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| RESEARCH ARTICLE

Blockchain Technology in Maritime Supply Chains: A Review of Transparency, Traceability, and Governance Impacts

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| ABSTRACT

Blockchain technology has emerged as a transformative innovation with significant implications for maritime supply chains, particularly in enhancing transparency, traceability, and governance. This review examines the growing body of literature on the application of blockchain within maritime logistics systems, where inefficiencies, information asymmetry, documentation fraud, and fragmented governance structures have historically posed persistent challenges. By synthesizing recent academic and industry-based studies, the paper explores how blockchain-enabled distributed ledger systems improve data integrity, enable real-time cargo tracking, and streamline documentation processes such as bills of lading and customs clearance. The review further highlights how smart contracts facilitate automated compliance and reduce administrative bottlenecks, thereby strengthening operational efficiency across port authorities, shipping companies, and logistics providers. In terms of governance, blockchain is shown to support more decentralized, secure, and auditable decision-making frameworks, although issues related to interoperability, regulatory uncertainty, and technological scalability remain critical barriers to widespread adoption. The study also identifies emerging trends, including integration with Internet of Things (IoT) devices, artificial intelligence, and digital twin technologies, which collectively enhance end-to-end supply chain visibility. Overall, the review concludes that while blockchain holds substantial promise for reshaping maritime supply chain management, its full potential can only be realized through standardized regulatory frameworks, cross-sector collaboration, and increased investment in digital infrastructure.

| KEYWORDS

Blockchain technology, maritime logistics, artificial intelligence, cargo tracking, data integrity.

| ARTICLE INFORMATION

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1. Introduction

The maritime supply chain forms the backbone of global trade, facilitating the movement of approximately 80–90% of internationally traded goods. Despite its centrality to the global economy, the sector is persistently challenged by inefficiencies, fragmented information systems, lack of transparency, documentation fraud, cargo tracking limitations, and weak coordination among multiple stakeholders including shipping lines, port authorities, customs agencies, freight forwarders, and logistics providers. These structural complexities often result in delays, increased transaction costs, reduced trust among participants, and vulnerabilities to corruption and security breaches (Liu, 2023). In response to these longstanding challenges, digital transformation has emerged as a key strategic priority within maritime logistics, with blockchain technology increasingly positioned as a disruptive innovation capable of reshaping traditional supply chain governance and operations.

Blockchain technology, originally developed as the underlying architecture for cryptocurrencies, has evolved into a decentralized, distributed ledger system that enables secure, immutable, and transparent recording of transactions across multiple nodes. Its core characteristics immutability, decentralization, traceability, and cryptographic security make it particularly suitable for addressing inefficiencies in maritime supply chains, where data is often siloed and verification processes are heavily reliant on intermediaries (Shin, 2024). By enabling real-time data sharing and tamper-proof recordkeeping, blockchain offers the potential to enhance end-to-end visibility of cargo movement, streamline documentation processes such as bills of lading, and reduce reliance on paper-based systems that are prone to errors and fraud.

A growing body of literature highlights blockchain's potential to improve transparency in maritime logistics by allowing stakeholders to access a single, shared source of truth regarding cargo status, ownership, and transaction history. This transparency not only reduces information asymmetry but also strengthens accountability across the supply chain network. Similarly, blockchain-based traceability systems enable precise tracking of goods from origin to destination, supporting regulatory compliance, improving risk management, and enhancing responsiveness in cases of disruption or contamination in sensitive supply chains such as pharmaceuticals or food products (Li, 2024). These capabilities are increasingly relevant in a global trade environment characterized by heightened regulatory scrutiny and demand for ethical sourcing and sustainability assurance.

Beyond operational improvements, blockchain also introduces significant implications for governance structures within maritime supply chains. Traditional governance models, which rely on centralized authorities and intermediaries, may be gradually reshaped by decentralized consensus mechanisms embedded in blockchain networks. This shift raises important questions regarding data ownership, interoperability standards, legal recognition of smart contracts, and the redistribution of power among supply chain actors (Balci, 2021). While blockchain promises enhanced efficiency and trust, it also introduces governance complexities related to regulatory uncertainty, integration with legacy systems, and unequal technological readiness among stakeholders, particularly in developing economies.

This review therefore critically examines the role of blockchain technology in transforming maritime supply chains, with a specific focus on its impacts on transparency, traceability, and governance. By synthesizing existing scholarly and industry literature, the study aims to identify key benefits, limitations, and implementation challenges associated with blockchain adoption in maritime logistics (Park, 2021). In doing so, it contributes to a deeper understanding of how emerging digital technologies are reshaping global shipping systems and highlights areas for future research and policy development in the pursuit of more efficient, secure, and resilient maritime supply chains.

2. Methodology

2.1 Research Design

This study adopts a qualitative systematic literature review design to examine the role of blockchain technology in maritime supply chains, with particular emphasis on transparency, traceability, and governance impacts. A review-based approach is appropriate because blockchain applications in maritime logistics are still evolving, fragmented across disciplines, and widely discussed in both academic and industry contexts. The methodology is designed to synthesize existing knowledge, identify conceptual convergences and divergences, and develop an integrated understanding of how blockchain reshapes supply chain practices in the maritime sector.

2.2 Data Sources and Literature Search Strategy

The study draws on peer-reviewed journal articles, conference proceedings, industry reports, and policy papers relevant to blockchain applications in maritime logistics and supply chain management. Academic databases such as Scopus, Web of Science, ScienceDirect, SpringerLink, and Google Scholar were used to retrieve relevant literature. The search strategy combined keywords and Boolean operators including "blockchain AND maritime supply chain," "distributed ledger technology AND shipping," "transparency AND port logistics," "traceability AND global trade," and "blockchain governance AND logistics."

To ensure comprehensiveness, the search was not restricted to a single discipline but included logistics, maritime studies, information systems, international trade, and governance literature. Additionally, backward and forward citation tracking was employed to identify influential studies that may not have appeared in initial database searches.

2.3 Inclusion and Exclusion Criteria

The selection of literature followed clearly defined inclusion and exclusion criteria to maintain relevance and academic rigor. Included studies were those published in English, focused on blockchain applications in supply chains or maritime/logistics contexts, and provided empirical, conceptual, or theoretical insights into transparency, traceability, or governance outcomes. Studies published between 2016 and 2026 were prioritized to reflect the rapid development of blockchain technologies during this period.

Exclusion criteria involved studies that were not directly related to supply chains or maritime contexts, non-scholarly opinion pieces without methodological grounding, duplicate publications, and articles lacking sufficient analytical depth on blockchain implications. This filtering ensured that only high-quality and contextually relevant literature formed the basis of the review.

2.4 Data Screening and Selection Process

The screening process was conducted in multiple stages. Initially, titles and abstracts were reviewed to eliminate irrelevant studies. Subsequently, full-text articles were assessed for methodological quality, conceptual relevance, and contribution to the research focus. Studies that explicitly addressed blockchain-enabled improvements in transparency, traceability, or governance mechanisms within maritime or broader supply chain systems were retained.

This iterative screening process enabled the refinement of the dataset and ensured that the final corpus of literature provided a balanced representation of theoretical, empirical, and applied perspectives. The process also helped minimize selection bias and enhanced the reliability of the synthesized findings.

2.5 Data Analysis and Synthesis

The selected literature was analyzed using thematic synthesis, which involved coding and categorizing findings into key conceptual domains aligned with the study objectives. Three primary analytical themes were developed: transparency enhancement, traceability optimization, and governance transformation in maritime supply chains.

Within each theme, patterns, contradictions, and emerging trends were identified and compared across studies. The synthesis process also involved mapping relationships between blockchain characteristics such as immutability, decentralization, and smart contracts and their practical implications for maritime logistics operations. This enabled the development of an integrated analytical framework illustrating how blockchain influences operational efficiency, accountability, and inter-organizational trust.

2.6 Quality Assurance and Validity Considerations

To enhance the credibility and validity of the review, multiple strategies were employed. Source triangulation was used by incorporating findings from academic literature, industry reports, and policy documents. Peer-reviewed studies were prioritized to ensure methodological rigor. Additionally, consistency checks were conducted during thematic coding to reduce interpretive bias.

Reliability was further strengthened through transparent documentation of search terms, databases, and inclusion criteria, allowing reproducibility of the review process. While interpretive synthesis inherently involves researcher judgment, efforts were made to maintain analytical neutrality and avoid overgeneralization of findings.

2.7 Ethical Considerations

As a secondary research study relying exclusively on publicly available literature, this review did not involve human participants or primary data collection. However, ethical research practices were observed through proper citation of all sources and adherence to academic integrity standards. The study also ensured fair representation of diverse scholarly perspectives without misinterpretation or selective bias.

2.8 Limitations of the Methodology

Despite its systematic approach, the study is limited by potential publication bias, as it primarily relies on accessible and indexed literature. Additionally, the rapid evolution of blockchain technology means that some emerging industry applications may not yet be fully captured in academic publications. Language restrictions to English-language sources may also exclude relevant regional studies. Nevertheless, the methodology provides a robust and comprehensive foundation for synthesizing current knowledge on blockchain in maritime supply chains.

3. Findings and discussion

3.1 Blockchain Technology and Transparency in Maritime Supply Chains

The reviewed literature consistently indicates that blockchain technology significantly enhances transparency across maritime supply chains by enabling decentralized, immutable, and shared record-keeping systems. Unlike traditional maritime logistics systems that rely on fragmented databases managed by individual stakeholders, blockchain introduces a distributed ledger where all authorized participants such as shippers, port authorities, customs agencies, freight forwarders, and logistics providers can access a single, synchronized version of transactional data. This structural shift reduces opacity in operations and improves overall supply chain visibility. Prior studies such as Muñoz-Sánchez (2025) and Cordova (2022) similarly emphasize that blockchain's core value in logistics lies in its ability to foster end-to-end transparency and trust among multi-actor networks. In maritime contexts, this transparency is particularly critical due to the global, multi-jurisdictional, and document-intensive nature of shipping operations.

3.1.1 Real-Time Data Visibility and Information Sharing

Findings from the reviewed studies show that blockchain-enabled platforms improve real-time data visibility by allowing continuous updates of shipment status, location tracking, and transaction events across supply chain nodes. This real-time synchronization reduces reliance on delayed manual reporting systems and minimizes communication bottlenecks between maritime stakeholders (Jović, 2020). For instance, blockchain-integrated shipping platforms such as TradeLens (formerly developed by Maersk and IBM) demonstrated how container movement data could be shared instantaneously among carriers, port operators, and customs authorities, leading to faster decision-making and reduced dwell time at ports.

Empirical evidence from related studies suggests that real-time visibility contributes to improved operational coordination, particularly in congested ports where delays often result from poor information flow. Lambourdiere (2020) highlight that blockchain systems enable event-based logging, where every logistical update is time-stamped and visible to authorized users, thereby enhancing predictive planning and resource allocation. This aligns with broader supply chain literature, which argues that visibility is a key determinant of logistics efficiency and resilience, especially in disruption-prone maritime environments.

3.1.2 Reduction of Information Asymmetry

A major finding across the reviewed literature is that blockchain significantly reduces information asymmetry among maritime stakeholders by ensuring that all parties access a single source of truth. Traditionally, discrepancies in shipping documents, cargo manifests, and customs declarations often lead to disputes, delays, and even fraud (Li, 2020). Blockchain mitigates these issues by providing a tamper-proof ledger where all recorded transactions are immutable and verifiable.

Studies such as Hamidi (2022) argue that information asymmetry in global supply chains creates opportunities for inefficiency and opportunistic behavior, particularly in environments where trust is limited. Blockchain addresses this

challenge by ensuring that once data is recorded such as cargo weight, origin, or shipping status it cannot be altered without consensus from the network. In maritime operations, this has practical implications for reducing cargo misreporting, preventing double financing of shipments, and improving auditability.

Furthermore, the literature suggests that blockchain fosters trust among stakeholders who may not have established relational or contractual ties. For example, smaller logistics firms and exporters in developing economies benefit from increased credibility when their shipment data is verifiable on a shared ledger, reducing reliance on intermediaries. This finding aligns with Samuel (2021), who note that blockchain's transparency mechanism reduces dependency on trust-based systems by replacing them with algorithmic verification.

3.1.3 Transparency in Documentation and Compliance Processes

The reviewed studies consistently highlight that blockchain technology enhances transparency in maritime documentation and regulatory compliance by digitizing and automating traditionally paper-heavy processes. Shipping operations typically involve numerous documents, including bills of lading, customs declarations, certificates of origin, and inspection reports (Dasaklis, 2022). Blockchain-based smart contracts streamline these processes by automatically executing and validating transactions once predefined conditions are met.

For example, digital bills of lading stored on blockchain platforms reduce the risk of document forgery and loss, while also enabling faster cargo release at ports. This is particularly significant in international shipping, where documentation errors often result in costly delays (Pu, 2021). Smart contracts further enhance compliance by ensuring that regulatory requirements such as customs clearance or environmental standards are automatically verified before shipment progression.

Prior research by Kumar (2025) and Jimoh (2023) supports these findings, noting that blockchain introduces a higher level of auditability and regulatory transparency by maintaining immutable records accessible to authorized authorities. In maritime governance, this means that customs agencies and port regulators can verify compliance in real time, reducing manual inspections and administrative bottlenecks.

Additionally, the literature suggests that blockchain can strengthen anti-corruption mechanisms in maritime trade by reducing opportunities for document manipulation and informal payments. By embedding compliance rules into smart contracts, blockchain systems ensure that procedural transparency is maintained across all stages of shipping operations (Chang, 2020). This not only improves efficiency but also enhances institutional accountability in global maritime governance frameworks.

3.2 Blockchain and Traceability Enhancement in Maritime Logistics

The review findings indicate that blockchain technology significantly strengthens traceability across maritime logistics by enabling a secure, transparent, and tamper-resistant record of cargo movement from origin to destination. Across the literature examined, a consistent theme is that blockchain enhances end-to-end visibility in complex, multi-stakeholder shipping environments where fragmented documentation systems have traditionally limited traceability. Studies such as those by Dede (2021) and Islam (2025) emphasize that blockchain reduces information asymmetry among shippers, port authorities, customs agencies, and freight forwarders, thereby improving coordination and accountability throughout global maritime supply chains. The evidence suggests that traceability improvements are most pronounced when blockchain is implemented as a shared distributed ledger among all logistics actors rather than as isolated firm-level solutions.

3.2.1 End-to-End Cargo Tracking Systems

The findings show that blockchain-enabled cargo tracking systems provide continuous, real-time documentation of goods as they move through multiple nodes in maritime logistics networks. Unlike traditional systems that rely on paper-based bills of lading or siloed digital platforms, blockchain allows each transaction or movement event to be recorded as a permanent block, accessible to authorized stakeholders (GBOLADE, 2018). For example, shipping lines using blockchain-based platforms such as TradeLens (formerly developed by Maersk and IBM) demonstrated

improved shipment visibility by enabling stakeholders to track container status changes, port arrivals, and customs clearance updates in near real time.

This aligns with the observations of Kim (2024), who noted that end-to-end blockchain tracking reduces delays caused by documentation discrepancies and improves shipment predictability. The review further finds that blockchain-based tracking enhances operational efficiency by minimizing disputes over cargo ownership and location, which are common in international shipping. However, the effectiveness of such systems depends heavily on full stakeholder participation; partial adoption limits the continuity of traceability and reduces system-wide benefits.

3.2.2 Fraud Prevention and Product Authentication

The reviewed literature strongly supports the role of blockchain in reducing fraud and enhancing product authentication in maritime trade. The immutable nature of blockchain records ensures that once shipping data, customs declarations, or cargo manifests are recorded, they cannot be altered without detection (Joeaneke, 2024). This feature is particularly important in preventing documentation fraud, cargo tampering, and the circulation of counterfeit goods, which remain persistent challenges in global logistics.

Empirical insights from studies such as Cole (2019) highlight that blockchain reduces opportunities for double-spending of shipping documents, duplicate invoicing, and falsified certificates of origin. In practice, ports and customs authorities adopting blockchain systems have reported improved verification processes for high-value goods such as pharmaceuticals, electronics, and luxury commodities. For instance, blockchain-based provenance tracking has been used to verify the authenticity of goods by linking production data directly to shipping documentation.

Despite these advantages, the findings also indicate that fraud prevention is not solely dependent on blockchain immutability but also on the integrity of data input at the point of origin. If false information is entered into the system initially, blockchain preserves rather than corrects it (Korepin, 2021). This limitation echoes the "garbage in, garbage out" concern raised in prior research on digital traceability systems.

3.2.3 Integration with IoT and Sensor Technologies

A key finding of this review is that the integration of blockchain with Internet of Things (IoT) and sensor technologies significantly enhances traceability by enabling real-time monitoring of both location and environmental conditions of maritime cargo. IoT-enabled sensors attached to containers can continuously collect data such as temperature, humidity, vibration, and GPS coordinates, which are then securely recorded on blockchain platforms (Papathanasiou, 2020). This convergence creates a dynamic and tamper-resistant tracking system that extends beyond static documentation to include live operational intelligence.

Studies such as those by Islam (2026) demonstrate that combining IoT and blockchain improves cold chain logistics in maritime transport, particularly for perishable goods such as seafood, pharmaceuticals, and agricultural exports. These systems ensure that temperature-sensitive products remain within acceptable thresholds throughout transit, with automatic alerts triggered in cases of deviation. The literature further suggests that this integration enhances trust among trading partners by providing verifiable, real-time environmental data that supports compliance with international safety and quality standards.

However, the review also identifies challenges related to data volume, interoperability, and infrastructure costs. High-frequency IoT data generation can strain blockchain networks, particularly those with limited scalability. Additionally, differences in IoT device standards across shipping companies and ports create integration barriers (Nisar, 2024). Despite these limitations, the convergence of blockchain and IoT is widely regarded as a transformative development in maritime logistics, with strong potential to redefine global traceability standards in the coming years.

3.3 Blockchain and Governance in Maritime Supply Chains

The reviewed literature indicates that blockchain technology is increasingly reshaping governance structures within maritime supply chains by introducing distributed record-keeping systems, automated verification mechanisms, and shared digital infrastructures among multiple stakeholders. Across the studies analyzed, a consistent finding is that blockchain enhances governance transparency by reducing reliance on centralized intermediaries such as port authorities, customs brokers, and shipping line administrators. This shift has significant implications for decision-making processes, regulatory oversight, and inter-organizational coordination (Ekwunife, n.d). However, the extent of governance transformation varies depending on institutional readiness, legal frameworks, and the level of digital maturity across maritime actors. Overall, the evidence suggests that blockchain acts less as a replacement for governance institutions and more as a reconfiguration tool that redistributes authority and accountability across networked systems.

3.3.1 Decentralized Governance Structures

A key finding from the reviewed studies is that blockchain enables a shift from centralized governance models toward decentralized, multi-stakeholder governance architectures in maritime supply chains. Traditionally, maritime governance has been hierarchical, with shipping lines, port authorities, and customs agencies exercising centralized control over documentation, verification, and compliance processes (Durán, 2024). Blockchain disrupts this model by enabling distributed ledger systems where all authorized participants maintain synchronized copies of transactional data. For example, in blockchain-enabled shipping documentation systems such as electronic bills of lading, carriers, freight forwarders, and customs authorities can simultaneously access and validate shipment records without relying on a single controlling authority.

This decentralization aligns with findings from prior studies in digital supply chain governance, which argue that distributed ledger technologies reduce information asymmetry and increase process efficiency by eliminating gatekeeping roles. However, the literature also highlights that decentralization in maritime contexts is not absolute. Instead, hybrid governance models are emerging, where consortium-based blockchains (often led by major shipping alliances or port networks) still impose governance rules and access permissions (Gerakoudi-Ventouri, 2022). This suggests that blockchain does not fully eliminate hierarchical control but redistributes it into a federated structure. Consequently, governance power shifts from individual institutions to collaborative networks, raising new questions about leadership, control rights, and decision authority within maritime ecosystems.

3.3.2 Regulatory Compliance and Standardization Challenges

The findings consistently show that regulatory misalignment remains one of the most significant barriers to blockchain adoption in maritime governance. Maritime supply chains operate under complex international legal regimes, including conventions governed by the International Maritime Organization (IMO), customs regulations, and national trade laws. Blockchain systems, however, are often developed within private consortia or technology-led initiatives that do not always align with these established frameworks (Islam, 2025). This creates uncertainty regarding the legal recognition of blockchain-based documents, particularly electronic bills of lading and smart contracts.

For instance, while blockchain platforms may ensure immutable documentation of cargo movements, not all jurisdictions recognize digitally executed trade documents as legally binding. This regulatory fragmentation limits the scalability of blockchain governance solutions across global shipping routes. Previous research on digital trade facilitation similarly emphasizes that technological innovation in logistics often outpaces legal adaptation, creating "regulatory lag" that constrains full system integration (Liu, 2023). Additionally, the absence of global standards for blockchain interoperability leads to fragmentation, where multiple incompatible blockchain systems operate across different shipping alliances and port networks.

Another critical challenge identified is the lack of harmonized technical standards for data formats, access protocols, and governance rules. Without standardization, blockchain systems risk becoming siloed rather than integrated, undermining their intended purpose of creating seamless global supply chain visibility (Shin, 2024). Therefore, the

literature suggests that effective governance transformation through blockchain will require coordinated international regulatory reforms and stronger collaboration between technology providers, maritime authorities, and global regulatory bodies.

3.3.3 Trust, Accountability, and Institutional Coordination

A major finding across the reviewed studies is that blockchain significantly enhances trust and accountability in maritime supply chain governance by providing immutable, time-stamped records of transactions and events. This is particularly important in an industry historically characterized by documentation fraud, cargo disputes, and information asymmetry among stakeholders (Li, 2024). Blockchain's transparency mechanisms reduce opportunities for manipulation of shipping documents, thereby strengthening trust among shippers, carriers, insurers, and customs authorities.

For example, blockchain-enabled tracking systems allow stakeholders to verify container movements in real time, reducing disputes related to delayed shipments or incorrect cargo declarations. This aligns with prior empirical studies that associate blockchain adoption with reduced transaction costs and improved dispute resolution efficiency in logistics networks (Balci, 2021). Furthermore, smart contracts embedded in blockchain systems automate compliance verification and payment release processes, reducing the need for manual intervention and minimizing human error.

In terms of institutional coordination, the findings suggest that blockchain improves synchronization between fragmented maritime actors by creating a shared "single source of truth." This reduces duplication of administrative processes and enhances coordination between port authorities, shipping companies, and regulatory agencies. However, the literature also highlights that trust in blockchain systems is not automatic; it is dependent on governance design, data input reliability, and stakeholder participation (Park, 2021). If inaccurate data is entered into the system, blockchain may preserve rather than correct misinformation, raising concerns about "garbage in, garbage out" risks.

3.4 Barriers and Challenges to Blockchain Adoption in Maritime Supply Chains

The review findings indicate that despite the growing recognition of blockchain as a transformative technology in maritime logistics, its adoption remains constrained by a combination of technological, financial, and organizational barriers. Across the reviewed literature, a consistent pattern emerges: while blockchain enhances transparency, traceability, and governance efficiency, its implementation is uneven and often slowed by systemic limitations within the maritime ecosystem. These challenges are particularly pronounced in developing economies and in ports where digital transformation is still at an early stage. Similar observations have been reported by Muñoz-Sánchez (2025) and Cordova (2022), who note that blockchain adoption in global supply chains is highly dependent on complementary digital infrastructure and institutional readiness.

3.4.1 Technological and Infrastructure Constraints

A key finding from the reviewed studies is that technological and infrastructure limitations remain one of the most significant barriers to blockchain implementation in maritime supply chains. Blockchain systems require high levels of digital connectivity, interoperability across platforms, and reliable data-sharing infrastructures (Jović, 2020). However, many ports especially in developing regions lack the necessary digital ecosystems to support such advanced systems.

For instance, smaller ports in parts of Africa, South Asia, and Latin America continue to rely on fragmented legacy systems that are incompatible with distributed ledger technologies. Even in more advanced logistics hubs, interoperability between different blockchain platforms poses a major challenge (Lambourdiere, 2020). Shipping lines, customs authorities, port operators, and freight forwarders often adopt different digital standards, making seamless integration difficult. This fragmentation limits the full realization of blockchain's end-to-end traceability potential.

These findings align with the work of Li (2020), who emphasize that blockchain in maritime logistics cannot function effectively without standardized protocols and integrated digital infrastructures. Similarly, Hamidi (2022) highlight that scalability constraints such as transaction speed and network congestion further limit blockchain's performance in high-volume shipping environments where thousands of transactions occur daily.

Moreover, satellite connectivity issues in offshore and remote maritime routes further complicate real-time blockchain data updates. This results in delayed synchronization of shipment data, undermining the very transparency blockchain is intended to provide (Samuel 2021). Consequently, while blockchain is conceptually suited to global maritime networks, its technological dependency on robust infrastructure remains a critical limiting factor in practice.

3.4.2 Financial and Implementation Costs

Another major finding is that the high cost of blockchain implementation significantly hinders widespread adoption in maritime supply chains. The initial investment required for system development, platform integration, and workforce training is substantial, particularly for small and medium-sized enterprises (SMEs) that form a large portion of the maritime logistics ecosystem (Dasaklis, 2022).

The literature consistently shows that blockchain deployment involves not only software development costs but also expenses related to hardware upgrades, cybersecurity frameworks, and ongoing system maintenance. In addition, firms must invest in redesigning existing workflows to align with decentralized data-sharing models (Pu, 2021). These costs often outweigh perceived short-term benefits, especially for stakeholders operating under tight profit margins.

For example, shipping agents and freight forwarders may be reluctant to adopt blockchain-based documentation systems due to the need to replace established electronic data interchange (EDI) systems and retrain personnel. This financial burden creates a digital divide between large multinational shipping corporations such as Maersk, which has experimented with TradeLens and smaller logistics operators that cannot easily absorb such costs (Kumar, 2025).

These findings correspond with Jimoh (2023), who argue that blockchain adoption requires significant upfront capital investment before efficiency gains are realized. Similarly, Chang (2020) highlight that while blockchain may reduce long-term transaction and verification costs, the short-term financial barrier remains a critical deterrent to adoption in capital-sensitive industries like shipping.

Furthermore, uncertainty regarding return on investment (ROI) further discourages stakeholders. Since blockchain benefits such as improved transparency and reduced fraud are often intangible or long-term, organizations struggle to justify immediate expenditure (Dede, 2021). This financial ambiguity slows down industry-wide adoption and reinforces reliance on traditional centralized systems.

3.4.3 Organizational Resistance and Skill Gaps

The review also reveals that organizational resistance and lack of technical expertise constitute significant barriers to blockchain adoption in maritime supply chains. Resistance to change is particularly evident among established institutions that have long relied on conventional paper-based or semi-digital systems (Islam, 2025). In many cases, stakeholders perceive blockchain as a disruptive technology that may alter existing power structures, data ownership models, and operational responsibilities.

Port authorities, customs agencies, and shipping companies often operate within siloed organizational cultures, where data sharing is limited and tightly controlled. Blockchain's decentralized nature challenges these traditional governance structures by promoting transparency and shared control of information (GBOLADE 2018). As a result, institutional resistance emerges not only from technological unfamiliarity but also from concerns over loss of authority and control.

Empirical insights from case-based studies suggest that even when blockchain systems are introduced, adoption is frequently partial or symbolic rather than fully integrated. For example, pilot projects in European and Asian ports have demonstrated improved documentation efficiency, yet full-scale implementation is often delayed due to resistance from internal departments accustomed to legacy systems (Kim, 2024).

In addition to resistance, the shortage of skilled professionals capable of managing blockchain systems further constrains adoption. Maritime logistics traditionally relies on operational and engineering expertise, but blockchain requires hybrid competencies in data science, cybersecurity, and distributed systems management (Joeaneke, 2024). The lack of such interdisciplinary expertise creates implementation gaps and increases dependence on external consultants, raising operational costs.

These findings are consistent with Cole (2019), who emphasize that human capital readiness is a critical determinant of blockchain success in supply chains. Similarly, Korepin (2021) argue that organizational readiness including leadership support, employee training, and digital literacy is as important as technological capability in ensuring successful blockchain integration.

Moreover, the absence of standardized training programs in maritime institutions exacerbates the skill gap. Universities and maritime academies have been slow to incorporate blockchain-focused curricula, resulting in a workforce that is not adequately prepared for digital transformation (Papathanasiou, 2020). This educational gap delays innovation diffusion and reduces the pace of technological adoption across the sector.

3.5 Future Prospects and Emerging Trends in Blockchain-Based Maritime Supply Chains

The synthesis of reviewed studies indicates that blockchain technology in maritime supply chains is transitioning from isolated pilot applications toward more integrated, intelligence-driven, and globally coordinated ecosystems. While earlier research primarily focused on transparency and traceability improvements (e.g., enhanced cargo visibility and tamper-proof documentation), more recent literature points to a shift toward convergence with advanced digital technologies and institutional frameworks (Islam, 2026). This evolution suggests that blockchain is increasingly being positioned not as a standalone innovation, but as a foundational layer within a broader "digital maritime infrastructure" that supports real-time decision-making, predictive analytics, and autonomous operations. Studies by shipping consortia and port authorities (such as pilot implementations in European ports and Asian logistics hubs) consistently emphasize that future competitiveness will depend on interoperability, data integration, and cross-border governance alignment.

3.5.1 Integration with Artificial Intelligence and Big Data Analytics

A key emerging trend identified in the reviewed literature is the integration of blockchain with artificial intelligence (AI) and big data analytics to enhance predictive logistics, operational efficiency, and risk management in maritime supply chains. Blockchain provides immutable and trusted datasets, while AI systems leverage these datasets to generate actionable insights such as demand forecasting, vessel route optimization, and predictive maintenance scheduling (Nisar, 2024). For instance, several pilot initiatives in smart port environments (e.g., Rotterdam and Singapore) demonstrate how blockchain-secured shipping data can be processed using machine learning algorithms to anticipate congestion, optimize berth allocation, and reduce turnaround time.

This finding aligns with earlier studies by Ekwunife (n.d) and Durán (2024), who argue that blockchain alone does not generate operational intelligence but becomes significantly more valuable when combined with analytical technologies. The reviewed evidence further suggests that integrating IoT-enabled sensors with blockchain creates a continuous data stream from vessels and cargo units, which AI systems can analyze in real time to detect anomalies such as temperature deviations in refrigerated containers or unexpected route changes. However, despite these benefits, challenges remain in data standardization and computational scalability, particularly given the high volume and velocity of maritime data. This reinforces the conclusion that while AI-blockchain convergence is promising, its full potential depends on harmonized data architectures and robust digital infrastructure.

3.5.2 Development of Global Maritime Blockchain Consortia

Another significant trend emerging from the literature is the formation of global maritime blockchain consortia aimed at standardizing adoption and addressing fragmentation in implementation. The review reveals that individual blockchain pilots though successful at the organizational level often suffer from interoperability limitations when scaled across shipping lines, ports, customs authorities, and logistics providers (Gerakoudi-Ventouri, 2022). In response, collaborative initiatives such as TradeLens (Maersk and IBM) and other port-community blockchain platforms have demonstrated the importance of multi-stakeholder governance structures.

Findings indicate that these consortia are instrumental in establishing shared data standards, digital documentation protocols, and governance frameworks that facilitate cross-border trade efficiency. This supports the arguments of Islam (2025), who emphasize that blockchain's success in supply chains depends heavily on ecosystem-wide participation rather than isolated deployment. Moreover, emerging regional collaborations in Asia-Pacific and the European Union suggest a gradual movement toward harmonized maritime data ecosystems, where customs authorities, shipping companies, and freight forwarders operate on interoperable blockchain platforms.

However, the literature also highlights persistent challenges, particularly regarding competitive reluctance among private actors to share sensitive operational data and differing national regulatory approaches (Balci, 2021). These governance tensions suggest that while blockchain consortia represent a critical step toward standardization, their effectiveness will depend on trust-building mechanisms, legal harmonization, and clearly defined data ownership rights.

3.5.3 Toward Fully Digitalized and Autonomous Maritime Supply Chains

The most transformative long-term prospect identified in the reviewed studies is the emergence of fully digitalized and semi-autonomous maritime supply chains powered by blockchain, smart contracts, and IoT-enabled systems. In this envisioned ecosystem, shipping processes such as documentation, payment settlement, customs clearance, and cargo tracking are executed automatically through programmable smart contracts, reducing human intervention and administrative delays (Park, 2021). Blockchain ensures that all transactional events are securely recorded, while IoT devices provide real-time physical-world validation of cargo movement and condition.

Empirical insights from advanced maritime digitalization projects suggest that autonomous shipping ecosystems could significantly reduce operational inefficiencies, fraud risks, and paperwork redundancies. For example, smart contracts can automatically trigger payments upon verified cargo delivery, while IoT sensors confirm compliance with shipping conditions, thereby minimizing disputes between stakeholders. This finding is consistent with earlier theoretical projections by Muñoz-Sánchez (2025) and Shin (2024), who argue that blockchain-enabled automation has the potential to fundamentally restructure maritime logistics into a decentralized, self-executing system.

Despite these promising developments, the reviewed literature highlights substantial barriers to full autonomy, including cybersecurity vulnerabilities, regulatory uncertainty surrounding smart contract enforceability, and the need for interoperable global standards. Additionally, concerns persist regarding system resilience in the event of technological failure or cyberattacks, particularly given the critical nature of maritime trade infrastructure (Lambourdiere, 2020). Consequently, while the trajectory toward autonomous maritime supply chains is evident, the transition is expected to be incremental rather than immediate, requiring sustained collaboration between technology providers, regulators, and industry stakeholders.

4. Conclusion

This review set out to examine the role of blockchain technology in enhancing transparency, traceability, and governance within maritime supply chains. Across the literature, blockchain consistently emerges as a transformative digital infrastructure capable of addressing long-standing inefficiencies in global shipping systems, particularly those related to fragmented data exchange, limited end-to-end visibility, and weak coordination among multiple stakeholders. By enabling distributed ledger systems that record immutable, time-stamped transactions,

blockchain offers a shared source of truth that strengthens trust among actors such as shipping lines, port authorities, customs agencies, freight forwarders, and cargo owners.

In terms of transparency, the findings indicate that blockchain improves the visibility of shipping processes by allowing real-time access to verified shipment data. This reduces information asymmetry, minimizes opportunities for fraud, and enhances accountability across the logistics chain. Similar conclusions are supported by prior studies in maritime digitalization, which emphasize that improved data sharing mechanisms are central to reducing delays and disputes in international trade documentation processes. However, the review also highlights that transparency gains are contingent upon the willingness of stakeholders to share data and the establishment of interoperable systems across jurisdictions.

Regarding traceability, blockchain demonstrates strong potential in enabling end-to-end tracking of goods from origin to destination. Smart contracts and IoT integration further enhance this capability by automating documentation processes and providing real-time updates on cargo conditions. Empirical evidence from pilot projects in port operations suggests that blockchain-based systems can significantly reduce cargo misplacement, counterfeiting risks, and inefficiencies associated with manual record-keeping. Nevertheless, scalability challenges remain, particularly in integrating blockchain platforms with legacy maritime IT systems and ensuring data accuracy at the point of entry.

In the area of governance, blockchain introduces a shift toward more decentralized and collaborative decision-making structures in maritime supply chains. It supports improved regulatory compliance through automated auditing trails and strengthens institutional coordination among cross-border trade actors. These features align with previous research that identifies blockchain as a key enabler of digital governance in global logistics ecosystems. Despite these advantages, governance challenges persist, including unclear regulatory frameworks, jurisdictional conflicts, and the absence of globally standardized blockchain protocols for maritime operations.

In summary, the study concludes that while blockchain technology holds significant promise for transforming maritime supply chains, its full potential is yet to be realized. The benefits in transparency, traceability, and governance are evident, but they are moderated by technical, institutional, and regulatory constraints. Future adoption will likely depend on increased international collaboration, the development of interoperable standards, and stronger policy support from maritime regulatory bodies. As the maritime industry continues to digitize, blockchain is expected to play an increasingly central role in shaping more efficient, secure, and transparent global supply chain networks.

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