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Blockchain for Maritime Regulatory Compliance: A Systematic Review of Digital Documentation and Audit Trail Solutions

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Abstract

Blockchain has emerged as a promising technology for strengthening maritime regulatory compliance by improving digital documentation, information integrity, traceability, transparency, and auditability across global maritime supply chains. Despite increasing research interest and numerous proposed applications, existing knowledge remains fragmented across different technological domains, limiting a comprehensive understanding of blockchain's contribution to regulatory compliance. This study systematically reviews the literature to examine blockchain technologies and applications supporting maritime regulatory compliance, evaluate their contribution to digital documentation and immutable audit trails, identify the challenges limiting implementation, and determine future research directions. A systematic literature review was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) Statement, with evidence synthesised from 130 peer-reviewed publications published between 2020 and 2026 using thematic synthesis. The review identifies digital documentation, immutable audit trails, customs and border compliance, certificate verification, and smart contract automation as the principal application areas through which blockchain enhances regulatory compliance. The findings further demonstrate that blockchain strengthens document authenticity, traceability, accountability, information sharing, and process automation while reducing fraud, administrative duplication, and document verification delays. However, widespread adoption remains constrained by governance challenges, interoperability limitations, legal and regulatory uncertainty, organisational resistance, scalability concerns, implementation costs, and the absence of internationally accepted standards. This study provides a comprehensive synthesis of current knowledge, identifies critical research gaps, and proposes future research directions to support the development of secure, interoperable, and institutionally accepted blockchain-enabled maritime regulatory compliance ecosystems.

Keywords: Blockchain; Maritime Regulatory Compliance; Digital Documentation; Audit Trails; Smart Contracts; Systematic Literature Review

1. Introduction

Maritime transport plays a central role in international trade by facilitating the movement of goods across

interconnected global supply chains. Shipping lines, ports, freight forwarders, customs authorities, terminal operators, regulatory agencies, and other logistics organisations collectively support the transportation of a substantial proportion of internationally traded merchandise [6, 108, 106, 109]. The effectiveness of maritime logistics therefore depends not only on operational efficiency but also on compliance with extensive legal, regulatory, safety, environmental, security, and trade-related requirements established at international, regional, and national levels [6, 31, 16, 7, 35].

Maritime regulatory compliance encompasses adherence to international conventions, customs regulations, environmental standards, port requirements, cargo security procedures, vessel safety rules, and trade documentation obligations [6, 91]. These requirements are administered by organisations such as the International Maritime Organization, the World Customs Organization, national customs administrations, maritime authorities, port authorities, and other regulatory institutions [6, 118, 7]. Shipping organisations operating across different jurisdictions must consequently demonstrate compliance with multiple regulatory frameworks throughout the shipment lifecycle, from cargo booking and document preparation to customs clearance, vessel operation, cargo release, and final delivery [35, 92].

The growing complexity of maritime regulation has increased the need for accurate, timely, complete, and verifiable information. Regulatory authorities frequently require evidence that prescribed procedures have been followed, mandatory inspections have been completed, applicable certificates remain valid, and cargo declarations accurately reflect the goods being transported [49, 24, 119]. Compliance therefore depends heavily on the effective management of documents such as Bills of Lading, cargo manifests, customs declarations, certificates of origin, inspection reports, dangerous goods declarations, environmental records, vessel certificates, insurance documents, and cargo release authorisations [66, 111, 93].

Despite continuing digital transformation across the maritime sector, many regulatory and documentation processes remain dependent on paper-based procedures, fragmented databases, manual verification, and limited information exchange between independent organisations [115, 85, 47, 93]. Different stakeholders frequently maintain separate versions of the same documents within organisational information systems that were not designed for seamless cross-organisational collaboration [35, 111, 30]. This fragmentation contributes to duplicated data entry, inconsistent records, prolonged document reconciliation, delayed customs clearance, increased administrative costs, and limited visibility across maritime supply chains [88, 30, 111, 66, 34].

Conventional documentation processes are vulnerable to forgery and fraud in maritime transport, including falsified ship certificates, forged cargo manifests, fraudulent or missing health certificates, and manipulation of shipping agreements [68, 58]. Weak certification systems and fragmented document handling also increase exposure to invalid, outdated, or improperly verified certificats [26, 8, 35]. Where documents move across multiple stakeholders and jurisdictions, different parties often hold separate versions of the same records, making authoritative status harder to establish [35, 37]. Serial handoffs can let inaccurate or fraudulent records propagate through the chain and remain difficult to detect downstream [58, 37]. Manual verification then adds time because officials must inspect documents, verify legality, use databases or special tools, and seek clarification from issuing authorities or counterpart agencies [26, 13]. These limitations can delay vessel turnaround, cargo release, customs processing, commercial settlements, and other time-sensitive maritime activities [37].

Reliable audit trails are therefore essential for supporting regulatory compliance within maritime logistics. An audit trail provides a chronological record of transactions, document submissions, approvals,

inspections, access activities, cargo movements, regulatory decisions, and other operational events [96, 82, 67]. Such records enable organisations and regulators to establish who performed a particular action, when the action occurred, what information was submitted or modified, and how a compliance process progressed over time [82, 78]. Audit trails support accountability, traceability, regulatory inspection, dispute resolution, fraud investigation, evidence preservation, and the reconstruction of historical events [99, 15, 10].

However, conventional audit trail mechanisms often remain distributed across editable and independently controlled organisational databases [48, 33, 3]. Authorised administrators may be able to modify or delete historical records, while stakeholders may retain incomplete or conflicting transaction histories. Limited interoperability also prevents regulators from obtaining a unified and verifiable account of events across the full maritime logistics process [33, 101, 63, 37]. As a result, the reliability of compliance evidence may depend on the integrity of individual organisations and the accuracy of records generated within isolated information systems.

Blockchain technology has emerged as a potential digital infrastructure for addressing some of these limitations. Blockchain provides a shared and cryptographically secured ledger through which authorised stakeholders can record, validate, and verify transactions across organisational boundaries [35, 63, 17]. Once validated, records are linked to previous transactions and preserved in a manner that makes subsequent alteration detectable [10, 35, 37]. This capability can strengthen the integrity of digital documentation and provide a more reliable foundation for maintaining chronological compliance records.

Several blockchain characteristics are particularly relevant to maritime regulatory compliance. Cryptographic hashing can support the verification of document integrity, while digital signatures can authenticate the organisations or individuals responsible for submitting and approving records [63, 35, 64, 14]. Timestamping can establish when regulatory or operational events were recorded, and distributed consensus can enable participating organisations to validate transactions according to agreed governance rules [63, 35, 29, 91, 98, 128, 90]. Smart contracts can further automate predefined compliance activities, including document approval, certificate validation, customs verification, cargo release, and regulatory reporting [63, 35, 91, 64, 111].

Blockchain may therefore provide a shared source of verifiable information for shipping companies, customs authorities, port operators, freight forwarders, regulators, and other authorised stakeholders. Through controlled information sharing, blockchain-enabled systems can reduce discrepancies between organisational records, strengthen document authenticity, preserve immutable audit histories, and improve the transparency of compliance-related activities [35, 66, 54, 64, 90, 70]. Permissioned blockchain architectures are especially relevant in this context because they can combine distributed recordkeeping with controlled membership, role-based access, confidentiality protections, and institutional governance [75, 3, 21, 64, 128].

Nevertheless, blockchain should not be regarded as an automatic solution to all maritime compliance challenges. The reliability of blockchain-based records remains dependent on the accuracy of the information initially submitted, the security of identity and access management mechanisms, the effectiveness of governance arrangements, and the integration of blockchain platforms with existing maritime information systems [35, 66, 75]. Blockchain adoption may also be affected by legal uncertainty, regulatory fragmentation, commercial confidentiality concerns, implementation costs, organisational resistance, scalability limitations, and the absence of internationally accepted interoperability standards [35, 63, 79].

Research concerning blockchain in maritime logistics has grown substantially in recent years. Existing studies have examined blockchain applications in cargo tracking, supply chain visibility, port operations, Electronic Bills of Lading, customs processes, shipping documentation, smart contracts, and logistics optimisation [66, 3, 63, 37]. Several studies have also investigated broader adoption challenges, including governance, trust, privacy, interoperability, organisational readiness, and regulatory acceptance [75, 35, 108].

Despite this growing body of research, literature remains fragmented across different application areas and disciplinary perspectives. Existing reviews frequently examine blockchain adoption within maritime logistics or supply chain management broadly, without providing a focused synthesis of its contribution to maritime regulatory compliance [47, 75, 111]. Digital documentation, immutable audit trails, certificate verification, customs compliance, trusted information exchange, and automated compliance processes are often discussed as separate technological applications rather than as interconnected components of a regulatory compliance ecosystem [3, 37, 111].

Consequently, there remains a need for a systematic review that consolidates existing knowledge regarding how blockchain supports maritime regulatory compliance, particularly through digital documentation and audit trail solutions. A focused synthesis is required to determine which blockchain mechanisms and applications have been investigated, what benefits have been reported, which implementation challenges remain unresolved, and where further research is required [66, 75, 76, 103, 111]. Such an analysis is important for distinguishing conceptual expectations from validated applications and for determining whether blockchain-enabled compliance systems are progressing towards practical and institutionally accepted deployment.

This systematic literature review addresses this gap by critically examining existing research on blockchain applications for maritime regulatory compliance. Specifically, it synthesises blockchain applications supporting digital documentation, immutable audit trails, customs and border compliance, certificate verification, smart contract automation, and trusted information sharing, while evaluating the technical, organisational, legal, economic, and governance factors influencing their adoption. By consolidating current evidence, the review identifies the principal barriers to implementation and highlights key research gaps and future research priorities for developing interoperable, secure, legally recognised, and operationally viable blockchain-enabled maritime compliance ecosystems.

While this review primarily synthesises technological applications of blockchain, it is conceptually informed by the principles of Socio-Technical Systems Theory (STS), which recognises that organisational outcomes emerge from the interaction between technological systems and social, organisational, and institutional factors. Within maritime regulatory compliance, blockchain implementation depends not only on distributed ledger technologies, smart contracts, and cryptographic mechanisms, but also on governance arrangements, regulatory acceptance, stakeholder collaboration, interoperability, and organisational readiness. Accordingly, this review interprets blockchain-enabled maritime regulatory compliance as a socio-technical ecosystem in which technological capabilities and institutional conditions must operate together to achieve effective, trusted, and sustainable compliance.

Accordingly, the review is guided by the following research questions:

RQ1: What blockchain technologies and applications are currently employed to support maritime regulatory compliance?

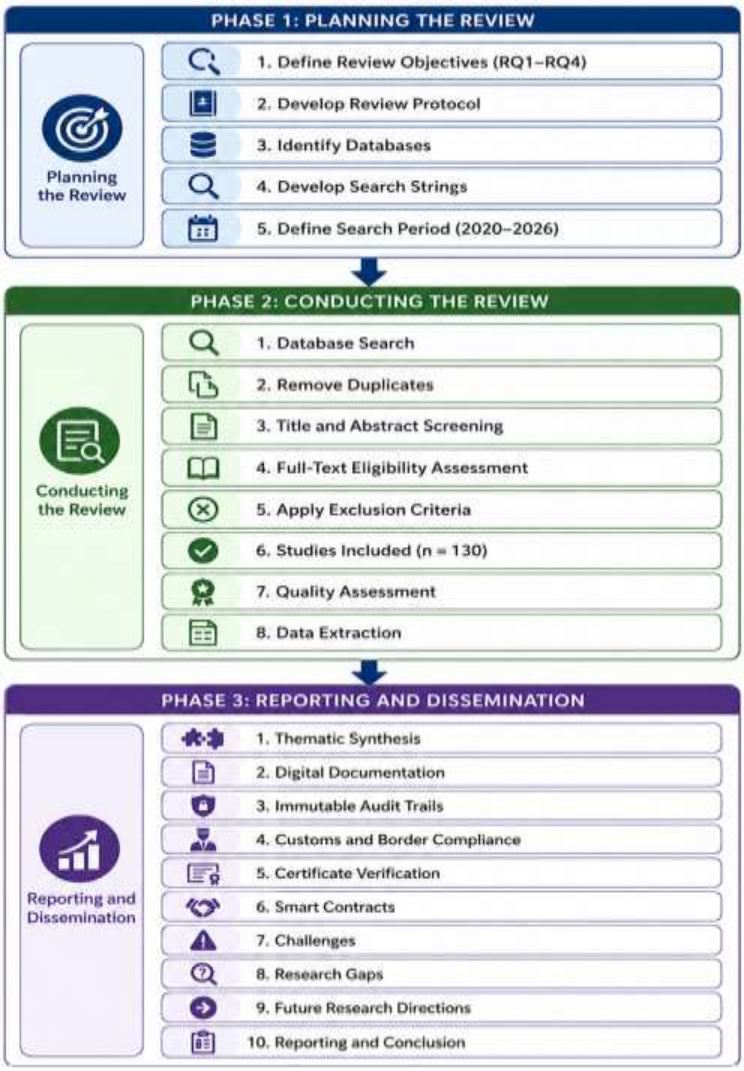
RQ2: How does blockchain improve digital documentation and audit trail management within maritime logistics?

RQ3: What challenges limit the adoption of blockchain for maritime regulatory compliance?
RQ4: What research gaps and future research directions exist for blockchain-enabled maritime compliance systems?

2. Methodology

This study employed a Systematic Literature Review (SLR) to synthesise existing knowledge regarding blockchain applications for maritime regulatory compliance, with particular emphasis on digital documentation, immutable audit trails, customs and border compliance, certificate verification, and smart contract automation. A systematic literature review was selected because it provides a transparent, rigorous, and reproducible approach for identifying, evaluating, and synthesising evidence from existing studies. The review methodology was guided by the systematic review procedures proposed by [131]. Furthermore, this review was conducted and reported in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) Statement to ensure methodological transparency, completeness, and reproducibility. This systematic literature review was not prospectively registered in a review registry such as PROSPERO or the Open Science Framework (OSF), and no formal review protocol was prepared.

Figure 1. Systematic Literature Review Methodology Adopted in This Study



The literature search was conducted between May and July 2026 across eleven scientific databases comprising Scopus, Web of Science, IEEE Xplore, ACM Digital Library, ScienceDirect, SpringerLink, Taylor & Francis Online, Emerald Insight, ProQuest, EBSCOhost, and Google Scholar. Google Scholar was used primarily to identify recently published studies and to perform backward and forward citation tracking. The review considered publications published between January 2020 and June 2026, reflecting the increasing adoption of blockchain technologies within maritime logistics, regulatory compliance, and digital trade ecosystems.

The search strategy combined keywords using Boolean operators (AND and OR). Representative search terms included *blockchain*, *distributed ledger technology*, *maritime regulatory compliance*, *maritime logistics*, *container shipping*, *electronic bill of lading*, *digital documentation*, *audit trail*, *customs compliance*, *border compliance*, *certificate verification*, *smart contracts*, *regulatory reporting*, *compliance automation*, *traceability*, *transparency*, *information sharing*, and *maritime supply chain*. Additional backward and forward citation searches were conducted to identify relevant studies that were not retrieved during the initial database search.

Publications were eligible for inclusion if they were peer-reviewed journal articles or conference papers published in English that examined blockchain applications within maritime logistics, container shipping, maritime supply chains, or maritime regulatory compliance. Eligible studies investigated one or more aspects of blockchain-enabled digital documentation, immutable audit trails, customs and border compliance, certificate verification, smart contracts, trusted information sharing, governance, interoperability, regulatory compliance, implementation challenges, or future research directions. Publications focusing exclusively on cryptocurrencies, blockchain performance benchmarking without maritime application, dissertations, editorials, book chapters, duplicate records, grey literature, or studies unrelated to maritime logistics or regulatory compliance were excluded.

Study selection was undertaken in two sequential stages. During the first stage, the titles and abstracts of all retrieved publications were screened against the predefined eligibility criteria. Publications considered potentially relevant proceeded to full-text review during the second stage. The screening and eligibility assessment were performed independently by the authors. Any differences in study selection were resolved through discussion until consensus was reached. No automation tools were used during the screening process.

The database search initially identified publications from the selected scientific databases. Following duplicate removal, the remaining records were screened using their titles and abstracts to determine their relevance to the research questions. Studies satisfying the initial screening criteria subsequently underwent full-text assessment against the predefined eligibility criteria. Publications that lacked direct relevance to blockchain applications for maritime regulatory compliance or did not contribute to the objectives of the review were excluded. Following the screening and eligibility assessment, 130 studies satisfied all inclusion criteria and were retained for the final review.

Figure 2. PRISMA 2020 Flow Diagram of the Study Selection Process

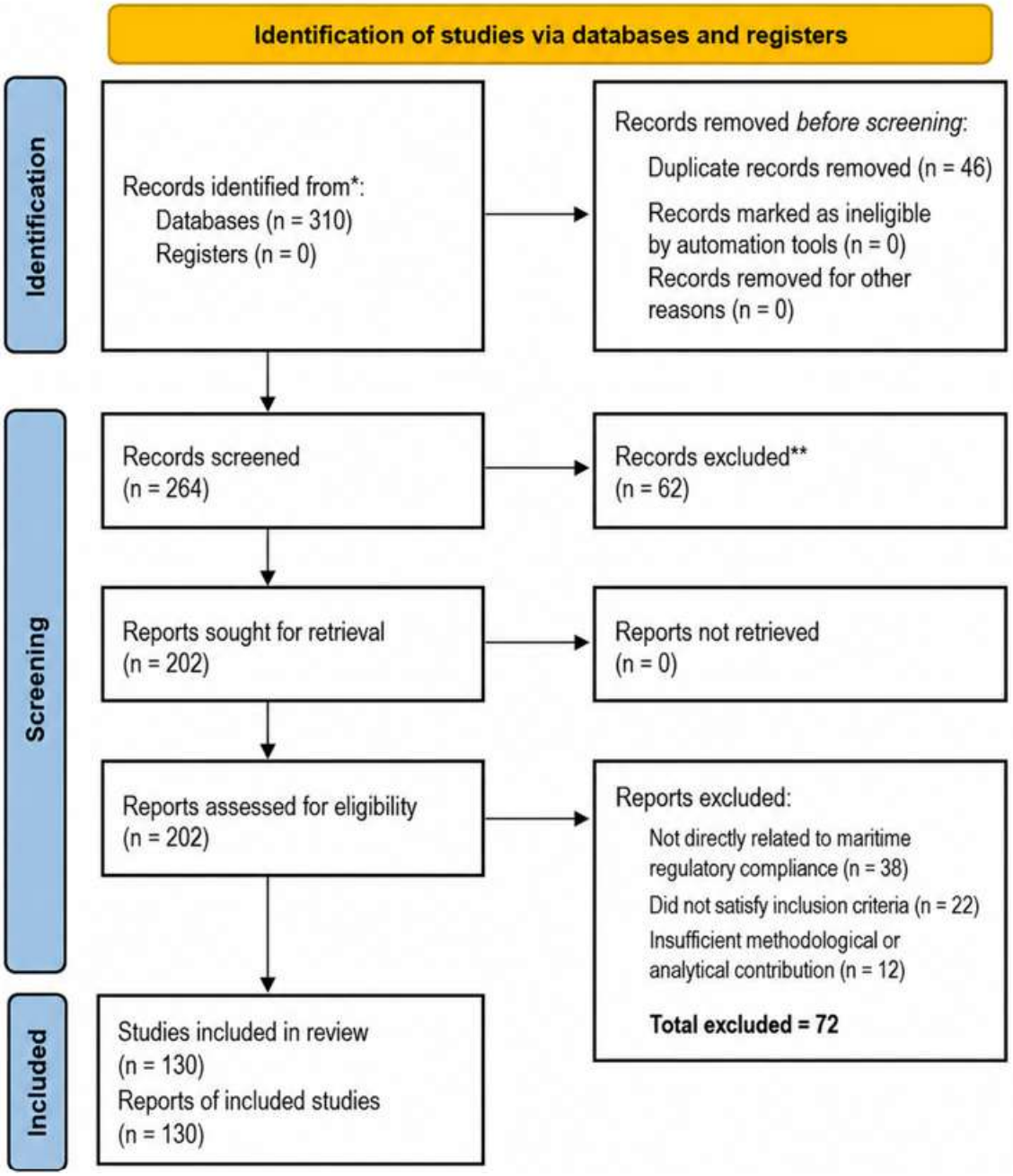


Figure 2 illustrates the PRISMA 2020 study selection process, summarising the identification, screening, eligibility assessment, and final inclusion of studies considered in this systematic literature review.

To ensure methodological quality, all included studies were independently assessed by the authors before being included in the final synthesis. Each publication was evaluated against predefined quality criteria, including relevance to the research questions, methodological rigour, clarity of findings, analytical quality, and contribution to understanding blockchain applications for maritime regulatory compliance. Any differences in quality assessment were resolved through discussion until agreement was reached. No automation tools were used during the quality assessment process.

Data extraction was undertaken independently by the authors using a structured Microsoft Excel extraction matrix developed specifically for this review. Prior to extraction, the data collection form was piloted using a small sample of studies and refined to ensure consistency. Any differences in extracted information

were discussed and resolved through consensus. For each included publication, bibliographic information, research context, research objectives, methodological approach, blockchain application area, blockchain mechanisms employed, reported benefits, implementation challenges, governance considerations, regulatory implications, and future research recommendations were systematically recorded. This structured process enhanced consistency, transparency, and traceability throughout the review.

The extracted evidence was analysed using thematic synthesis. Initially, recurring concepts were identified through inductive coding across the selected studies. Similar concepts were subsequently grouped into higher-order themes representing digital documentation, immutable audit trails, customs and border compliance, certificate verification, smart contract automation, implementation challenges, research gaps, and future research directions. These themes directly informed the structure of the review and enabled the synthesis to address each of the research questions systematically.

Although every effort was made to ensure methodological rigour, certain limitations should be acknowledged. The review was restricted to English-language peer-reviewed publications published between January 2020 and June 2026. Furthermore, because blockchain technologies, maritime regulations, and international digital trade standards continue to evolve rapidly, additional evidence may emerge after the review period. Nevertheless, this systematic literature review provides a comprehensive, transparent, and methodologically robust synthesis of the current state of knowledge regarding blockchain applications for maritime regulatory compliance.

3. Results

3.1 Digital Documentation

The thematic synthesis identified digital documentation as the most extensively investigated application of blockchain technology for maritime regulatory compliance. Across the reviewed studies, researchers consistently recognised that traditional documentation processes remain one of the principal sources of inefficiency within maritime logistics because they rely on fragmented information systems, paper-based records, manual verification procedures, and repeated document exchange among multiple independent stakeholders [84, 89]. Consequently, blockchain has been widely proposed as a trusted digital infrastructure for managing compliance-related documents by providing secure, immutable, and shared records that improve information integrity, traceability, and accessibility throughout the maritime supply chain [42, 84].

One of the most prominent findings concerns the application of blockchain to Electronic Bills of Lading (eBLs). The reviewed studies consistently identify the Bill of Lading as one of the most critical documents in maritime trade because it simultaneously serves as evidence of the contract of carriage, a receipt for goods, and a document of title [42, 65]. The literature demonstrates broad agreement that blockchain-enabled eBLs improve document security by creating immutable transaction histories that preserve ownership transfers, endorsements, and document revisions in a verifiable manner [42, 65]. By replacing conventional paper-based Bills of Lading with digitally authenticated records, blockchain reduces opportunities for document loss, duplication, forgery, and unauthorised modification while facilitating faster document exchange between shipping companies, freight forwarders, financial institutions, and port authorities [42, 89]. Nevertheless, several studies acknowledge that the widespread adoption of blockchain-enabled eBLs remains constrained by differences in legal recognition, interoperability between digital platforms, and the absence of universally accepted implementation standards across jurisdictions [89].

A second major finding relates to cargo documentation, which encompasses documents such as cargo manifests, packing lists, shipment declarations, cargo status updates, and transportation records [25, 95, 97]. The reviewed studies consistently report that blockchain enables these documents to be managed through a shared distributed ledger, allowing authorised stakeholders to access synchronised and authenticated information without maintaining multiple independent versions of the same records [22, 52, 104]. This approach reduces inconsistencies between organisational databases, improves cargo visibility throughout the transportation lifecycle, and enhances coordination among shipping lines, freight forwarders, terminal operators, customs authorities, and logistics providers [57, 74, 102]. Researchers further suggest that blockchain-supported cargo documentation improves operational transparency by enabling stakeholders to trace the history and status of shipments using a single trusted record rather than relying on fragmented organisational information systems [18, 20, 32, 94,108].

The literature also identifies customs documentation as a significant area of blockchain application. International trade requires the continuous exchange of customs declarations, commercial invoices, certificates of origin, import and export permits, inspection reports, and supporting regulatory documentation before cargo can be released [100, 120, 121]. Across the reviewed studies, blockchain is consistently proposed as a mechanism for improving customs documentation by enabling secure information sharing between customs administrations, port authorities, shipping companies, and freight forwarders through a common distributed ledger [12, 69, 112, 114, 121]. Researchers report that this shared approach reduces repetitive document submission, improves document authenticity, and enables customs officials to verify regulatory information more efficiently than conventional paper-based processes [27, 77]. However, several studies emphasise that the effectiveness of blockchain-enabled customs documentation depends upon regulatory cooperation, interoperable customs systems, and harmonised legal frameworks governing the recognition of digital trade documents [5, 64, 108, 120].

Another important finding emerging from the thematic analysis concerns the management of inspection reports. Maritime operations involve numerous inspections relating to cargo, vessels, customs, safety, environmental compliance, and security, all of which generate records that support regulatory oversight and operational accountability [9, 83]. The reviewed studies suggest that blockchain provides a secure platform for recording inspection outcomes, preserving the chronological history of inspection activities, and preventing subsequent modification of inspection records [59, 61, 129]. Researchers argue that immutable inspection records strengthen regulatory compliance by providing trusted evidence during audits, investigations, and dispute resolution while improving confidence in the authenticity of inspection outcomes [91, 105]. Several studies further indicate that blockchain-enabled inspection records reduce administrative effort by enabling regulators and authorised stakeholders to retrieve verified inspection histories from a common digital repository rather than collecting documentation from multiple independent organisations [118, 122].

Across all reviewed studies, several recurring benefits of blockchain-enabled digital documentation were consistently identified. The most frequently reported advantage is the transition from fragmented paper-based processes to trusted digital documentation, which simplifies document management and improves the efficiency of information exchange among geographically dispersed stakeholders [23; 108; 120]. The literature also demonstrates strong consensus that blockchain enhances document integrity through cryptographic protection and immutable recordkeeping, thereby reducing opportunities for document forgery, unauthorised modification, and information loss [23, 87]. Additional benefits include improved traceability, greater operational transparency, reduced administrative duplication, faster document

verification, shorter customs clearance times, and enhanced collaboration across maritime supply chains [35, 108]. Collectively, these improvements contribute to more efficient regulatory compliance while strengthening stakeholder confidence in the authenticity and reliability of exchanged documentation.

Overall, the thematic synthesis demonstrates that blockchain-enabled digital documentation represents the most mature and extensively researched application of blockchain for maritime regulatory compliance. Although the reviewed studies focus on different document types and operational contexts, they consistently converge on the conclusion that blockchain improves the integrity, traceability, accessibility, and security of compliance-related documentation through the establishment of a shared and trusted digital record [35, 37, 64, 91, 108]. At the same time, the literature indicates that technological capability alone is insufficient to achieve widespread implementation. Realising the full benefits of blockchain-enabled digital documentation requires internationally recognised legal frameworks, interoperable digital infrastructures, common technical standards, and collaborative governance arrangements capable of supporting trusted information exchange across the global maritime ecosystem [32, 35, 47, 76, 108].

3.2 Immutable Audit Trails

The thematic synthesis identified immutable audit trails as one of the most consistently reported blockchain applications for strengthening maritime regulatory compliance. According to the reviewed studies, researchers recognised that conventional audit mechanisms are frequently fragmented across independently managed organisational databases, making it difficult to establish a complete, reliable, and verifiable history of compliance-related activities [35, 41, 51, 66, 91]. This fragmentation limits transparency, complicates regulatory investigations, and increases the risk of inconsistent or manipulated records. Consequently, blockchain has been widely proposed as a trusted platform for maintaining immutable audit trails that preserve the chronological history of operational and regulatory events while ensuring the integrity and authenticity of recorded information [36, 56].

One of the principal findings concerns the creation of tamper-proof records. The reviewed studies consistently demonstrate that blockchain enhances record integrity by storing validated transactions within cryptographically linked blocks that cannot be altered without consensus from the participating network [23, 46, 61, 72]. Unlike conventional databases, where authorised users may modify or delete historical records, blockchain permanently preserves transaction histories, making unauthorised alterations readily detectable [110, 123]. Researchers argue that this immutability strengthens confidence in compliance records by ensuring that regulatory documentation, operational events, and approval activities remain authentic throughout their lifecycle [39, 81]. Nevertheless, several studies acknowledge that while blockchain protects stored information from subsequent modification, it cannot guarantee the accuracy of data at the point of entry, emphasising the continued importance of trusted data sources and effective governance mechanisms [44, 124].

A second major finding relates to event logging, which emerged as one of the most widely investigated applications of blockchain-enabled audit trails. Maritime logistics involves numerous operational and regulatory events, including cargo loading and unloading, vessel departures and arrivals, customs inspections, document approvals, cargo transfers, and regulatory clearances [3, 35, 66, 80,108]. The reviewed studies consistently report that blockchain enables these activities to be recorded sequentially within a shared distributed ledger, thereby creating a permanent and verifiable chronological history of events [40, 50, 125]. Researchers suggest that immutable event logs improve operational visibility by allowing authorised stakeholders to reconstruct the complete sequence of logistics activities while supporting regulatory monitoring, compliance verification, and operational accountability [73, 86].

However, some studies caution that continuous event recording may generate substantial transaction volumes, requiring scalable blockchain architectures capable of maintaining performance without compromising security or availability [28, 38].

The thematic analysis also identified cargo history as a significant application area. Cargo typically passes through multiple organisations before reaching its final destination, with each stakeholder generating operational records that contribute to the overall shipment history [32, 63, 66, 85]. Conventional tracking systems often maintain these records within isolated organisational databases, resulting in fragmented information and inconsistent cargo histories [60, 63, 85]. Across the reviewed studies, blockchain is consistently proposed as a mechanism for consolidating cargo events within a shared immutable ledger, enabling authorised stakeholders to trace cargo movement from origin to final delivery using a single trusted record [32, 63, 85]. Researchers report that comprehensive cargo histories improve supply chain visibility, facilitate customs inspections, strengthen regulatory compliance, and provide reliable evidence during commercial disputes and incident investigations [32, 3, 108].

Another important finding concerns the management of vessel history. Maritime operations require continuous documentation of vessel registration, maintenance activities, inspections, safety certifications, ownership records, and environmental compliance throughout the operational lifecycle of a vessel [54,108]. The reviewed studies indicate that blockchain provides a secure platform for maintaining these records by preserving complete historical information within an immutable ledger accessible to authorised regulatory and commercial stakeholders [54, 91]. Researchers argue that blockchain-enabled vessel histories improve the efficiency of regulatory inspections, simplify maintenance verification, and strengthen confidence in vessel compliance with international maritime regulations [21, 91]. At the same time, several studies emphasise that successful implementation requires effective interoperability between blockchain platforms and existing vessel management systems, port information systems, and regulatory databases [21, 79, 90].

The literature further identifies the preservation of regulatory evidence as a key contribution of blockchain-enabled audit trails. Regulatory compliance depends upon maintaining verifiable evidence demonstrating adherence to customs procedures, environmental regulations, safety standards, security requirements, and operational policies [91, 107]. Across the reviewed studies, blockchain is consistently recognised as an effective mechanism for preserving regulatory evidence by recording compliance-related transactions in a manner that prevents subsequent modification while maintaining complete audit histories [35, 85, 91]. Researchers suggest that immutable regulatory evidence simplifies compliance audits, supports regulatory investigations, strengthens legal defensibility, and improves dispute resolution by providing authorised stakeholders with authenticated historical records that can be independently verified [85, 91, 96]. These capabilities enhance confidence in regulatory decision-making while reducing the administrative burden associated with collecting evidence from multiple independent information systems [19,108].

Across all reviewed studies, several recurring benefits of blockchain-enabled immutable audit trails were consistently identified. The most frequently reported advantage is the establishment of trusted and verifiable records that strengthen accountability across maritime operations [32, 85]. The literature also demonstrates broad agreement that blockchain improves transparency by enabling authorised stakeholders to access consistent and authenticated transaction histories while reducing information asymmetry between participating organisations [21, 35, 51]. Additional benefits include enhanced non-repudiation through cryptographic authentication, improved traceability of operational activities, greater confidence

in compliance evidence, and more efficient regulatory auditing and investigation processes [32, 96, 107]. Collectively, these capabilities contribute to stronger governance, improved stakeholder trust, and increased confidence in the integrity of maritime compliance records [19, 76, 107].

Overall, the thematic synthesis demonstrates that immutable audit trails represent one of the most mature and strategically important blockchain applications for maritime regulatory compliance. Despite differences in implementation approaches and application domains, the reviewed studies consistently converge on the conclusion that blockchain significantly improves the preservation, verification, and traceability of compliance-related records through immutable and chronologically ordered transaction histories [91, 96, 108]. However, the literature also indicates that achieving these benefits requires more than technological implementation alone. Sustainable adoption depends upon scalable blockchain infrastructures, interoperable digital ecosystems, robust identity and access management, effective consortium governance, and regulatory acceptance capable of supporting trusted audit mechanisms across the global maritime industry [63, 85].

3.3 Customs and Border Compliance

The thematic synthesis identified customs and border compliance as one of the most significant application areas of blockchain technology within maritime regulatory compliance. Across the reviewed studies, researchers consistently recognised that customs processes remain highly dependent on the timely exchange of accurate and trustworthy information among shipping companies, customs administrations, port authorities, freight forwarders, importers, exporters, and other regulatory agencies [35, 85; 96; 108]. However, conventional customs procedures continue to rely on fragmented information systems, repeated submission, manual verification, and limited interoperability between participating organisations, contributing to administrative delays, increased operational costs, and compliance inefficiencies [32, 69]. Consequently, blockchain has been widely proposed as a secure and transparent platform for modernising customs operations through trusted information sharing, improved document integrity, and enhanced cross-border collaboration [69, 112].

One of the principal findings concerns the application of blockchain to customs clearance. The reviewed studies consistently demonstrate that blockchain enables customs authorities to access authenticated documentation through a shared distributed ledger, reducing the need for traders to repeatedly submit identical information to multiple regulatory agencies [69, 108]. Researchers argue that secure access to verified cargo declarations, Bills of Lading, inspection reports, certificates, and supporting trade documentation improves the efficiency and reliability of customs verification while reducing administrative duplication [21,108]. Furthermore, blockchain-supported customs clearance enables earlier validation of regulatory requirements, allowing customs authorities to identify inconsistencies before cargo reaches national borders and thereby reducing delays associated with manual compliance verification [34]. Nevertheless, several studies emphasise that successful implementation depends on regulatory cooperation, institutional readiness, and legal recognition of blockchain-based documentation within national customs frameworks [69, 93].

A second major finding relates to cross-border information sharing, which emerged as a critical requirement for effective international trade. Maritime supply chains operate across multiple jurisdictions, requiring continuous exchange of operational and regulatory information between organisations subject to different legal, technological, and administrative environments [54, 63, 85, 108]. The reviewed studies consistently report that blockchain facilitates cross-border information sharing by providing authorised stakeholders with access to synchronised and authenticated records maintained on a common distributed

ledger [54, 64, 69, 85,108]. Researchers suggest that this shared information environment improves coordination between customs administrations, shipping companies, logistics providers, and border agencies while reducing inconsistencies arising from fragmented organisational databases [63, 108]. However, the literature also highlights that cross-border implementation remains constrained by differences in national legislation, regulatory policies, technological maturity, and governance arrangements, all of which influence the interoperability of blockchain-enabled customs ecosystems [85, 108].

The thematic analysis further identified trade documentation as one of the most extensively investigated applications supporting customs and border compliance. International trade depends on numerous commercial and regulatory documents, including Bills of Lading, cargo manifests, commercial invoices, customs declarations, certificates of origin, packing lists, and inspection reports [37, 54, 64, 108, 111]. According to the reviewed studies, blockchain is consistently proposed as a trusted mechanism for securely managing these documents through immutable storage, cryptographic verification, and controlled information sharing [21, 37, 54, 64]. Researchers report that maintaining trade documentation on a shared distributed ledger reduces inconsistencies between organisational records, simplifies document reconciliation, and enables customs authorities and other regulatory stakeholders to verify documentation more efficiently [64, 69]. Several studies further suggest that blockchain improves the authenticity and traceability of trade documentation by preserving complete transaction histories that support regulatory audits and compliance verification [35, 64]. Despite these reported advantages, researchers consistently acknowledge that widespread implementation requires internationally recognised standards for digital trade documentation and effective integration with existing customs information systems [37, 85, 111].

Another important finding concerns the role of port authorities within blockchain-enabled customs and border compliance. Port authorities coordinate vessel arrivals, cargo handling, customs inspections, security procedures, and regulatory operations, making them central participants within maritime compliance ecosystems [37, 54, 108, 111]. The reviewed studies indicate that blockchain improves operational coordination by enabling port authorities to access trusted information from multiple stakeholders through a shared distributed ledger, thereby reducing delays associated with fragmented communication and inconsistent documentation [37, 54, 108, 111]. Researchers argue that blockchain-supported information exchange enhances collaboration between port operators, customs administrations, shipping companies, terminal operators, and freight forwarders while improving situational awareness during cargo handling and border control activities [35, 108]. Nevertheless, several studies emphasise that effective implementation depends on interoperability between blockchain platforms and existing port community systems, as well as clearly defined governance arrangements that regulate stakeholder participation and information access [37, 108, 111].

Across all reviewed studies, several recurring benefits of blockchain-enabled customs and border compliance were consistently identified. The most frequently reported advantage is the acceleration of customs processing through secure digital documentation, automated information exchange, and more efficient verification of regulatory requirements [37, 69]. The literature also demonstrates broad agreement that blockchain reduces manual verification by providing customs officials with immediate access to authenticated records rather than requiring repeated document submission and reconciliation [37, 51, 69]. Additional benefits include improved transparency, enhanced trust between trading partners, stronger document integrity, reduced administrative costs, greater operational efficiency, and more effective cross-border collaboration among public and private sector stakeholders [64, 69, 108]. Collectively, these

improvements contribute to more reliable customs operations while supporting secure and efficient international trade [21, 35, 37].

Overall, the thematic synthesis demonstrates that blockchain provides a robust technological foundation for modernising customs and border compliance within maritime logistics. Despite differences in application domains and implementation strategies, the reviewed studies consistently converge on the conclusion that blockchain strengthens customs operations through secure customs clearance, trusted cross-border information sharing, improved trade documentation, and enhanced collaboration with port authorities [35, 69, 111]. However, the literature also indicates that technological capability alone cannot transform customs processes. Sustainable implementation requires harmonised legal frameworks, interoperable digital infrastructures, internationally accepted documentation standards, and coordinated governance among customs administrations, port authorities, and commercial stakeholders to establish trusted blockchain-enabled border compliance ecosystems [63, 85, 108].

3.4 Certificate Verification

The thematic synthesis identified certificate verification as a critical application of blockchain technology for strengthening maritime regulatory compliance. Across the reviewed studies, researchers consistently recognised that maritime operations depend on a wide range of certificates issued by regulatory authorities, classification societies, inspection agencies, and accredited organisations to demonstrate compliance with international conventions, national regulations, and industry standards [63, 75, 107]. These certificates provide evidence that vessels, crew members, cargo, and operational processes satisfy prescribed legal, environmental, and safety requirements before participating in maritime activities [37, 75, 91]. However, conventional certificate management remains susceptible to document forgery, fragmented information systems, lengthy verification procedures, and administrative inefficiencies that can delay operational and regulatory processes [37, 63]. Consequently, blockchain has been widely proposed as a trusted digital infrastructure for issuing, storing, managing, and verifying certificates in a secure, transparent, and immutable manner [37, 75].

One of the principal findings concerns the management of vessel certificates. Commercial vessels are required to maintain numerous statutory and classification certificates demonstrating compliance with international maritime regulations governing seaworthiness, safety, environmental protection, and operational performance [75, 85, 91, 127]. The reviewed studies consistently report that blockchain enables these certificates to be digitally issued, cryptographically authenticated, and permanently recorded within an immutable distributed ledger, allowing authorised stakeholders to verify certificate validity without relying on multiple independent information sources [29, 37, 75, 85, 91]. Researchers argue that blockchain simplifies regulatory inspections by reducing the time required to authenticate vessel documentation while minimising the risk of altered, duplicated, or expired certificates being presented during compliance assessments [37, 79]. Nevertheless, several studies acknowledge that successful implementation requires interoperability between blockchain platforms and existing maritime information systems, together with regulatory acceptance of blockchain-based digital certification [35, 75, 79, 85].

A second major finding relates to crew certificates, which verify the qualifications, competencies, medical fitness, and professional training of seafarers [51, 63, 107]. Maritime organisations routinely verify these certificates to ensure compliance with international conventions and competency requirements before assigning operational responsibilities [51, 63, 107]. Across the reviewed studies, blockchain is consistently proposed as a secure mechanism for maintaining authenticated digital records of crew qualifications, enabling employers, maritime administrations, and inspection authorities to verify certificate authenticity

directly from a trusted distributed ledger [51, 63, 107]. Researchers report that blockchain-based verification reduces administrative delays associated with manual document checking while limiting opportunities for fraudulent qualifications, falsified professional credentials, and expired certifications [51, 63]. However, the literature also highlights that widespread implementation depends on collaboration among maritime administrations, training institutions, certification bodies, and international regulatory organisations responsible for issuing and recognising professional qualifications [79, 107].

The thematic analysis further identified cargo certificates as an important area of blockchain application. International trade requires various certificates confirming the origin, quality, inspection status, health compliance, and regulatory conformity of goods before cargo can proceed through customs and border control processes [37, 85, 107]. The reviewed studies consistently demonstrate that blockchain improves cargo certificate management by securely recording certificate issuance, validation, modification, and verification within an immutable ledger accessible to authorised stakeholders [29, 37, 66, 91]. Researchers suggest that blockchain reduces administrative complexity by enabling customs authorities, importers, exporters, freight forwarders, and shipping companies to verify authenticated certificates from a common digital repository rather than relying on fragmented document exchanges [37, 47, 108]. Several studies indicate that blockchain strengthens border compliance by improving confidence in certificate authenticity while reducing opportunities for document manipulation and fraudulent declarations [21, 37, 79].

Another significant finding concerns the management of safety certificates, which provide evidence that vessels, equipment, operational procedures, and cargo handling activities comply with internationally recognised safety standards [85, 91]. According to the reviewed studies, blockchain is consistently recognised as a secure platform for maintaining safety certificates by preserving immutable records of certificate issuance, renewal, inspection, suspension, and revocation activities [29, 85, 91]. Researchers argue that blockchain enhances the efficiency of vessel inspections and port State control examinations by enabling regulators and inspection authorities to access verified certification records immediately, thereby reducing the administrative effort associated with manual verification [37, 91, 127]. Nevertheless, several studies note that effective implementation requires integration with existing maritime safety management systems and internationally harmonised standards governing digital certification and information exchange [75, 79, 85].

Across all reviewed studies, several recurring benefits of blockchain-enabled certificate verification were consistently identified. The most frequently reported advantage is the improvement of certificate authenticity through cryptographic authentication, distributed validation, and immutable record preservation, enabling stakeholders to verify that certificates originate from authorised issuing bodies and remain unchanged following issuance [29, 75, 79, 85]. The literature also demonstrates broad agreement that blockchain significantly reduces opportunities for certificate fraud by preventing unauthorised modification and providing complete audit histories of certificate lifecycle events [21, 75, 91, 127]. Additional benefits include faster certificate verification, improved regulatory transparency, enhanced operational efficiency, reduced administrative burden, strengthened stakeholder trust, and more reliable compliance monitoring across maritime operations [79, 107, 127]. Collectively, these capabilities contribute to more secure and efficient regulatory verification processes while supporting greater confidence in digital certification throughout the maritime supply chain [21, 35, 79, 127].

Overall, the thematic synthesis demonstrates that blockchain provides a robust foundation for modernising certificate verification within maritime regulatory compliance. Although the reviewed studies examine different categories of certificates and operational contexts, they consistently converge on the conclusion

that blockchain enhances the authenticity, integrity, traceability, and accessibility of digital certification through immutable and verifiable records [29, 35, 47, 66, 79]. However, the literature also indicates that technological capability alone is insufficient to transform certification practices. Achieving widespread adoption requires internationally recognised legal frameworks, interoperable digital certification standards, effective identity management mechanisms, and coordinated governance among maritime administrations, classification societies, certification authorities, and other regulatory stakeholders to establish trusted blockchain-enabled certification ecosystems capable of supporting global maritime operations [75, 79, 85].

3.5 Smart Contracts

The thematic synthesis identified smart contracts as one of the most transformative blockchain capabilities for improving maritime regulatory compliance. Across the reviewed studies, researchers consistently recognised that while blockchain provides secure and immutable recordkeeping, smart contracts extend these capabilities by enabling the automatic execution of predefined rules, business logic, and regulatory procedures without continuous human intervention [35, 51, 63)]. Maritime compliance involves numerous repetitive processes requiring verification, approval, coordination, and decision-making among multiple independent stakeholders, making these activities well suited to automation [51, 63,108]. Consequently, the reviewed literature consistently proposes smart contracts as mechanisms for improving the efficiency, consistency, transparency, and reliability of compliance-related operations throughout the maritime logistics ecosystem [21, 35, 63, 107].

One of the principal findings concerns the application of smart contracts to compliance verification. Maritime organisations are required to demonstrate continuous compliance with customs regulations, international conventions, environmental requirements, port regulations, and security policies before commercial activities can proceed [35, 51, 91, 107]. Traditionally, compliance verification depends on manual examination of documentation by customs officials, port authorities, shipping companies, and regulatory agencies, resulting in administrative delays and inconsistent decision-making [51, 63]. The reviewed studies consistently demonstrate that smart contracts can automate this process by evaluating blockchain-based records against predefined regulatory requirements and automatically determining whether compliance conditions have been satisfied [91]. Researchers argue that automated compliance verification improves operational efficiency, reduces processing time, enhances consistency in regulatory decision-making, and minimises human error during routine compliance assessments [91]. However, several studies emphasise that automated verification remains dependent on the quality and accuracy of the information initially recorded on the blockchain, highlighting the continued importance of reliable data governance and validation mechanisms [21, 91, 130].

A second major finding relates to document approval, which emerged as one of the most frequently investigated applications of smart contracts within maritime logistics. Regulatory compliance requires numerous approvals relating to shipping documents, customs declarations, inspection reports, cargo manifests, certificates, and commercial transactions, many of which involve sequential validation by multiple independent organisations [108, 111, 130]. The reviewed studies consistently report that smart contracts can automate these approval workflows by verifying predefined approval conditions, recording authorised decisions on the blockchain, and automatically progressing transactions once all required approvals have been obtained [63, 107, 130].Researchers suggest that automating document approval reduces administrative delays, improves document traceability, eliminates repetitive manual verification, and strengthens confidence in regulatory decisions through the creation of immutable approval histories

[32, 63, 107]. Nevertheless, the literature also acknowledges that certain approval processes involve legal interpretation, discretionary judgement, or exceptional circumstances that continue to require human oversight despite increasing levels of automation [35].

The thematic analysis further identified cargo release as a significant application area for blockchain-enabled smart contracts. Cargo release is a critical stage within maritime logistics because goods may only be released after satisfying customs requirements, regulatory approvals, financial obligations, inspection outcomes, and document verification procedures [35; 51)]. Across the reviewed studies, blockchain-based smart contracts are consistently proposed as mechanisms for continuously monitoring these requirements and automatically authorising cargo release once all predefined conditions have been fulfilled [32, 35, 63]. Researchers report that automated cargo release reduces waiting times, improves coordination among shipping companies, customs administrations, terminal operators, and freight forwarders, and minimises delays caused by manual communication and document reconciliation [32]. Several studies further indicate that smart contract automation enhances regulatory compliance by ensuring that cargo cannot be released unless every mandatory compliance requirement has been successfully verified [91, 122]. However, the literature recognises that regulatory authorities must retain the ability to intervene when exceptional circumstances, emergency situations, or additional inspections require manual decision-making beyond predefined contractual rules [35].

Another important finding concerns the automation of broader regulatory workflows. Maritime regulatory compliance encompasses numerous interconnected activities, including inspections, permit applications, customs declarations, environmental reporting, certification processes, regulatory notifications, and communication between public and private sector organisations [35, 51, 91, 107]. The reviewed studies consistently demonstrate that many of these repetitive administrative processes can be coordinated through programmable smart contracts that automatically execute regulatory workflows according to predefined policies and business rules [91, 107]. Researchers argue that workflow automation reduces administrative burden, accelerates compliance processes, improves procedural consistency, and provides regulators with complete audit histories documenting every stage of workflow execution [91, 107]. At the same time, several studies acknowledge that regulatory requirements continue to evolve in response to legislative amendments, policy reforms, and international agreements, requiring smart contracts to operate within governance frameworks that support controlled updates while preserving system integrity and legal compliance [35, 51].

Through all reviewed studies, several recurring benefits of blockchain-enabled smart contracts were consistently identified. The most frequently reported advantage is the automation of repetitive compliance activities, which reduces administrative workload, accelerates transaction processing, and improves the efficiency of regulatory operations [35, 51, 91]. The literature also demonstrates broad agreement that smart contracts enhance consistency by applying identical regulatory rules across all participating organisations, thereby reducing procedural variability and human error [63, 91]. Additional benefits include improved transparency, stronger accountability, enhanced traceability of regulatory decisions, faster document processing, reduced operational costs, and greater confidence in the integrity of automated compliance procedures [32, 35]. Collectively, these capabilities support more efficient and reliable maritime regulatory compliance while strengthening trust among participating stakeholders [21, 91].

Overall, the thematic synthesis demonstrates that smart contracts significantly extend the capabilities of blockchain beyond secure recordkeeping by enabling the automated execution of compliance-related processes throughout maritime logistics. Although the reviewed studies examine different operational

scenarios and implementation approaches, they consistently converge on the conclusion that smart contracts improve compliance verification, document approval, cargo release, and regulatory workflow management through programmable automation governed by predefined rules [35, 63, 107, 111, 130]. However, the literature also indicates that technological capability alone cannot ensure successful implementation. Sustainable adoption requires supportive legal frameworks, interoperable digital infrastructures, robust governance mechanisms, secure identity management, and continued human oversight for complex regulatory decisions to ensure that automation complements rather than replaces effective regulatory governance within the global maritime industry [35, 51, 130].

4. Discussion

4.1 Overall Synthesis

This systematic literature review synthesised current evidence on the application of blockchain technology to maritime regulatory compliance, with particular emphasis on digital documentation, immutable audit trails, customs and border compliance, certificate verification, and smart contracts. Across the reviewed studies, blockchain was consistently recognised as a promising digital infrastructure capable of improving the integrity, transparency, traceability, and security of compliance-related processes throughout the maritime logistics ecosystem [29, 35, 66; 79]. Although individual studies examined different technologies, operational contexts, and stakeholder perspectives, the thematic analysis revealed a strong consensus that blockchain addresses many of the limitations associated with conventional compliance systems, particularly fragmented information management, manual verification procedures, paper-based documentation, and limited interoperability between independent organisations [11, 35, 63, 66].

The findings demonstrate that blockchain's contribution extends beyond the digitisation of existing processes. Rather than functioning solely as a document management platform, blockchain establishes a shared and trusted environment in which authorised stakeholders can securely create, exchange, verify, and preserve regulatory information throughout the shipment lifecycle [29, 47, 108]. Digital documentation emerged as the most mature application area, reflecting the industry's ongoing transition towards paperless trade and electronic document management [108]. Similarly, immutable audit trails were consistently identified as mechanisms for strengthening accountability and regulatory oversight by providing tamper-resistant records that preserve the complete history of operational and compliance activities [11, 29, 47, 108].

The review further demonstrates that blockchain offers considerable potential for modernising customs and border compliance through trusted information sharing, streamlined customs clearance, and improved management of trade documentation [11, 37, 51, 108]. Likewise, blockchain-based certificate verification provides a secure mechanism for authenticating vessel, crew, cargo, and safety certificates while reducing opportunities for document fraud and improving the efficiency of regulatory inspections [37, 51]. The literature also highlights smart contracts as an important advancement beyond secure recordkeeping by enabling the automation of compliance verification, document approval, cargo release, and regulatory workflows according to predefined business and regulatory rules [35, 85].

Collectively, these findings indicate that blockchain should be viewed not as a collection of independent technological applications, but as an integrated digital infrastructure capable of supporting trusted regulatory compliance across the maritime sector. The reviewed studies consistently demonstrate that the greatest value of blockchain is realised when these applications operate together within a collaborative

ecosystem that enables secure information sharing, transparent governance, and coordinated decision-making among maritime stakeholders [66, 75, 85, 91, 108].

From a socio-technical perspective, the findings demonstrate that successful blockchain adoption cannot be explained solely by technological capability. Although blockchain provides mechanisms for secure documentation, immutable audit trails, certificate verification, and automated compliance processes, their effectiveness depends upon complementary organisational, legal, governance, and regulatory arrangements. This reinforces the central proposition of Socio-Technical Systems Theory that technological innovation and organisational structures must evolve together to achieve sustainable system performance. The thematic synthesis therefore suggests that future blockchain-enabled maritime compliance initiatives should adopt an integrated socio-technical approach that balances technological advancement with institutional readiness, governance, and stakeholder collaboration.

Figure 2 presents the conceptual framework developed from the thematic synthesis of the reviewed literature. It illustrates how blockchain technology enables maritime regulatory compliance through five interconnected application areas, namely digital documentation, immutable audit trails, customs and border compliance, certificate verification, and smart contracts. Collectively, these application areas strengthen transparency, traceability, and accountability, thereby supporting more effective maritime regulatory compliance.

Figure 3. Conceptual framework of blockchain-enabled maritime regulatory compliance

Source: Developed by the author based on the thematic synthesis of the reviewed literature.

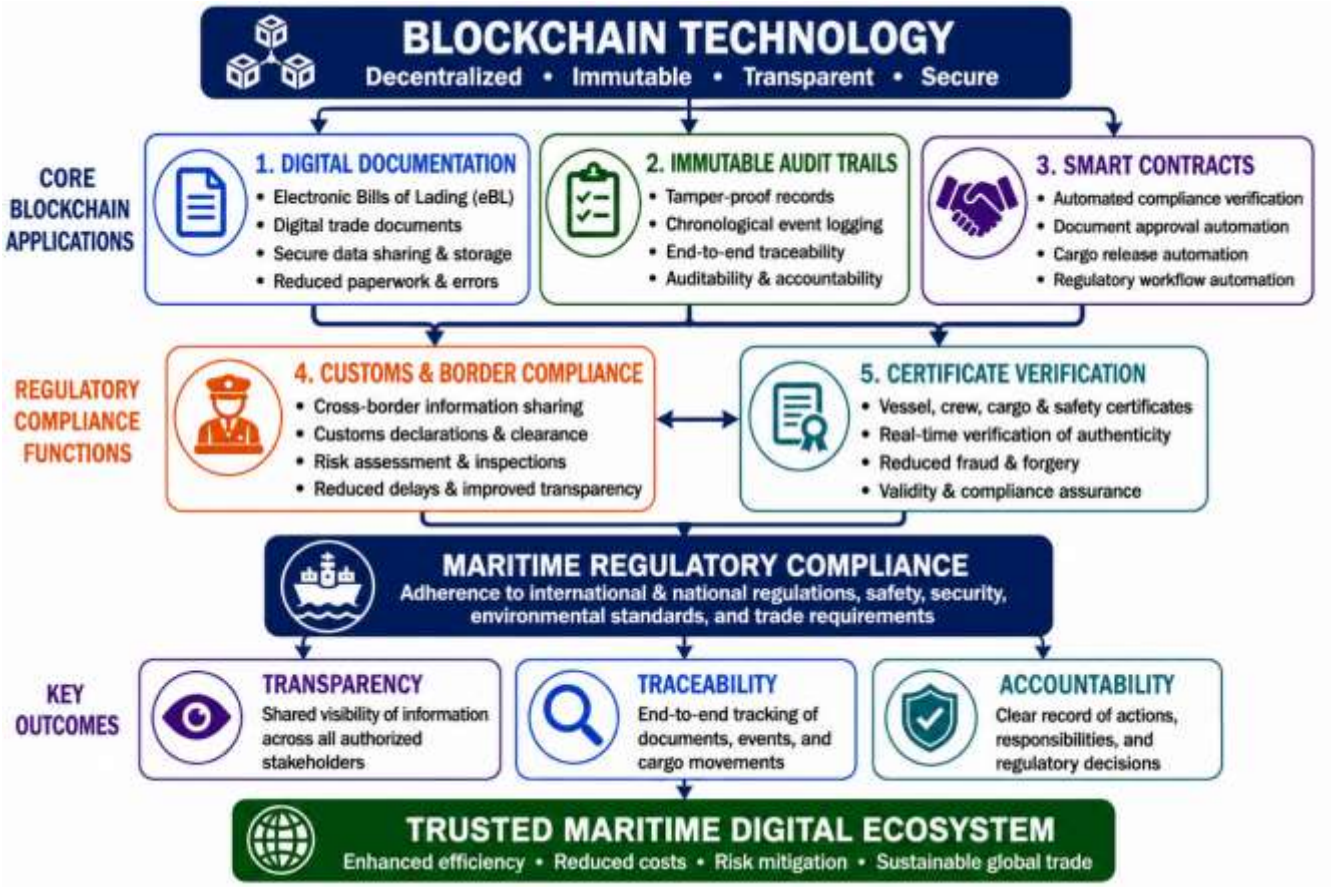


Table 1 summarises the principal thematic findings identified through systematic review. It highlights the major blockchain applications discussed across the reviewed studies together with their primary benefits and the principal implementation challenges associated with each application area.

Table 1. Summary of blockchain applications for maritime regulatory compliance

Source: Developed by the author based on the thematic synthesis of the reviewed literature.

Theme	Principal Blockchain Application	Key Benefits	Main Challenges
Digital Documentation	Electronic Bills of Lading (eBLs), digital trade documents	Improved document integrity, faster document exchange, reduced paperwork	Legal recognition, interoperability, standardisation
Immutable Audit Trails	Tamper-proof records and event logging	Traceability, accountability, auditability	Scalability, governance, data quality
Customs and Border Compliance	Cross-border information sharing and customs clearance	Faster customs processing, improved transparency, reduced duplication	Regulatory harmonisation, interoperability
Certificate Verification	Digital verification of vessel, crew, cargo and safety certificates	Reduced fraud, faster verification, improved authenticity	Standardisation, legal acceptance
Smart Contracts	Automated compliance verification and regulatory workflows	Process automation, operational efficiency, consistency	Legal uncertainty, governance, human oversight

The thematic summary presented in Table 1 provides a consolidated overview of the principal blockchain applications identified in the reviewed studies, highlighting their associated benefits and the key implementation challenges discussed throughout literature.

4.2 Benefits

The thematic synthesis identified several recurring benefits associated with blockchain adoption for maritime regulatory compliance. The most consistently reported benefit is the improvement of transparency, achieved through the establishment of a shared distributed ledger that enables authorised stakeholders to access synchronised and verifiable compliance information [35, 37, 79]. Increased transparency reduces information asymmetry between organisations, improves stakeholder confidence, and facilitates more effective regulatory oversight throughout maritime operations [47, 75, 107].

A second major benefit concerns data integrity and document authenticity. The reviewed studies consistently demonstrate that cryptographic hashing, digital signatures, and immutable recordkeeping significantly reduce opportunities for document forgery, unauthorised modification, and information loss [29, 37, 51, 63, 85]. These capabilities strengthen confidence in regulatory documentation while improving the reliability of evidence used during customs inspections, compliance audits, and legal proceedings [37, 79, 107].

The literature also reports substantial improvements in traceability and accountability. Blockchain enables complete historical records of documents, cargo movements, vessel activities, inspections, and regulatory decisions to be maintained within immutable audit trails, allowing stakeholders to reconstruct operational events and verify compliance activities with greater confidence [29, 35, 85]. This enhanced traceability

supports dispute resolution, fraud investigation, regulatory enforcement, and organisational accountability across complex maritime supply chains [35, 37].

Another frequently reported benefit is operational efficiency. Researchers consistently suggest that blockchain reduces administrative duplication by eliminating repeated document submission, streamlining verification procedures, automating routine compliance activities, and improving information exchange between participating organisations [11, 47, 60, 63]. Smart contracts further contribute to operational efficiency by automating predefined regulatory workflows, reducing processing times, and minimising delays associated with manual decision-making [37, 85, 91, 107].

Finally, the reviewed studies indicate that blockchain strengthens stakeholder collaboration and trust by establishing a common platform through which shipping companies, customs authorities, port operators, freight forwarders, regulators, and other participants can exchange trusted information without relying exclusively on central intermediaries [35, 108]. This collaborative environment supports more coordinated regulatory compliance while improving confidence in shared operational data [35, 75,108, 127].

4.3 Challenges

Despite the considerable benefits reported throughout the reviewed literature, blockchain adoption for maritime regulatory compliance remains constrained by several interrelated challenges. One of the most frequently identified barriers concerns interoperability, as existing maritime operations rely on diverse legacy systems, digital platforms, and national information infrastructures that were not designed to operate within blockchain environments [51, 63, 75]. The absence of internationally accepted interoperability standards continues to limit seamless information exchange across organisational and jurisdictional boundaries [11, 51, 75, 79, 85].

Literature also consistently identifies legal and regulatory uncertainty as a significant obstacle to adoption. Although blockchain provides secure digital records, many jurisdictions have yet to establish comprehensive legal frameworks recognising blockchain-based documentation, smart contracts, and electronic trade records as legally equivalent to conventional paper documents [35, 51]. This uncertainty discourages investment and limits the willingness of organisations to replace established compliance procedures with blockchain-enabled alternatives [11, 47, 51, 108].

Another recurring challenge concerns governance and stakeholder collaboration. Blockchain networks require multiple independent organisations to cooperate within shared governance structures that define participation rules, decision-making processes, data ownership, access permissions, and dispute resolution mechanisms [37, 75, 108]. Researchers consistently argue that achieving consensus among stakeholders with differing commercial interests, regulatory responsibilities, and technological capabilities remains one of the most complex aspects of blockchain implementation [66, 85].

The reviewed studies further highlight technical and organisational constraints, including scalability, implementation costs, cybersecurity requirements, systems integration, and shortages of blockchain expertise within maritime organisations [35, 51, 79]. These challenges are particularly significant for smaller organisations that may lack the financial and technical resources required to participate effectively in blockchain-enabled compliance ecosystems [11, 47, 51, 108].

Importantly, the literature also recognises that blockchain cannot resolve all compliance challenges independently. The reliability of blockchain records remains dependent upon the quality, completeness, and accuracy of the information initially entered into the system, reinforcing the importance of effective identity management, trusted data sources, and robust governance arrangements [35, 91, 129].

Consequently, blockchain should be regarded as an enabling technology rather than a complete solution to maritime regulatory compliance [35, 51, 79].

4.4 Practical Implications

The findings of this review have important implications for policymakers, regulatory authorities, maritime organisations, and technology developers seeking to modernise regulatory compliance processes. For policymakers and regulators, the review highlights the need to establish harmonised legal and regulatory frameworks that support the recognition of blockchain-based documentation, digital certificates, and smart contract execution across different jurisdictions [35, 51, 63, 71]. International collaboration will be essential to develop common standards that facilitate cross-border interoperability and regulatory acceptance [35, 65, 85].

For maritime organisations, including shipping companies, port authorities, customs administrations, and logistics providers, the findings suggest that blockchain adoption should be approached as an organisational transformation rather than simply a technology implementation. Successful deployment requires investment in governance structures, stakeholder collaboration, workforce development, and integration with existing digital infrastructures to ensure sustainable adoption [35, 85, 108].

For technology developers, the review demonstrates the importance of designing blockchain solutions that prioritise interoperability, scalability, security, and integration with established maritime information systems. Permissioned blockchain architectures incorporating robust identity management, role-based access control, and selective information sharing appear particularly well suited to the regulatory requirements of maritime compliance environments [35, 63, 79, 85].

Finally, the review provides important implications for future research and industrial implementation. The thematic synthesis demonstrates that while blockchain technologies have reached a high level of conceptual maturity, empirical evidence from large-scale operational deployments remains limited [51, 66, 75, 79, 108]. Future research should therefore focus on validating blockchain-enabled compliance systems within real maritime environments, evaluating long-term organisational outcomes, and developing internationally accepted governance and interoperability frameworks capable of supporting trusted digital compliance across the global maritime industry [35, 79, 108].

5. Research Gap

The thematic synthesis reveals that although blockchain has attracted considerable attention as a solution for maritime regulatory compliance, the existing body of knowledge remains characterised by several important research gaps. While the reviewed studies consistently demonstrate the potential of blockchain to improve digital documentation, auditability, customs compliance, certificate verification, and workflow automation, much of the current evidence remains conceptual or based on small-scale pilot implementations rather than mature operational deployments [51, 66, 76, 89]. Consequently, significant opportunities remain for advancing both academic understanding and practical implementation of blockchain-enabled regulatory compliance within the maritime industry.

One of the most significant gaps concerns the limited availability of industrial-scale deployments. The majority of reviewed studies evaluate blockchain through conceptual frameworks, simulation models, prototypes, laboratory experiments, or isolated pilot projects [21, 91]. Comparatively few investigations examine blockchain operating within large-scale commercial maritime environments involving multiple ports, customs administrations, shipping companies, and international regulatory agencies [35, 66]. As a result, there remains insufficient empirical evidence regarding the long-term operational performance,

organisational impact, scalability, and sustainability of blockchain-enabled compliance systems under real-world conditions [76, 79, 108].

A second major gap relates to the absence of longitudinal evaluation studies. Most existing research evaluates blockchain implementations over relatively short periods, focusing primarily on technical feasibility or immediate operational outcomes [76, 79, 108]. Limited attention has been given to understanding how blockchain adoption influences organisational practices, stakeholder collaboration, regulatory effectiveness, user acceptance, governance maturity, and operational resilience over extended periods [11, 75, 89, 108]. Longitudinal studies are therefore needed to assess whether the reported benefits remain sustainable as blockchain ecosystems evolve and expand [75, 79, 108].

The review also identifies a substantial gap in the development of standardised blockchain architectures for maritime regulatory compliance. Although numerous studies propose different blockchain frameworks, consensus mechanisms, governance models, and system architectures, there is little agreement regarding best practices for designing interoperable compliance platforms capable of supporting diverse maritime stakeholders [66, 76, 85]. This lack of architectural standardisation complicates technology adoption, increases implementation complexity, and limits the scalability of blockchain solutions across international maritime supply chains [11, 79, 85].

Another recurring gap concerns interoperability standards. The reviewed literature consistently highlights interoperability as essential for blockchain adoption, yet comparatively few studies propose comprehensive technical or governance frameworks capable of integrating blockchain with legacy maritime information systems, port community systems, customs platforms, and international trade infrastructures [76, 79, 89]. Existing research largely acknowledges interoperability challenges without providing validated solutions capable of supporting seamless cross-platform and cross-jurisdictional information exchange [35, 79].

The thematic synthesis further demonstrates a limited integration of blockchain with emerging digital technologies, particularly artificial intelligence, the Internet of Things, digital twins, and advanced data analytics [79, 85, 91]. While several studies recognise the complementary capabilities of these technologies, empirical research investigating integrated solutions remains scarce [75,79, 91]. Consequently, there is limited understanding of how intelligent automation, predictive analytics, sensor-generated data, and blockchain-based trust mechanisms can collectively improve maritime regulatory compliance and decision-making [21, 85, 91].

Another important gap concerns the lack of comprehensive performance evaluation. Many reviewed studies focus primarily on conceptual advantages or functional demonstrations while providing limited quantitative assessment of system performance, transaction throughput, latency, scalability, energy consumption, implementation cost, or regulatory efficiency [21, 79, 89]. Standardised evaluation metrics capable of comparing different blockchain platforms and implementation approaches remain largely absent, making it difficult to assess their relative effectiveness across varying maritime operational contexts [76, 108].

The literature also reveals insufficient attention to legal and regulatory frameworks governing blockchain adoption. Although many studies acknowledge legal uncertainty as a barrier to implementation, comparatively few investigate how existing maritime legislation, international conventions, electronic trade regulations, and data protection laws should evolve to support blockchain-enabled compliance systems [35, 51, 89]. Greater collaboration between legal scholars, policymakers, and technology

researchers is therefore required to establish harmonised regulatory environments capable of supporting secure digital compliance across multiple jurisdictions [35, 51, 63, 85, 89].

Finally, the review identifies a significant gap in the development of international governance models for blockchain-enabled maritime ecosystems. Successful implementation depends on effective governance arrangements that define stakeholder responsibilities, decision-making processes, identity management, access control, dispute resolution, and network participation [75, 89]. However, existing studies provide limited guidance regarding governance structures capable of supporting large-scale international blockchain networks involving diverse commercial organisations, regulatory authorities, and public institutions [35, 66]. Similarly, there remains a shortage of cross-border validation studies that evaluate blockchain performance across multiple countries, regulatory systems, and international trade corridors, despite the inherently global nature of maritime transport [5, 63, 66].

Overall, the thematic synthesis demonstrates that current blockchain research has established a strong conceptual and technological foundation for improving maritime regulatory compliance. However, important gaps remain in industrial validation, longitudinal assessment, architectural standardisation, interoperability, integration with emerging technologies, performance evaluation, regulatory development, governance design, and international implementation [75, 76, 79]. Addressing these gaps will be essential for advancing blockchain from promising pilot initiatives towards scalable, trusted, and operationally sustainable compliance infrastructures capable of supporting the future digital transformation of the global maritime industry [75, 76, 79].

6. Future Research Directions

The thematic synthesis demonstrates that blockchain has established a strong conceptual foundation for improving maritime regulatory compliance. However, the reviewed literature also indicates that technology remains at an early stage of industrial maturity, with numerous opportunities for further investigation. Future research should therefore extend beyond proof-of-concept implementations towards developing integrated, scalable, and operationally sustainable blockchain ecosystems capable of supporting increasingly complex regulatory environments [35, 79].

One promising direction concerns the integration of artificial intelligence (AI) with blockchain to enable intelligent regulatory compliance. While blockchain provides trusted and immutable records, AI technologies offer advanced capabilities for data analysis, anomaly detection, predictive decision-making, and automated risk assessment [51]. Future research should investigate how AI can analyse blockchain-generated compliance data to identify regulatory violations, detect fraudulent activities, predict compliance risks, and support more informed decision-making by customs authorities, port operators, and maritime regulators [51]. Such integration has the potential to transform compliance management from a reactive process into a proactive and intelligence-driven capability [51].

Another important research direction involves the application of digital twin technologies within blockchain-enabled maritime ecosystems. Digital twins can provide virtual representations of vessels, ports, cargo movements, and logistics operations that continuously reflect real-world conditions through synchronised operational data [1, 53, 117]. Future studies should investigate how blockchain can provide trusted data for digital twins while ensuring the integrity, authenticity, and traceability of information used to support operational monitoring, compliance verification, predictive maintenance, and regulatory decision-making [51, 117].

The reviewed literature also highlights significant opportunities for deeper Internet of Things (IoT)

integration. Although several studies recognise the complementary relationship between blockchain and IoT, empirical investigations remain limited [45, 79]. Future research should explore secure mechanisms through which IoT sensors can automatically capture operational events, environmental conditions, cargo status, and vessel activities before recording authenticated information directly onto blockchain platforms [85, 91]. Such integration could substantially reduce manual data entry while improving the accuracy, timeliness, and reliability of compliance-related information [85, 108].

A further priority concerns cross-chain interoperability. As multiple blockchain platforms continue to emerge across the maritime sector, future blockchain ecosystems will require seamless communication between independent distributed ledger networks [62]. Future studies should therefore investigate interoperability frameworks capable of enabling secure data exchange across heterogeneous blockchain platforms while maintaining regulatory consistency, security, and information integrity throughout international maritime operations [62, 79, 85, 91].

The thematic synthesis further identifies zero-knowledge proofs (ZKPs) as an important area for future investigation. Maritime regulatory compliance requires organisations to demonstrate compliance while simultaneously protecting commercially sensitive information [35]. Future research should evaluate how advanced privacy-preserving cryptographic techniques such as zero-knowledge proofs can enable stakeholders to prove regulatory compliance without revealing confidential operational or commercial data, thereby strengthening both privacy protection and regulatory transparency.

Another promising research direction involves the adoption of self-sovereign identity (SSI) for maritime stakeholders. Current identity management approaches often depend on centralised authorities responsible for issuing and managing digital identities [128]. Future research should investigate decentralised identity frameworks that allow organisations, vessels, crew members, inspectors, and regulatory authorities to securely control and verify their own digital credentials while improving trust, authentication, and access management across blockchain-enabled compliance ecosystems [128].

The reviewed studies also suggest considerable opportunities for developing automated compliance auditing. Although blockchain provides immutable audit trails, most existing audit activities continue to depend on manual interpretation and document verification [35, 79, 91]. Future investigations should examine how blockchain, smart contracts, and intelligent analytics can be combined to automate compliance auditing, continuously monitor regulatory adherence, generate real-time audit evidence, and reduce the administrative burden associated with traditional inspection processes [91].

Another important direction concerns real-time customs compliance. Current customs procedures frequently involve periodic document submission and post-event verification, limiting responsiveness during international trade operations [108]. Future research should investigate blockchain-enabled customs platforms capable of supporting continuous compliance monitoring, real-time information sharing, automated customs verification, and immediate regulatory decision-making through integrated digital trade ecosystems [108, 91]. Such capabilities could substantially improve customs efficiency while strengthening border security and trade facilitation [79, 108].

The literature further identifies the growing importance of quantum-resistant blockchain technologies. Advances in quantum computing may eventually challenge the cryptographic algorithms currently used to secure blockchain platforms [(35)]. Future studies should therefore investigate post-quantum cryptographic mechanisms capable of preserving the long-term security, integrity, and authenticity of blockchain-based regulatory records while ensuring resilience against emerging computational threats [35, 79].

Finally, future research should prioritise the development of international blockchain standards for maritime regulatory compliance. The reviewed literature consistently demonstrates that fragmented governance, inconsistent regulatory requirements, and limited interoperability remain significant barriers to large-scale blockchain adoption [35, 79]. Future investigations should therefore focus on internationally harmonised standards governing blockchain architectures, digital documentation, certificate management, interoperability, smart contract implementation, identity management, and cross-border information exchange [35, 85]. Such standardisation will be essential for enabling trusted collaboration among governments, maritime organisations, technology providers, and international regulatory bodies while supporting the widespread adoption of blockchain-enabled compliance across the global maritime industry [35, 108].

Overall, the thematic synthesis indicates that future blockchain research should move beyond demonstrating technological feasibility towards developing intelligent, interoperable, secure, and globally coordinated compliance ecosystems. Advancing these research directions will contribute to the evolution of blockchain from isolated pilot initiatives into operational digital infrastructures capable of supporting transparent, efficient, and trustworthy maritime regulatory compliance on an international scale [35, 79, 91,108].

7. Conclusion

This systematic literature review examined the application of blockchain technology for maritime regulatory compliance by synthesising current evidence on five principal application areas: digital documentation, immutable audit trails, customs and border compliance, certificate verification, and smart contracts. The thematic synthesis demonstrates that blockchain has emerged as a promising digital infrastructure capable of addressing many of the longstanding challenges associated with conventional compliance systems, including fragmented information management, paper-based documentation, manual verification procedures, limited transparency, and weak interoperability among maritime stakeholders [35, 76, 79].

The review indicates that blockchain provides substantial benefits for improving integrity, authenticity, traceability, and accessibility of regulatory information throughout the maritime supply chain. Digital documentation enables the secure management of electronic trade records, while immutable audit trails strengthen accountability by preserving complete and tamper-resistant transaction histories [35, 108]. Similarly, blockchain enhances customs and border compliance by facilitating trusted cross-border information sharing and more efficient customs clearance processes. Technology also improves certificate verification through secure digital certification and strengthens regulatory workflow management by enabling smart contract automation for compliance verification, document approval, cargo release, and other administrative processes [69, 121].

Despite these advantages, the review demonstrates that blockchain adoption remains constrained by several important technical, organisational, legal, and governance challenges. The reviewed studies consistently identify interoperability limitations, regulatory uncertainty, governance complexity, implementation costs, scalability concerns, and integration with legacy information systems as significant barriers to widespread adoption [55, 113 Furthermore, blockchain cannot independently guarantee regulatory compliance, as the reliability of blockchain-based systems continues to depend upon trustworthy data sources, effective identity management, appropriate governance arrangements, and supportive legal frameworks [2, 4, 55].

The thematic synthesis also reveals several important research gaps. Existing studies remain largely concentrated on conceptual models, prototype implementations, and pilot projects, with comparatively limited empirical evidence derived from industrial-scale deployments and long-term operational evaluations. Additional research is required to develop standardised blockchain architectures, improve interoperability, integrate blockchain with emerging technologies such as artificial intelligence and the Internet of Things, establish internationally harmonised governance frameworks, and evaluate blockchain performance within real maritime operational environments [35, 79, 108].

From a practical perspective, the findings provide valuable guidance for policymakers, regulatory authorities, maritime organisations, and technology developers seeking to modernise regulatory compliance. Successful blockchain implementation requires more than technological innovation; it demands coordinated governance, legal recognition of digital records, internationally accepted interoperability standards, organisational readiness, and sustained collaboration among all stakeholders participating within maritime compliance ecosystems [11, 35, 76, 79, 91].

Overall, the thematic synthesis demonstrates that blockchain possesses significant potential to transform maritime regulatory compliance by enabling secure, transparent, and trustworthy digital ecosystems that improve collaboration, accountability, and operational efficiency across international maritime supply chains. While important implementation challenges remain, the continued advancement of blockchain technologies, together with supportive governance and regulatory frameworks, is expected to play a pivotal role in the ongoing digital transformation of global maritime compliance. Consequently, blockchain should be regarded not merely as an emerging technology, but as a strategic enabler of more resilient, efficient, and trusted maritime regulatory systems capable of supporting the future demands of international trade and global shipping operations [11, 35, 76, 79, 91].

8. References

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