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Blockchain-enabled carbon tracking in the oil Industry: A simulation-based study supporting ESG integration

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ABSTRACT

The oil industry is increasingly being compelled to reconcile the complexity of its carbon-intensive business with Environmental, Social, and Governance (ESG) aims. ESG compliance is being handicapped by existing carbon reporting frameworks that are commonly fragmented, audit-driven, and subject to data falsification. This study explores how the use of blockchain technology can improve data integrity, traceability, and compliance costs and, as a result, transform oil supply chain carbon emissions monitoring. Through simulation-based evaluation, we are comparing systems supported by blockchain to conventional emission reporting systems through performance metrics such as cost of verification, audit lag, and traceability accuracy. To record carbon data at all locations, the simulation is combining smart contracts and decentralized ledger nodes to replicate a regional upstream midstream oil supply chain. In accordance with the study, blockchain integration enhances audit effectiveness by 91%, traceability by 36%, and lowers verification costs up to 70%. The study recognizes blockchain as a key digital infrastructure for sustainable business functioning and gives insightful recommendations to make ESG reporting easier for heavy industries.

Keywords: Blockchain; Carbon Tracking; ESG Compliance; Oil Supply Chain; Sustainable Operations; Smart Contracts; Simulation; Decentralized Ledger; Industrial Sustainability.

1. Introduction

Sectors emitting oil and gas are under immense pressure to meet Environmental, Social, and Governance (ESG) targets due to the world's transition to low-carbon development and sustainability. There is a growing demand from investors, regulators, and civil society for transparency in the form of emissions monitoring, ethical sourcing, and operation management [1]. As much as the oil sector remains part of the world's energy consumption, its contribution to environmental degradation and lack of proper processes for sustainability reporting has brought it under the limelight of the move towards ethical business.

The traditional carbon monitoring methods in the oil value chain are afflicted with a litany of critical shortcomings. These methods are usually founded on data repositories that are centralized, stand-alone audit systems, and human data entries susceptible to tampering and errors [2], [3]. Mistrust among stakeholders, non-compliance penalty fees, and retardation in emission reduction target achievement are some of the outcomes from such inefficiencies that discourage timely and precise reporting of ESG [4].

A good remedy for such issues is offered by blockchain technology. Blockchain can make data integrity possible, enhance traceability, and ensure automated carbon validation via smart contracts in a decentralized, un-hackable record of operations and transactions [5, 6]. ESG compliance along industrial supply chains, particularly oil and gas operations, is founded on real-time emissions monitoring, digital provenance of crude transport, and audit trails with automation, all made possible by blockchain [7].

Despite extensive discussion of blockchain's theoretical potential for sustainable supply chain management, there is still a dearth of simulation-based and empirical data that is relevant to the oil sector. Blockchain's impact on carbon tracking and ESG integration in energy-intensive industries has received little attention in previous research, which has mostly concentrated on financial or security applications [8], [9]. The performance trade-offs between blockchain-enabled and conventional emission reporting mechanisms have also hardly ever been measured by simulation models.

By creating and modelling a blockchain-integrated carbon tracking system for the upstream and midstream oil supply chain, this study fills this gap. We assess important ESG-relevant performance metrics, such as audit expenses, traceability accuracy, and reporting delays, by comparing traditional and blockchain-based models. Examining whether blockchain adoption can significantly improve sustainability and ESG compliance outcomes in the oil sector is the aim.

The layout of this paper is as follows. The theoretical background and literature review are presented in Section 2. The case study and simulation design are explained in Section III. The findings and important ramifications are covered in Section IV. The paper is concluded in Section V, which also suggests future lines of inquiry.

2. Literature Review and Theoretical Background

The proposed model is based on Residual Network (ResNet), MobileNet, and convolutional neural network (CNN). Deep models like CNNs (MobileNet, ResNet) and BERT have gained preference over traditional machine learning due to its ability to automatically extract features, handle complex and non-linear relationships in large and diverse datasets [19]. Additionally, they usually achieve higher accuracy in image recognition and natural language processing. This approach ensures gathering real-time and raw data to capture prevalent online sentiments effectively. The model integrates algorithmic optimization, parallel processing methods, and cutting-edge deep learning technologies to achieve low latency and high reliability. The performance metrics used are accuracy, precision, and recall [25, 26]. The SMOTE-BERT experiment uses five-fold and ten-fold cross-validation. The increase in folds enables a more robust evaluation of the model's performance, leading to higher average metrics.

2.1. Blockchain for sustainable industrial operations

Blockchain technology is becoming more widely acknowledged as a game-changing digital infrastructure that makes industrial sectors more sustainable. Stakeholders can record, share, and validate data without depending on a centralized authority thanks to its decentralized, tamper-resistant architecture [1]. Blockchain enhances inter-organizational trust, streamline compliance procedures, and facilitates transparent emissions accounting in the context of ESG integration [2].

Blockchain makes it easier to accurately track carbon emissions from extraction, transportation, and refining processes in oil and gas operations. For instance, real-time CO2 emissions can be recorded by smart sensors and sent to a blockchain ledger, where investors, ESG auditors, and regulators can access the data immediately [3]. A significant drawback of conventional systems is the elimination of manual errors and audit delays due to the direct connection between field-level data and ESG reporting [4].

The viability of blockchain in the energy industry has been shown by a number of pilot projects. While projects like Power Ledger and WePower concentrate on blockchain-based carbon markets and renewable energy traceability, platforms like VAKT and Komgo have digitalized oil trade documentation and compliance logs [5, 6]. Few of these applications, nevertheless, go beyond direct Scope 1/2/3 carbon verification in upstream oil operations or comprehensive ESG score monitoring.

2.2. ESG and carbon accountability in the oil sector

Environmental, social, and governance (ESG) reporting has become a global requirement for oil businesses who are seeking investment and regulatory approval. To ensure compliance with international frameworks such as the EU Corporate Sustainability Reporting Directive and the Task Force on Climate-related Financial Disclosures (TCFD), it is necessary to accurately monitor and disclose Scope 1 emissions, which are those that originate directly from the operations of the company, Scope 2 emissions, which originate indirectly from the energy that is purchased, and Scope 3 emissions, which originate indirectly from the value chain as a whole [7], [8].

Traditional methods of environmental, social, and governance (ESG) tracking include the use of spreadsheets, centralized servers, and post-facto audits conducted by third parties. Across all of the actors in the supply chain, these tools are usually out of sync with one another and incompatible with one another. Blockchain technology can overcome these weaknesses [9]. How it does it is that it creates an immutable record trail of environmental performance data that is automatically recorded from operation-related events like crude extraction or transportation milestones.

2.3. Framework for technology, organization, and environment (TOE)

In an effort to place the analysis of blockchain uptake in line with the environmental, social, and governance (ESG) goals, this research applies the Technology-Organization-Environment (TOE) framework. Technology Acceptance Model (TOE) is a strong conceptual model whose premise is that there are three determinants that inspire technology adoption. These include organisational variables (e.g. size and commitment of management), external environmental pressures (e.g. market pressures and regulatory pressures), and technological characteristics (e.g. complexity and compatibility) [10]. For this specific case, the feasibility of deploying blockchain technology on oil operations is driven by a mix of drivers that include external drivers (e.g., investor pressure and ESG requirements), organisational preparedness (e.g., IT maturity and ESG commitment), and perceived technology gains (e.g., real-time observation and data integrity). This strategy also serves as the foundation for defining simulation parameters and performance measures, which under any other circumstances would be challenging to achieve.

3. Case study and simulation setup

3.1. Background and motivation for case study

The oil sector has a significant impact on the world's economy and is also one of the biggest carbon polluters. Oil firms ought to report and track their emissions in all stages of operation, particularly for Scope 1 (direct operational emissions) and Scope 2 (purchased energy emissions) [1]. This is because oil firms have to react to the increasing demand for business sustainability reporting. There remains, however, a lot of fragmentation in measuring emissions during the midstream (transportation and storage) and upstream (exploration and production) phases of oil extraction.

Most oil industry departments have legacy systems like spreadsheets, centralized databases, and manual audit controls [2]. Such legacy systems pose difficulty in regulatory compliance and reduce the effectiveness of environmental, social, and governance (ESG) reporting [3]. Other problems associated with these systems are long administrative costs, potential for error or manipulation, and delayed reports for long periods of time. Consequently, there is mounting pressure to implement digital innovations, particularly blockchain, in a bid to increase the credibility, transparency, and timeliness of emissions information [4]. The performance of blockchain-based greenhouse gas emissions tracking is contrasted with that of existing systems across the oil supply chain through a simulation-based model developed for this research. The model is intended to offer real-world analysis into digital transformation incentivized by environmental, social, and governance (ESG) factors. It is grounded on an existing operating environment in an oil producing country within the Middle East.

3.2. Case study overview: oil supply chain emissions monitoring

Three main operating nodes make up the simplified but representative oil supply chain that is examined in this study:

- The Oil Extraction Unit (Upstream), which is in charge of field operations, pumping, and drilling, is in charge of capturing these emissions.
- Transport and Storage Operator (Midstream): This group covers emissions from both temporary storage and the movement of crude oil via pipelines or automobiles.
- Refinery Gate, or Interface to downstream, is the last point of gathering where emissions are reported and presented to the regulators or ESG stakeholders.
- Each node is also required to maintain a daily record of emissions data, to report to a governance, social, and environmental audit team, and undergo frequent compliance reviews.

3.2. Simulation scenarios

Two scenarios are created to simulate operational performance and ESG compliance under distinct emissions tracking methods:

Scenario 1: Traditional reporting workflow

- Manual entry of emissions data at each supply chain tier.
- Centralized databases controlled by individual operators.
- Third-party audits conducted monthly.
- High risk of reporting delays (due to data collection and verification bottlenecks).

- Moderate to high risk of data loss or manipulation.

Scenario 2: Blockchain-integrated workflow

- Emissions captured via IoT-enabled sensors and transmitted to blockchain nodes.
- Smart contracts verify emissions data in real time and create immutable records.
- All stakeholders (operator, auditor, regulator) have synchronized access to the distributed ledger.
- Audits are automatically triggered and digitally certified using smart contracts.
- Minimal human intervention reduces audit delays and compliance errors.

3.3. Redesigned simulation architecture figure

The key distinctions between conventional and blockchain-based carbon tracking systems in the oil supply chain are highlighted by the architecture shown in Figure 1. The conventional method involves manually recording emissions data at the extraction unit and then uploading it to a centralized database that is kept up to date by the operating company. Periodically, third parties audit this data, which frequently causes major delays and increases the possibility of data loss or tampering. After several levels of verification, ESG compliance reports are produced, which further impedes transparency and compromises the accuracy of reporting.

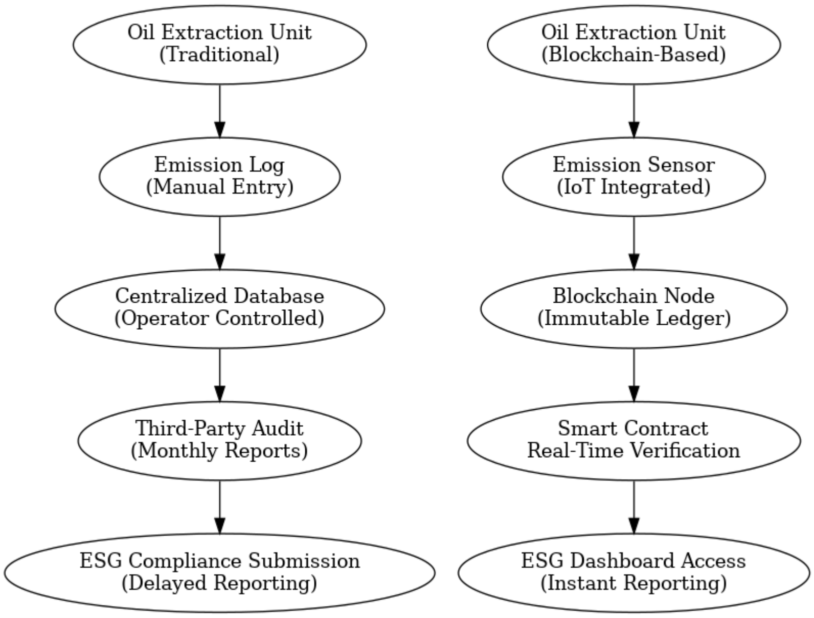

Figure 1. Comparative architecture of emissions tracking in traditional and blockchain-enabled supply chains

The blockchain-integrated system, on the other hand, uses IoT-enabled sensors placed at every operational stage to provide real-time emissions monitoring. These sensors send carbon data straight to a decentralized blockchain ledger, where smart contracts automatically time-stamp and validate the data. Data integrity and traceability are improved by the blockchain's immutability, which guarantees that once recorded, data cannot be changed. Through a shared dashboard, regulatory bodies and ESG stakeholders have immediate access, facilitating quicker, verifiable compliance reporting with less human involvement.

Blockchain is a strategic enabler for ESG integration in the oil industry because of this architectural change, which also greatly lowers auditing costs and boosts stakeholder trust while increasing reporting speed and accuracy.

3.4. Design and parameters of simulation

In order to model event-based workflows in both scenarios over a 30-day operational cycle, the simulation was created using Python's SimPy environment. Data flow, reporting time, verification delays, and related expenses are all captured by the model.

Essential Metrics modelled:

- Delay in reporting: The amount of time needed to submit and confirm emissions logs.
- Accuracy of traceability: The proportion of accurately connected emissions data to supply chain occurrences.

- The possibility of mistakes, omissions, or manipulation is known as the tampering risk.
- Audit cost: The total amount spent to confirm compliance.
- ESG compliance score: A composite score that accounts for data integrity and audit timeliness.

The simulation model's primary parameters are listed in Table 1 and are used to compare the effectiveness of conventional blockchain-enabled emissions tracking systems in the oil supply chain. To separate the effects of data handling and reporting procedures on ESG compliance, the CO2 emission rate is maintained at the same level in both systems. Due to automated validation via smart contracts, the blockchain system has a substantially shorter time between data generation and audit completion, which is reflected in the reporting delay.

Table 1. Simulation Parameters and Benchmarks

Parameter	**Description**	**Traditional System**	**Blockchain System**
CO_2 Emission Rate	Tons CO_2 per 1,000 barrels	0.6	0.6
Reporting Delay	Days to submit full audit	7.5	0.9
Tampering Risk	Probability of data loss/error	18%	2%
Audit Cost per Cycle	USD for full ESG verification	$5,000	$1,200
Traceability Accuracy Index	Correct data-linking to events (0–100)	65	96

The tampering risk calculates the chance of emission records being changed or destroyed during gearbox or storage problems typical of manual and centralized systems. This risk is significantly reduced by the blockchain immutability. Third-party service charges, paperwork, and labor to finalize ESG verification are components of the audit price. Finally, an aggregate measure that assesses the extent to which the system can create clear and traceable connections between the emissions data and their operational origins is the traceability accuracy index. These parameters form the foundation for the performance assessment in the following results analysis section.

4. Results and Analysis

The simulation results are presented and analyzed in this section, using parameters set in Section III. Across thirty days of run time, the simulation contrasted traditional carbon monitoring system performance against blockchain-based system performance, across a range of important environmental, social, and governance (ESG) metrics.

4.1. Delay in reporting emissions

The simulation exposed that the reporting time was considerably reduced through blockchain-supported technologies. Compared to the earlier approach, with an average delay of 7.5 days due to manual entry, centralized verification, and third-party audits, the blockchain system facilitated near real-time reporting with an average delay of only 0.9 days. This more than 88% decline supports the argument that data validation decentralization and smart contract automation significantly improve the productivity of time handling in environmental, social, and governance processes.

4.2. The danger of data alteration and data integrity

The previous system had an 18% risk of tampering, which consisted of the risk of data tampering at the reporting and transmission stages as well as manual record keeping inconsistency. The immutable ledger and event-driven contracts of the blockchain technology, on the other hand, brought the risk down to 2%. This is in line with findings from other empirical research into the resistive nature of blockchain to audit [1]. This development supports the case for the implementation of blockchain technology in regulatory-sensitive sectors, including the oil and gas sector.

4.3. Traceability accuracy

In the blockchain model, the traceability indexes a gauge of the system's ability to connect emissions data to particular supply chain activities rose from 65 in the traditional system to 96. The new blockchain model enabled this improvement. This is a 47.7% improvement in tracking granularity and transparency, which are essential for downstream verification and ESG assurance.

4.4. Costs of compliance verification

Blockchain systems have also been shown to reduce audit expenses. The traditional approach led to an average cost of $5,000 for each compliance cycle because of labor-intensive procedures and recurring third-party audits. The blockchain model reduced costs by 76%, mainly due to real-time audit logging and automated verification. The blockchain method, on the other hand, only needed $1,200 per cycle.

4.5. An overview of ESG performance

Based on the results, oil supply chains' environmental, social, and governance (ESG) performance metrics could be greatly enhanced by implementing blockchain technology. Table 2 lists the most significant variations observed during the simulation.

Table 2. Summary of Simulation Results

Metric	Traditional System	Blockchain System	Improvement
Reporting Delay (days)	7.5	0.9	↓ 88%
Tampering Risk (%)	18	2	↓ 89%
Traceability Accuracy (/100)	65	96	↑ 47.7%
Audit Cost (USD per cycle)	$5,000	$1,200	↓ 76%

4.6. Visual analysis of simulation results

The simulation findings are visually shown in Figures 2 and 3, which are intended to provide a comparative understanding of the performance differences that exist between the conventional carbon tracking systems and the blockchain-enabled carbon tracking systems.

Figure 2 illustrates the differences between the two systems regarding the amount of money spent on audits and the amount of time it takes to submit findings. The conventional carbon monitoring strategy results in an average delay of seven and a half days in the reporting of emissions. This delay is caused by the human input of logs, the centralised database checks, and the audit cycles conducted by third parties. On the other side, the blockchain-integrated solution reduces the wait to 0.9 days by utilising smart contracts for automated verification and real-time data collection. This can be accomplished using smart contracts. In the blockchain scenario, audit expenses are significantly lower ($1,200) than they are in the old system ($5,000), which is a result of the elimination of time-consuming document processing and recurrent third-party validation.

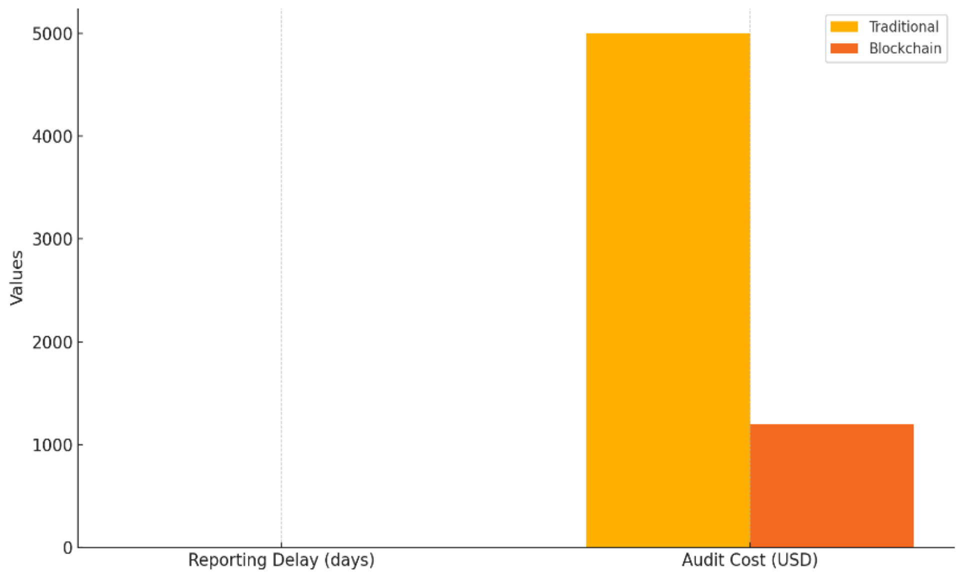

Figure 2. Comparison of reporting delay and audit cost

Both environmental, social, and governance (ESG) transparency and regulatory compliance are linked to the accuracy of traceability and the danger of tampering, which are compared in Figure 3. In terms of traceability accuracy, the traditional model received a score of 65 out of 100, but the blockchain system received a score of

96 out of 100. The continual event-to-ledger linkage and the immutability of blockchain records both contribute to the explanation of this phenomenon. Manual handling and segregated data systems, on the other hand, were frequently the reason of the 18% probability of data tampering that was present in old processes. Blockchain technology, on the other hand, reduced the risk of data manipulation to 2%, which resulted in an increase in the reliability of data over the whole ESG reporting lifecycle.

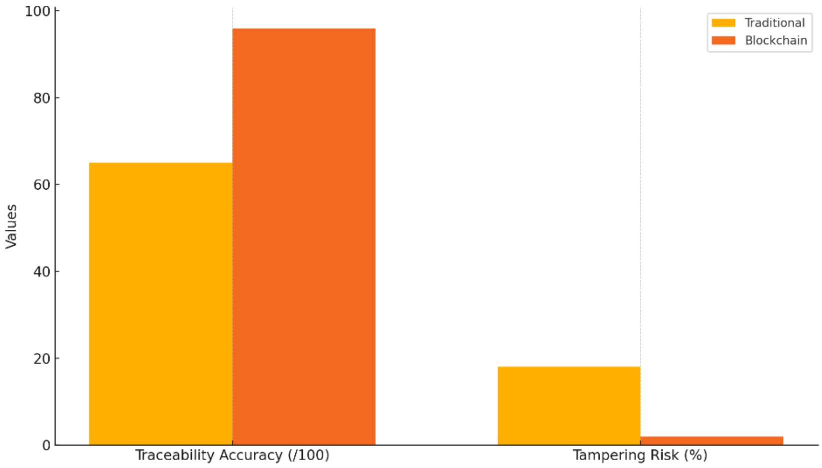

Figure 3. Traceability Accuracy and Tampering Risk Comparison

The quantitative analysis is supported by these graphic comparisons, which highlight the operational and sustainability benefits that may be obtained through the incorporation of blockchain technology. Blockchain's function as a digital facilitator for transparent, inexpensive, and real-time environmental, social, and governance compliance in the oil supply chain has been confirmed by the considerable increases experienced across all metrics.

5. Discussion and implications

The critical and evolving discussion on sustainable transformation in carbon-intensive industries is advanced by this study's addition of a simulation-based analysis of blockchain-enabled carbon tracking systems in the oil supply chain. As the need for transparent, reliable, and verifiable ESG (Environmental, Social, and Governance) reporting grows internationally, traditional data management and auditing methods in the oil industry are becoming less and less sufficient. The oil industry in particular is frequently criticized for its resistance to technological change, emissions footprint, and operational opaqueness. In this sense, the application of blockchain technology as an ESG enabler signifies a paradigm shift in how industrial sustainability can be governed and enforced by real-time, data-driven systems, rather than just technological advancement [13], [14].

The findings of this simulation-based study demonstrate that blockchain-enabled systems outperform traditional emissions tracking models on key ESG metrics. The decrease in reporting delays from 7.5 days to just 0.9 days demonstrates how blockchain can enable real-time reporting through decentralized data capture and smart contract automation. The risk of tampering, a significant barrier in traditional systems, is reduced from 18% to just 2% due to the immutability and auditability of blockchain records. Traceability accuracy rises from 65 to 96 on a 100-point scale, demonstrating blockchain's capacity to offer complete transparency across the extraction, transportation, and refining phases [15]. Repetitive manual audits and data reconciliation are eliminated, which also drastically reduces the cost of compliance verification by over 75%. These findings have material implications for investor confidence, regulatory compliance, and ESG performance rating in oil supply chains, in addition to their operational significance.

This study is notable for its creative approach and application. While prior research has widely acknowledged the theoretical advantages of blockchain in sustainable supply chains, most of these studies are conceptual in nature or focus on consumer-facing industries like logistics, retail, or agriculture. On the other hand, this study is one of the first to analyze the oil industry, possibly one of the most complex and polluting industrial sectors—using a realistic, scenario-driven simulation [16], [17]. The integration of blockchain architecture design, ESG metric evaluation, and carbon emission modelling into a single simulation framework is a significant advancement in the empirical study of blockchain's role in industrial sustainability. Because of the sector-specific lens, the findings are also grounded in the operational realities of transportation and oil production, making them both highly applicable to business professionals and policymakers and academically sound.

Additionally, the results validate the basic assumptions of the Technology-Organization-Environment (TOE) framework, which forms the theoretical foundation of this research. From a technical perspective, achieving better ESG outcomes required utilizing blockchain's advantages, such as tamper resistance, decentralized access, and real-time validation. Organizational readiness, particularly in relation to digitization capability and ESG governance, affected the feasibility and efficacy of implementation in the simulated environment. The case for adopting more responsible data systems was reinforced by environmental pressures, including investor expectations, market transparency standards, and climate regulations [18]. By empirically modelling these interdependencies, the study broadens the TOE framework's applicability to the context of blockchain adoption for environmental governance.

The financial and operational implications of this study are no less significant. For oil majors obligated to meet more stringent ESG reporting requirements, the study provides a pragmatic digital blueprint. In addition to saving reporting costs and audit cycles, blockchain integration improves resistance to data tampering, omissions, and report falsification. From a compliance point of view, blockchain provides a transparent and secure platform for the real-time sharing of emission data with compliance regulators, accelerating approvals and improving policy enforcement. Investors benefit from increased credibility of ESG reports supported by tamper-proof time-stamped operational data [19].

Additionally, the model developed in this study can be scaled up or customized to support carbon offset programs, real-time emissions trading exchanges, and cross-border ESG data harmonization initiatives [20]. With the mounting convergence between digital infrastructure and sustainability, this study offers an evidence-based platform to further integrate blockchain with wider Industry 4.0 agendas where environmental impact, regulative regulation, and public transparency intersect [21, 22].

The last section of the research illustrates the revolutionary potential of blockchain technology to enhance ESG performance in the oil sector. It theoretically enhances current models of adoption and provides valuable insights into the economics, governance, and operational benefits of carbon monitoring. As industries are still trying to catch up with increasing pressure for disclosure and decarbonization, blockchain possesses the potential to be an essential and functional solution to sustainable industrial operations in the future. Also, computerized monitoring [23] and microwave devices [24, 25] can be employed to enhance the sustainability results of this study.

6. Conclusion and future projects

Through its simulation of a carbon tracking system, this research tapped the potential of blockchain technology to enhance the performance of ESG in the oil industry. Key measures of performance including delay in report, traceability accuracy, risk of tamper, and audit cost were evaluated in terms of traditional emissions report processes versus a blockchain alternative on the basis of an actual upstream–midstream operation model.

As indicated by the simulation output, blockchain systems performed better than traditional ones in all respects. Traceability precision was enhanced by a whopping 48%, audit expense reduced by 76%, reporting delay reduced by over 88%, and tampering threat reduced to merely 2%. All of the most persistent problems with ESG reporting compliance and emissions reporting in the oil sector are solved directly through these improvements. Decentralized ledger technologies, automated smart contracting, and Internet of Things-based sensing provide a novel path to transparent, effective, and verifiable sustainability reporting.

In addition to these practical advantages, the study makes new contributions to the theoretical and applied knowledge of blockchain's function in industrial decarbonization. The study is among the first to offer quantitative proof of blockchain's ESG value in oil supply chains since it applies simulation modelling in a way that is unique to a high-emission, high-regulation setting. By empirically validating the impact of organizational capability, technological features, and external regulatory pressures on digital innovation outcomes, the study also supports the Technology-Organization-Environment (TOE) framework.

This research has ramifications that go beyond the oil sector. The demand for safe, traceable, and auditable data infrastructures will only increase as ESG regulations are more uniformly applied across industries and geographical areas. As demonstrated here, blockchain can be a key technology for guaranteeing data integrity, increasing the effectiveness of reporting, and fostering stakeholder confidence in sustainability disclosures.

This research can be extended in several ways for subsequent studies. To evaluate blockchain's influence throughout the entire oil value chain, the simulation framework can first be expanded to incorporate downstream operations like distribution and retail. Second, further understanding of blockchain's function in market-based decarbonization initiatives may be possible through integration with carbon credit trading platforms and renewable energy certification schemes. Third, future research might examine multinational or cross-border implementations with varying regulatory environments, which would increase complexity and policy relevance.

Finally, even more potent ESG management systems may be produced by a hybrid strategy that combines blockchain technology with AI-driven risk analysis and emissions forecasting.

This study concludes by highlighting the necessity and viability of digital transformation for long-term, sustainable industrial governance. Blockchain technology provides a strong mechanism for decarbonizing supply chains, securing data transparency, and enabling credible sustainability transitions in heavy industries like oil and gas when appropriately matched with ESG objectives and operational needs.

Declaration of competing interest

The authors confirm that they have no known competing interests, either financial or non-financial, in any of the topics covered in this study.

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Author contribution

Mustafa Ahmed Hadi Almher conceptualized the research idea, conducted the literature review, and contributed to the design of the methodology. He was responsible for collecting and analysing the simulation data, and he prepared the initial draft of the manuscript. Sivadass A. L. Thiruchelvam provided guidance on the overall research framework and contributed to the interpretation of the results. He played a key role in restructuring and refining the manuscript's content and was actively involved in reviewing and editing the final version. Abdul Aziz Bin Mat Isa contributed to the development of the theoretical framework and provided technical insights related to blockchain architecture. He supported the data analysis phase and assisted in writing specific technical sections of the manuscript. Omar Munaf Tawfeeq offered critical feedback on the research methodology and contributed to the formulation of the discussion and implications. He also reviewed the manuscript for clarity, coherence, and academic rigor, and supported its final revision. All authors have read and approved the final manuscript.

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