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REVOLUTIONISING FREIGHT LOGISTICS: THE ROLE OF BLOCKCHAIN IN CARGO HANDLING OPERATIONS

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ABSTRACT

This article explores how blockchain technology is transforming freight handling in the logistics sector by examining its effects on cargo handling operations. To ensure a comprehensive review of the academic literature and to identify relevant documents, the study followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. An analysis was conducted on 21 documents (out of 103), published between 2019 and 2024, which were retrieved from the Scopus database. The findings reveal that blockchain technology significantly enhances cargo handling by improving efficiency, transparency, and data security through real-time tracking, automated verification, and immutable data storage—thereby transforming traditional logistics operations into more reliable, cost-effective, and trustworthy systems. This review offers valuable insights for logistics professionals, supply chain managers, policymakers, and technology developers seeking to improve cargo handling through innovative digital solutions.

Introduction

Cargo handling is a critical component of the transportation industry, particularly in the marine sector. It involves the loading, unloading, and movement of cargo and containers at ports (Rodrigues *et al*., 2020). The adoption of advanced technologies, such as the Internet of Things (IoT), Big Data, blockchain, augmented intelligence, and data-science-based interfaces, has significantly enhanced operational efficiency, reduced costs, and improved data-driven decision-making. Smart port technologies provide numerous advantages, including better data management, streamlined logistics, and environmentally sustainable operations.

Ports serve as essential hubs for maritime trade and transport, enabling the transfer of goods and passengers between land and sea. Key components of port operations include Cargo Handling Equipment (CHE), containerisation, and task-specific handling procedures (Rodrigues *et al*., 2020). CHE, such as gantry cranes, reach stackers, top handlers, forklifts, straddle carriers, terminal tractors, and yard trucks, plays a pivotal role in managing cargo efficiently. Containerisation has simplified loading, unloading, and transit processes, reducing damage risks and accelerating turnaround times. While cargo handling practices vary between air and ocean transport, automation, especially through technologies like Automated Guided Vehicles, (AGVs) consistently enhance productivity and reduces labour costs. Additionally, sustainability is increasingly prioritised through the adoption of alternative fuels and eco-friendly equipment.

Blockchain technology, originally designed to support the digital currency Bitcoin (Ammous, 2016) has garnered substantial attention across industries for its ability to provide decentralised, transparent, and immutable records of transactions. It operates through a distributed ledger that eliminates the need for a central authority, ensuring data integrity and security across a shared network (Baygin *et al*., 2022). Smart contracts, automated programs that execute transactions when predefined conditions are met, further streamline processes such as documentation, payments, and customs clearance.

In logistics and cargo handling, blockchain has demonstrated significant potential. For example, the Port of Rotterdam, one of the world's largest smart ports, integrates blockchain with data analytics and automated equipment to enhance operational efficiency and sustainability. The port has also developed collaborative networks with local institutions to support its digital transformation (Belmoukari *et al*., 2023). Figure 1 illustrates the blockchain workflow in cargo handling, highlighting its role in addressing key industry challenges such as inefficiency, fraud, and lack of transparency.

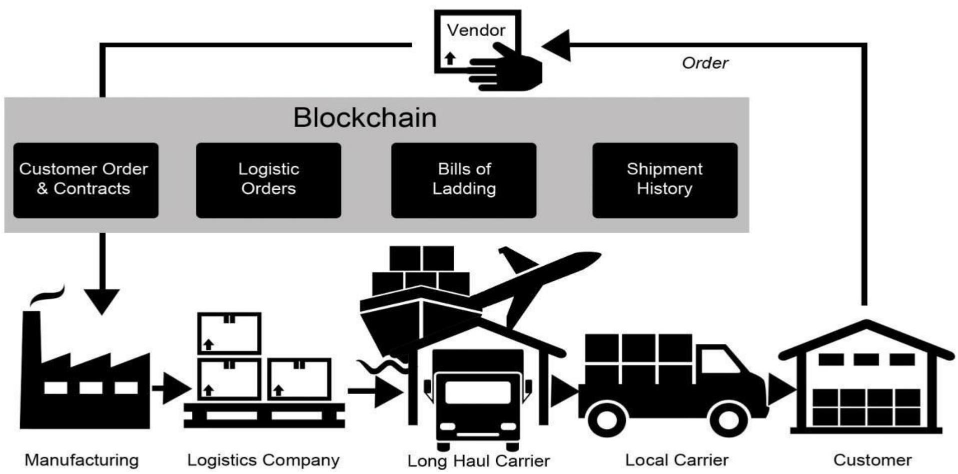

Figure 1: Blockchain Logistics
Source: Eric and Eric (2018)

Literature reviews show that blockchain enhances traceability, security, and data integrity in logistics. Baygin *et al*. (2022) emphasises the blockchain's ability to manage workflows without intermediaries, while Priya *et al*. (2024) highlight its impact on maritime logistics safety and reliability. Tian (2016) demonstrated its application in tracking agricultural products to prevent counterfeiting, and Hackius and Petersen (2017) identified its potential for increasing transparency and automating procedures in logistics. Francisco and Swanson (2018) reported benefits in real-time cargo tracking, and Kshetri (2018) noted improved cybersecurity due to decentralisation. These developments result in fewer errors, faster processing times, and significant cost savings.

This systematic literature review aims to examine the current research on blockchain technology with a focus on its application and effectiveness in cargo handling. The review seeks to answer the following research question: What are the effects of blockchain technology on cargo handling operations?

Methodology

This systematic review was conducted in accordance with the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA)_2020 guidelines (www.prisma-statement.org). PRISMA (2020) statement offers an updated framework to improve the transparency and completeness of reporting in systematic reviews and meta-analyses. The flow diagram comprises of three main stages: Identification, Screening, and Inclusion. In the Identification stage, relevant studies were retrieved from the Scopus database using keyword combinations related to blockchain and cargo handling. The Scopus database was selected as the sole source for this systematic literature review due to its comprehensive coverage, robust indexing, and relevance to the research domain. Boolean operators (AND, OR) were applied to enhance search precision. The search was conducted on 10 May 2024, using the following terms: "blockchain" OR "distributed ledger" AND "digital" AND "cargo handling" OR "container handling". The inclusion criteria used to search the Scopus database is presented in the Table 1.

Table 1: Inclusion and exclusion criteria applied in the database search

Criteria	Inclusion	Exclusion
Year	From 2019 to 10th of May 2024	Before 2019 and after 10th of May 2024
Type	Articles and conference articles	Review or book chapter
Source	Journal and conference proceeding	Other sources
Language	English	Non-English

During the Screening stage, duplicate records were removed, followed by a review of titles and abstracts. Full-text articles of potentially relevant studies were assessed for eligibility. Studies not meeting the inclusion criteria were excluded at this stage. Figure 2 illustrates the entire selection process: A total of 103 records were initially identified through database searching (Identification stage). Of these, 35 records were excluded due to a lack of relevance to the topic. The remaining 68 records were screened based on titles and abstracts, leading to the exclusion of 19 irrelevant records. Of the 49 remaining records, 19 could not be retrieved for full-text review. Among the 30 full-text articles assessed for eligibility, nine were excluded because they did not address the actual application of blockchain technology (Screening stage). Ultimately, 21 studies were included in the qualitative synthesis (Included stage).

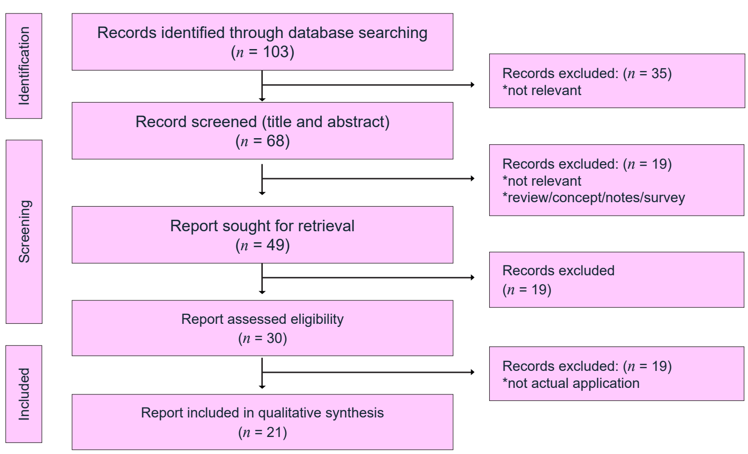

Figure 2: Flowchart of the PRISMA

Source: Authors

Results and Discussion

Table 2 presents a detailed classification of the impact of blockchain applications on various cargo handling components: Component 1 represents increased efficiency, Component 2 corresponds to transparency and traceability, and Component 3 relates to security and data integrity. This table offers comprehensive insights into the classification of blockchain applications by component, context, and the technologies involved, providing a clearer understanding of how blockchain is practically implemented in cargo handling.

Among the reviewed studies, 47.62% (10 articles) focused on improving efficiency (Component 1), indicating this area has received the most research attention. Transparency and traceability (Component 2) accounted for 28.57% (6 articles), while security and data integrity (Component 3) were the focus of 23.81% (5 articles). Regarding the application context, efforts to enhance efficiency dominated Component 1, whereas transparency improvements are most prominent within Component 2. Overall, blockchain technology has demonstrated significant potential to improve efficiency, security, and transparency across various domains.

The technologies associated with blockchain applications in cargo handling include digitalisation, Artificial Intelligence (AI), Hyperledger Fabric, Ultra-High Frequency (UHF) RFID, IoT, machine learning, transfer learning, Non-Fungible Tokens (NFTs), and Intelligent Automated Transport Systems (IATS).

Blockchain protects data integrity by ensuring digital documents are easily verifiable and tamper resistant. It also enables smart contracts, which reduces cost and builds trust by automating transactions and workflows. UHF Radio Frequency Identification (RFID) and Internet of Things (IoT) devices facilitate real-time tracking and management of physical assets while maintaining a secure and immutable record of asset history and movements. Machine learning algorithms applied to blockchain data can identify patterns and generate predictions, enhancing fraud detection and decision-making processes.

Furthermore, blockchain technology combined with smart contracts and distributed file systems such as Private Interplanetary file system (IPFS) supports secure data sharing, model training, and storage. Hyperledger Fabric offers a modular, scalable architecture that supports flexible blockchain implementations. AI complements blockchain operations by enhancing data analysis, automating processes, and strengthening security measures. Together, blockchain and IoT technologies improve data integrity, security, and real-time asset tracking, thereby enhancing operational efficiency in cargo handling.

Table 2: Integration of blockchain applications in freight and cargo handling

References	Component	Application Context	Technologies
Tsiulin and Reinau (2021)	1	Blockchain scenarios for the shipping industry	Blockchain and digitalisation
Le *et al*. (2023)	2	Blockchain prototype	Blockchain
Padmanabhan *et al*. (2022)	2	Blockchain network solution	Blockchain and smart contract
Baygin *et al*. (2022)	1	Smart cargo transportation	Blockchain, UHF, RFID, and IoT
Karumanchi *et al*. (2022)	2	Blockchain-enabled supply chain	Blockchain and machine learning.

Priya *et al*. (2024)	2	Blockchain-enabled transfer learning	Transfer learning, blockchain, smart contracts, and private IPFS
Gao *et al*. (2022)	3	Fabric blockchain	Hyper ledger Fabric and blockchain
Almuqren *et al*. (2023)	1	Blockchain-assisted vehicle and cargo matching	Blockchain and AI
Elmay *et al*. (2022)	2	Traceability and auctioning of shipping containers and cargo	Blockchain NFTs
Balfaqih *et al*. (2023)	1	Blockchain-enabled IoT logistics system	Blockchain and IoT
Yu *et al*. (2024)	1	Pricing competition and empty container repositioning	blockchain
Tyagi *et al*. (2023)	1	Supply chain operation	Blockchain and AI
Azimov and Petrova (2022)	1	Logistic system	blockchain
Shanthi *et al*. (2023)	3	Deep learning based autonomous transport system	Blockchain and IATS
Wang *et al*. (2021)	1	Port logistics capability	Blockchain
Tesei *et al*. (2021)	3	Seaport logistic vehicles	Blockchain
Thakur *et al*. (2023)	3	Robotic swarms	Blockchain
Valchanov and Aleksieva (2022)	3	Smart transportation	Blockchain and IoT
Duran *et al*. (2021)	2	Smart ports	Blockchain and IoT
Kim and Kim (2023)	1	Blockchain-based railroad non-stop customs clearance system	Blockchain
Mukhamedova and Mukhamedova (2024)	1	Organisation of the transportation process and supply chain	Blockchain and smart contract

According to Kim and Kim (2023), compared to traditional customs clearance methods, the blockchain-based Non-Stop Customs Clearance (NSCC) system excels in integrity, security, and reliability. Reducing customs clearance time can significantly improve the performance of freight transportation via railroads in cross-border trade. By leveraging blockchain's decentralised and tamper-proof architecture, NSCC ensures that documentation and transaction records are securely shared among customs authorities, logistics providers, and traders in real time. This eliminates the need for manual verification at border checkpoints, minimises delays, and enhances the transparency and traceability of goods throughout the supply chain. Ultimately, it leads to more predictable delivery schedules and lower operational costs.

One of the primary benefits of blockchain technology is its regulatory approach to minimising issues associated with database management systems (Padmanabhan *et al*., 2022). Blockchain securely stores essential data related to orders, shipments, and the matching of available vehicles with cargo. This data includes sender and receiver details, cargo type and quantity, destination, vehicle information, pickup and delivery times, and any special requirements. Blockchain provides a trusted platform for storing transactional data and records. Participants share transaction details across a large network of untrusted nodes, which are resistant to deletion or modification through cryptographic proofs, making blockchain a reliable source for future auditing and accounting (Almuqren *et al*., 2023).

Baygin *et al*. (2022) demonstrated that data from IoT sensors could be transferred to cloud-based servers while only transactions relevant to smart contracts are stored on the blockchain, resulting in significant cost savings. Similarly, Balfaqih *et al*. (2023) showed that implementing smart logistics systems enabled effective distribution of high-value goods with traceability and condition monitoring capabilities. The proposed blockchain-based IoT logistics system supports efficient shipment tracking and management, providing a fully secure, trusted, cost-effective, and efficient solution capable of improving high-value shipment management in the contexts of smart cities and global trade.

Azimov and Petrova (2022) highlighted that blockchain technology significantly benefits the logistics sector by improving workflow efficiency, optimising data storage, and enhancing supply chain management. These improvements are especially valuable in complex cargo handling operations where multiple stakeholders rely on timely and accurate information. By reducing human error and delays in documentation, blockchain fosters greater reliability, real-time tracking, and transparency across the entire logistics cycle, which is crucial for modern global trade environments.

Regarding transparency and traceability, six articles were identified. Transparency and traceability are crucial for supply chain visibility and stakeholder confidence. These studies emphasise enhancing supply chain accountability and visibility. For example, Duran *et al*. (2021) reported that blockchain technology impacts the maritime industry by building efficient commercial ecosystems, improving information and communication processes by eliminating article use, and incorporating smart contracts that provide autonomy, trust, security, speed, cost savings, and precision. The combination of blockchain and crowdsourcing transforms data into actionable knowledge for effective decision-making.

Karumanchi *et al*. (2022) briefly explained how blockchain improves supply chain traceability and accessibility. The transactions recorded on a blockchain network are immutable, and the blockchain's structure, where blocks link sequentially, enhances transaction security (Elmay *et al*., 2022). The developed blockchain model provides essential features such as data immutability and traceability, which are critical for these applications. Once data is created, it is time-stamped and traceable within the blocks (Padmanabhan *et al*., 2022). Le *et al*. (2023) showed that blockchain security remains robust when attackers control less than 50% of the total computing power, highlighting the importance of preventing computing power centralisation through measures such as warning systems to detect such trends. Priya *et al*. (2024) emphasised the benefits of blockchain in enhancing safety and reliability in maritime logistics, noting an 18.9% improvement in computational time compared to standard transfer learning methods.

The least frequently reported impact relates to security and data integrity. These improvements address data security by creating an immutable and secure ledger that protects against data manipulation. Blockchain also enhances authentication and builds stakeholder trust. Five articles (Table 2) focus on this component. For instance, Gao *et al*. (2022) highlighted how blockchain's distributed storage, immutability, and traceability establish a secure data-sharing platform that enhances maritime data transparency, achieves format standardisation, and promotes information symmetry among enterprises, while also meeting shipping logistics systems' security and computational cost requirements.

Tesei *et al*. (2021) proposed a distributed ledger-based credential management system to enable transparent, real-time tracking of logistic vehicles and cargo within terminals. Thakur *et al*. (2023) discussed how blockchain adoption could create a secure and trustworthy robotic swarm system, addressing possible security threats, blockchain failures, swarm robotics challenges, and appropriate consensus mechanisms. Blockchain reduces costs and transaction validation times, decreases the risk of attacks by limiting validation to known nodes, and increases privacy by restricting read permissions to selected nodes (Valchanov & Aleksieva, 2022).

According to Shanthi *et al*. (2023), blockchain technology in cargo handling represents a transformative shift in the logistics industry, offering unparalleled security, transparency, and efficiency. Blockchain technology in cargo handling represents a transformative shift in the logistics and supply chain industry by enhancing security, transparency, and operational efficiency across all stages of cargo movement. As a decentralised and tamper-proof digital ledger, blockchain ensures that all transactions such as cargo loading, unloading, customs clearance, and delivery are recorded in an immutable and verifiable manner, significantly reducing the risks of fraud, data manipulation, and unauthorised access. It offers real-time traceability and shared visibility among stakeholders including shippers, freight forwarders, port operators, and customs authorities, fostering greater trust, accountability, and collaboration.

The integration of smart contracts enables automatic execution of critical operations once predefined conditions are met, streamlining workflows, reducing articlework, and minimising delays and human error. Additionally, blockchain supports the secure digital exchange of documents like electronic Bills of Lading (eB/L), accelerating cargo processing and reducing administrative burdens. By enabling seamless interoperability with IoT devices and data platforms, blockchain also enhances decision-making and risk management capabilities. Overall, its adoption strengthens the resilience, responsiveness, and integrity of global cargo handling operations, setting a new standard for efficiency and reliability in modern logistics.

Conclusions

This study systematically reviewed and analysed recent scholarly publications on the application of blockchain technology in cargo handling. By examining the distribution of publications, the contexts of blockchain use, and the associated technologies, the study provides a comprehensive review of the current state and impact of blockchain in the logistics sector.

The analysis of publications from 2019 to 2024 reveals a growing global interest in blockchain technology, particularly in its application to cargo handling. India and China are leading contributors to the research output, reflecting their active engagement in advancing blockchain-based logistics solutions. The evolution of blockchain from initial scepticism to widespread adoption corresponds with its increasing maturity and practical applications across various industries, including freight and supply chain management.

In cargo handling, blockchain technology has demonstrated substantial potential to enhance operational efficiency, transparency, and security. Efficiency improvements dominate current research, focusing on streamlining workflows, accelerating processing times, and reducing errors in cargo tracking and documentation. Transparency and traceability are also pivotal, enabling better supply chain visibility and fostering stakeholder trust through immutable transaction records and real-time monitoring. Although less emphasised, security and data integrity remain critical, with blockchain's inherent features providing tamper-resistant ledgers and robust authentication mechanisms that safeguard against fraud and data manipulation.

The integration of complementary technologies such as IoT, Artificial Intelligence, smart contracts, and distributed ledger platforms further amplifies the blockchain's impact, facilitating real-time asset tracking, automated workflows, and secure data sharing. These innovations collectively contribute to more reliable, cost-effective, and trustworthy cargo handling systems that can meet the demands of smart cities and global trade.

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Conflict of Interest Statement

The authors declare that they have no conflict of interest.

Author Contributions Statement

The authors confirm contribution to the article as follows: Study conception and design: Adel Gohari, Rudiah Md Hanafiah, Teh Sabariah Abd Manan; data collection: Nurdiana Sakeri, Olakunle Oloruntobi; analysis and interpretation of results: Nurdiana Sakeri; draft manuscript preparation: Adel Gohari, Kasypi Mokhtar, Arife Tugsan Isiacik Colak, Amir Sharifuddin Ab Latip, Haspinor binti Teh. All authors reviewed the results and approved the final version of the manuscript.

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