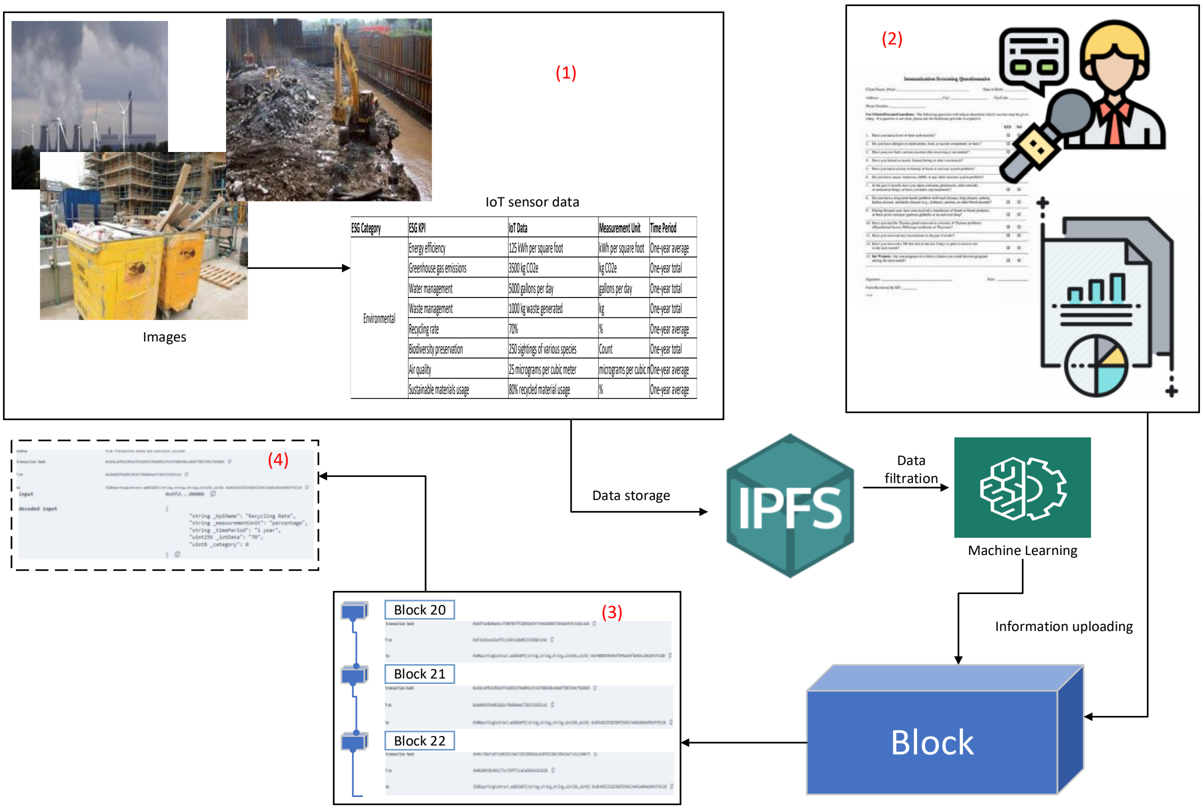

Figure 7: Information management.

6. DISCUSSION

6.1 Findings

The research significantly contributes to the evolving landscape of ESG data management within the construction industry by proposing and implementing a novel conceptual framework employing blockchain technology. A design science approach is used, ensuring a methodical exploration of complex issues related to technology and information systems (Werner *et al.*, 2021). The framework integrates a hybrid blockchain model, leveraging both public and private blockchains, offering a multifaceted solution to the challenges faced in traditional ESG reporting.

The construction industry faces significant challenges in reporting ESG metrics, including data fragmentation, lack of transparency, and inconsistencies in data collection and reporting standards (Shen et al., 2020). These challenges hinder the ability of organizations to provide accurate and reliable ESG information, leading to difficulties in assessing sustainability performance and compliance. The proposed framework addresses these issues by leveraging a hybrid blockchain model that combines the transparency of public blockchains with the controlled access of private blockchains. This system ensures that ESG data is immutable and verifiable, reducing the risk of data manipulation and enhancing trust among stakeholders (Werner et al., 2021). Furthermore, the integration of smart contracts within the blockchain automates compliance checks and data reporting, ensuring that ESG metrics are consistently monitored and reported in real-time (Kumar Singh et al., 2023). By resolving these key challenges, the framework not only improves the accuracy and reliability of ESG reporting but also aligns with the broader goals of sustainability and responsible business practices in the construction industry.

The key strength lies in the proposed hybrid blockchain's versatility and scalability, successfully demonstrated through a Hyperledger Fabric-based prototype. This approach accommodates the nuances of ESG reporting by seamlessly integrating IoT sensors for environmental data with a private blockchain for social and governance data. The hybrid model's design effectively addresses scalability concerns, ensuring optimal performance without compromising data security (Tao *et al.*, 2023). It provides a robust foundation for transparent and accountable ESG data management. The integration of IoT sensors for environmental data collection is a pivotal advancement. Automated data collection through sensors not only enhances efficiency but also reduces the chances of errors and manipulation inherent in manual reporting. The use of public blockchain for environmental data ensures transparency, immutability, and traceability, aligning with the principles of blockchain technology (Zhong *et al.*, 2022). This approach also fosters confidence among investors and the public by providing an auditable and accountable record of a company's environmental impact.

The private blockchain, implemented using Hyperledger Fabric, facilitates secure and permissioned data collection for social and governance aspects. The involvement of all stakeholders, including employees, managers, and the management board, in surveys and feedback processes through smart contracts ensures a comprehensive and diverse dataset. The emphasis on privacy and control in private blockchains is particularly crucial for sensitive data such as internal records and HR information (Quayson *et al.*, 2023b). The proposed framework aligns with the broader movement toward more inclusive and transparent corporate governance practices. The study underscores the pivotal role of smart contracts in automating processes and ensuring the trustless execution of predefined agreements. Smart contracts deployed on the blockchain contribute to the immutability of data and enhance the security of transactions. The deterministic nature of smart contracts ensures consistent outcomes across all nodes, contributing to the overall resilience of the blockchain network (Safa *et al.*, 2019). This level of automation reduces reliance on intermediaries, streamlines processes, and mitigates the risk of fraud and unauthorized alterations in ESG data.

The consensus-based ESG management model discussed in the research is another noteworthy contribution. The proposed consensus mechanism involves various entities and peers, preventing any single entity from manipulating data. This decentralized model ensures that data consensus is obtained through the signing of the organization's peers, enhancing security and reducing the risk of data manipulation by intermediaries (Zhong *et al.*, 2022). The involvement of multiple stakeholders in the consensus process contributes to a more robust and trustworthy ESG data management ecosystem. The prototype implementation using Hyperledger Fabric provides tangible evidence of the feasibility of the proposed framework. The development tools employed, including Hyperledger Fabric 2.2, Docker Engine, and Go programming language, showcase a practical realization of the conceptual model (Tao *et al.*, 2021). The system's robustness is further emphasized by the successful deployment of smart contracts and the integration of IoT sensor data, demonstrating the adaptability and effectiveness of blockchain technology in the construction industry. In a nutshell, the following contributions are noted:

1. A novel hybrid blockchain framework is introduced, combining public and private blockchains to address ESG data management challenges in the construction industry. The public blockchain ensures transparency and immutability of environmental data, while the private blockchain offers secure, permissioned access to sensitive social and governance data.
2. Smart contracts are incorporated to automate ESG compliance checks and real-time data reporting. This reduces human errors, increases efficiency, and ensures consistent monitoring and accurate reporting of ESG metrics, overcoming inefficiencies in traditional ESG reporting processes.
3. IoT sensors are integrated for automated environmental data collection, ensuring continuous monitoring of metrics such as energy usage, carbon footprint, and air quality. This enhances the accuracy of data collection and reduces the chances of data manipulation and manual errors.
4. The framework facilitates secure and controlled access to social and governance data through a private blockchain, involving multiple stakeholders, including employees, managers, and top management, in surveys and feedback processes via smart contracts. This ensures comprehensive data collection while maintaining data privacy.
5. A consensus mechanism is utilized that decentralizes data validation, involving multiple stakeholders to verify ESG data. This reduces the risk of data manipulation and ensures the trustworthiness of ESG reports, building a more secure and transparent data management system.
6. The feasibility of the framework is demonstrated through a prototype implemented with Hyperledger Fabric, Docker Engine, and the Go programming language. The practical implementation showcases the viability of combining blockchain and IoT for real-time, transparent, and secure ESG data management in the construction industry.

Thus, while the framework offers a robust and innovative pathway for transparent, automated, and accountable ESG reporting in construction, it also opens avenues for further technical refinement, pilot implementations, and exploration of regulatory and organizational barriers to adoption.

6.2 Implications of the research

This research, rooted in a design science approach, significantly contributes to the theoretical landscape of ESG data management in the construction industry. By applying Peffers et al.'s (2007) methodology, the study effectively addresses intricate issues related to technology and information systems. The theoretical underpinning of the proposed hybrid blockchain model, incorporating public and private blockchains, extends the applicability of blockchain technology to the nuanced challenges posed by ESG reporting. The integration of IoT sensors, smart contracts, and a consensus-based management model enriches the theoretical foundation by offering a holistic and robust approach to ESG data collection, ensuring transparency, immutability, and accountability.

In practical terms, this study has profound implications, particularly for the construction industry and organizations engaged in ESG reporting. The implementation of the proposed conceptual framework through a Hyperledger Fabric-based prototype demonstrates the practical feasibility of the hybrid blockchain model. The use of Hyperledger Fabric, Docker Engine, and the Go programming language provides a tangible and deployable solution for companies seeking to enhance their ESG reporting practices. The integration of IoT sensors for environmental data collection presents a practical advancement, automating data gathering and ensuring real-time, accurate information. The smart contract-based automation simplifies processes, reduces reliance on intermediaries, and enhances the efficiency of ESG data management. The consensus-based approach, involving multiple stakeholders, establishes a practical foundation for decentralized and trustworthy ESG reporting. The prototype's successful implementation serves as a useful guide for organizations looking to adopt blockchain for ESG data management.

The study's findings offer valuable insights for integrating blockchain into industry practices, especially in sectors requiring meticulous ESG reporting, such as construction. The hybrid blockchain model, accommodating both public and private aspects, provides a flexible solution applicable across diverse industries. Organizations can leverage the study's outcomes to design and implement blockchain-based systems for transparent and accountable ESG reporting. The incorporation of IoT sensors and smart contracts can streamline data collection and automate reporting processes, reducing manual errors and enhancing the overall reliability of information. This practical integration aligns with the global movement toward sustainable and transparent business practices.

Practically, the proposed framework contributes to building enhanced stakeholder confidence. Investors, regulatory bodies, and the public can benefit from a more transparent and accountable ESG reporting system facilitated by blockchain. The decentralized nature of the consensus model and the immutability of data ensure that reported ESG information is trustworthy. This increased confidence can have practical implications for investors, influencing their decisions to support environmentally and socially responsible companies. The integration of third-party services into the proposed system provides an additional layer of assurance, enabling independent verification and ratings, thereby enhancing the practical value of ESG reporting.

From a practical standpoint, the study facilitates the adoption of sustainable practices by providing a technological infrastructure that incentivizes organizations to adhere to ESG norms. The use of blockchain ensures that data regarding environmental impact is accurately captured and transparently reported. This, in turn, promotes environmentally sustainable practices as organizations become more accountable for their actions. The practical implication lies in the potential transformation of industry practices towards greater sustainability, driven by the transparent and immutable ESG reporting facilitated by the proposed hybrid blockchain model. Overall, the theoretical and practical implications of this study resonate with the broader goals of promoting transparent, accountable, and sustainable ESG reporting in the construction industry. The hybrid blockchain model, enriched by IoT sensors, smart contracts, and consensus mechanisms, offers a robust theoretical foundation that is practically deployable, paving the way for improved industry practices and stakeholder confidence in ESG reporting.

7. CONCLUSION

This research addresses a significant knowledge gap by examining blockchain technology's effectiveness in tackling specific challenges within the construction industry. The primary focus is summarizing existing challenges in ESG practices and evaluating the potential of blockchain to address these challenges. A thorough literature review was conducted to identify and understand challenges in ESG practices and highlight the potential benefits of blockchain technology. Following this, a conceptual framework leveraging blockchain was proposed to enhance the ESG assessment in construction organizations. The aim was to fill the gap in understanding and offer practical solutions.

A prototype system was developed using Hyperledger Fabric (HLF, version 2.0) to validate the proposed framework. This system provides a tangible representation of the conceptual framework in action, demonstrating the feasibility of using blockchain to address ESG challenges in construction. The study utilizes a design science approach to ensure the effectiveness and practicality of the proposed framework. The blockchain-enabled conceptual framework comprises four layers: (1) Authorization, (2) Data Collection, (3) Blockchain, and (4) Application, with the Blockchain layer serving as the core component. Smart contracts were implemented to automate ESG reporting, and a consensus process was employed to manage inspection data securely. The results indicate that blockchain technology can significantly streamline ESG reporting management in the construction industry, offering a more efficient, transparent, and secure method for collecting, verifying, and reporting ESG data. By integrating blockchain with IoT sensors and smart contracts, the framework ensures real-time data collection and compliance, reduces human errors and prevents data manipulation. This innovative approach not only enhances the accuracy and trustworthiness of ESG reporting but also promotes greater stakeholder involvement and accountability. The findings provide valuable insights for construction researchers and practitioners, showcasing the potential of blockchain to address the persistent challenges in ESG data management and contribute to more sustainable and responsible business practices.

Despite the robustness of the proposed model and its innovative features, this research has a limitation. While the framework aims to enhance the efficiency of ESG data through blockchain technology, its success depends heavily on the establishment of standardized ESG reporting frameworks, ESG audits, certifications, and addressing complex government structures and bureaucratic hurdles. Moreover, understanding the specific requirements and maturity levels of different industries, as well as the challenges they face in implementing this framework, is crucial. A comprehensive plan developed through collaboration between enterprises and government entities is necessary to address these issues effectively.

Future research in blockchain technology and ESG practices within the construction industry should focus on exploring blockchain interoperability, which will be crucial for establishing interconnected networks, ensuring transparency, and fostering collaboration. Addressing scalability issues and optimizing blockchain performance will be essential to accommodate the growing volume of construction data. Additionally, investigating governance models, user adoption challenges, and security considerations will contribute to the successful implementation of blockchain in ESG reporting systems. Further exploration of cross-industry collaboration, lifecycle analysis, regulatory frameworks, and assessing the broader social and economic impacts will provide comprehensive insights for advancing sustainability practices in construction.

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