

Blockchain Adoption in E-Commerce Supply Chain Management: A Bibliometric Analysis and Conceptual Framework

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Abstract

Blockchain technology is increasingly being applied to e-commerce supply chains. The vast amount of sensitive telemetry information created by connected Cyber Physical Systems (CPS) presents major challenges in terms of security, privacy and network latency when processing large amounts of data. This project therefore proposes a new, bifurcated hybrid architecture which uses real-time adaptive trust mechanisms to process high frequency IoT data streams. This will enable an improvement on the inherent latency and scalability issues caused by the blockchain scalability trilemma. Through a comprehensive bibliometric analysis, this paper intends to create a robust base for understanding how the area of smart logistics is developing and closing the gap that exists between experimental technological innovation and its sustainable application. Using a combination of Longitudinal Evolutionary Diagrams (LED), Strategic Thematic Mapping (STM) and Keyword Co-occurrence Networks (KCN) we intend to extract the thematic clusters of blockchain-based logistics and identify key knowledge gaps arising from 2020- 2026. We propose to complete a Thematic Diagram Analysis (TDA) to evaluate the longitudinal thematic development of authors' keywords from 2020- 2026 and establish the key technical benchmarks required to support our subsequent Bibliometric Evaluation. In order to meet our objectives, we are using Discrete Event Simulation (DES) modelling to simulate our proposed architecture under representative ecommerce high frequency data flows.

Keywords: Blockchain; Smart Logistics; Dynamic Trust Routing; Scalability Trilemma; Bibliometric Analysis

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1.Introduction

The COVID-19 pandemic created a significant acceleration of digital transformation of global ecommerce and the use of advanced, data intensive smart logistics models and supply chain networks. These are focused on being agile, resilient, and sustainable (Farfán Chilicaus et al. 2025). As such, modern smart logistics now utilize IoT, AI, and cloud based solutions for real time tracking, optimized omni-channel distribution and green urban delivery solutions(Kalkha et al. 2023; Golinska-Dawson and Sethanan 2023; Idrissi et al. 2024; Woschank et al. 2020). Additionally, expected future advancements including 6th generation wireless networks, federated learning for the internet of things, and immersive technology will create even greater levels of interconnectedness and autonomous decision making

capabilities throughout the entire supply chain(Alghamedy et al. 2024; Kostadimas et al. 2025; Najafi et al. 2024). However, the substantial amounts of sensitive telemetry data from all of these new, connected cyber physical systems presents serious challenges to protect against data security threats, data privacy issues and increased network latency. Therefore there is an urgent need for secure decentralized data management frameworks to provide data protection in high frequency logistics environments (Gamboa-Cruzado et al. 2025). Blockchain technology (BCT), has become popular for being an effective structural answer to address many of the issues that are associated with these vulnerabilities. Through using Decentralized Consensus, Immutable Data Management, and Trustless Transparency; BCT allows for the

development of Advanced Applications such as Digital Asset Tokenization in E-commerce Logistics Financing(Harish et al. 2023); and Enhanced Digital Information Sharing in Specialized Agricultural Networks (Abdullah and Alani 2025). Although it may have a huge impact on securing IoT Data Flows and Automating Processes through Smart Contracts, Widespread Industrial Adoption will be greatly hindered by numerous Socio-Technical Barriers related to Ineffective Organizational Policies, High Investment Costs, and Limited Technical Expertise(Khan et al. 2023; Surange et al. 2026). More importantly, The Technology Suffers From The Structural Trade-Offs of The Blockchain Scalability Trilemma, Algorithmic Friction That Forces Structural Trade-Offs between Global Decentralization, Cryptographic Security And Transaction Throughput (Lohmer et al. 2022). The use of Volatile Ecommerce Telemetry on high frequency in Consensus Protocols will result in increased latency and computational overhead and therefore render monolithic Blockchain Architectures incapable of meeting the Real Time Requirements of Dynamic Cloud and IoT Based Logistics Operations(Shukla et al. 2023). The friction created by this process is far from just being an issue of theory, it actually causes a discontinuity in the flow of goods and capital. An example of how this friction creates problems is evident in ECommerce Logistics Financing (LF) which has both cyber and physical tracking requirements for capital access. If there is too much delay in receiving data then the trust mechanism may be invalidated, thus halting operations (Harish et al. 2023). With this realization of the limitations of Monolithic Blockchain Architectures there is a significant shift taking place within the field of academia. There is a shift away from theoretical or "black box" conceptualization of blockchain solutions and towards more concrete and practical forms of performance engineering and empirical validation(Hübschke et al. 2025). Many early implementations were designed without consideration to Human-Computer Interaction (HCI) issues which resulted in poor usability that limited the actual utilization of the technologies capabilities(Tharatipyakul and Pongnumkul 2021). Furthermore, Multi Criteria Decision Analysis (MCDA) demonstrates that the successful implementation of Digital Tools into Supply Chain Systems requires a careful balance of multiple stakeholder interests against strict project constraints including, but not limited to, Cost Overrun Constraints and Logistics Delay Constraints (Kwok and Chang 2025). Both bibliometric and systematic review studies have demonstrated that while sustainability and transparency continue to be top priorities of current research, a major limitation in understanding

the true industrial feasibility of these systems continues to exist due to the lack of standardized performance metrics and the continued reliance on Simulated Environments for testing purposes (Gamboa-Cruzado et al. 2025; Farfán Chilicaus et al. 2025). To close the persistent gap between experimental development and the widespread deployment of large-scale industrial applications, researchers are now focusing on Interoperable Architectures capable of managing large numbers of IoT devices. Additionally, this shift represents an important transition: Successful Digital Transformation is no longer evaluated solely based on Cryptographic Security but rather based upon the quantifiable reduction of Operational Latency and the facilitation of "Trust Transfer" directly from the Ledger to previously Untrusted Supply Chain Partners (Yavaprabhas et al. 2025; Rejeb et al. 2021; Pattanayak et al. 2024).

2. Objective and Research Questions

The main goal of this research project is to assess the process of how blockchain technology has progressed within E-commerce Supply Chains from theoretical ideas to large-scale real-world industrial implementations. This research project develops an innovative Hybrid Architecture by combining High-Frequency IoT Telemetry and Adaptive Trust Mechanisms as part of an integrated solution to address the algorithmic friction and latency associated with Scalability Bottleneck of Blockchain's Scalability Trilemma. Through a detailed Bibliometric Analysis to identify both the Intellectual Structure and Thematic Evolution of the field, this research will develop a robust framework to enable high throughput, low latency Cyber Physical Systems which will close the persistent gap between Experimental Technology and Sustainable Operational Integration, this study is guided by the following Formulated Research Questions (RQs):

RQ1: How has the volume and intellectual structure of scientific literature regarding blockchain in e-commerce supply chains evolved between 2020 and 2026?

RQ2: Which authors, institutions, and countries form the central collaborative networks driving the transition from conceptual frameworks to applied technical models?

RQ3: How have the core research themes shifted away from generic blockchain traceability toward specialized consensus architectures and empirical performance benchmarking?

RQ4: What are the emerging "motor themes" and unresolved architectural bottlenecks that define the future agenda for highly scalable, low-latency logistics infrastructure?

This paper provides a solid foundation to evaluate how Smart Logistics has evolved over time, by developing an overall framework that bridges the theoretical gap in order to help create both sustainable and high through-put Cyber Physical Systems.

3. Literature Review and Theoretical Foundations

This section combines the present literature on the integration of blockchain into industrial supply chain systems in order to evaluate and critique how theoretical models are being used as practical frameworks for the application of technology. We establish our knowledge of the most recent findings regarding research on this topic by identifying three recent systematic reviews which highlight an ongoing historical “paradox of architecture” and provide the technological benchmarks needed to inform our subsequent bibliometric evaluation.

3.1 Synthesis of Previous Systematic Literature Reviews

Over the last ten years, there is an explosion in scholarly research on using blockchain in SCM that started with discussion of decentralized trust and moved to highly applicable, domain specific architectures for blockchain (Lohmer et al. 2022; Kuzior and Sira 2022; Saberi et al. 2019). The first two foundational systematic literature reviews by (Queiroz et al. 2020; Varriale et al. 2021) positioned blockchain as a disintermediation tool and one which can enable stakeholder to implement automated collaborative resource allocation and reduce information asymmetry via an immutable ledger. Most recent bibliometric analysis also confirms the direction and magnitude of the trend demonstrating how blockchain fundamentally alters inter-organizational relationships. As demonstrated by (Yavaprabhas et al. 2025) who use Stewart’s (2003) “Trust Transfer Theory” to operationalize blockchain as a “trust building machine”, blockchain enables users to build trust in traceable shared platforms and thereby establish trust in previously unknown or untrusted supply chain partners (Rejeb et al. 2021). The area of study has evolved as a body of research. More recently, research has focused on much more complex cyber-physical systems. For example, (Muñoz-Sánchez et al. 2025; Kamilaris et al. 2019) showed how blockchain can eliminate many inefficiencies in both maritime and agricultural supply chains by providing an instantaneous view into the status of each transaction. Additionally, the use of IoT combined with blockchain has been shown to be effective for securing the origin of data (Safeer et al. 2024; Galvez et al. 2018); Moreover, combining distributed ledger technology with Industry 4.0 technologies will inherently increase digital supply chain resiliency through increased resistance to internal disruptions (Al-Banna et al. 2023; Kalkha et al. 2023; Tamilarasan et al. 2026).

Finally, (Harish et al. 2023) demonstrated that using blockchain is successful at bridging the gap between cyber (data/information) and physical (goods/products) flow in LF (logistics financing). Blockchain’s use of digitalized measures of operational capacity rather than the traditional use of financial indicators enables small- and medium-sized logistics companies to obtain capital by using transparent operating performance criteria (Moretto et al. 2019). Nevertheless, there are also substantial differences in levels of maturity among those studies. (Queiroz et al. 2020) state that, prior to adoption, an overall lack of trust is the major obstacle for entry. In addition, (Tharatipyakul and Pongnumkul 2021), report a considerable absence of HCI and UI concerns within present design architecture which may lead to limited use of systems. Overall, technology-based experimentation will continue to be much greater than the standardization and integration requirements necessary to move from proof-of-concepts into the production oriented large scale applications (Gamboa-Cruzado et al. 2025; Choi et al. 2020).

3.2 The Paradox of Architecture in Blockchain Supply Chains

Despite the many recognized advantages of decentralized ledger systems, this study reveals a long-standing theoretical void by identifying what it terms an “Architecture Paradox” through its analysis of the current literature. The Architecture Paradox is demonstrated in how scholars continually identify blockchains as a solution to the lack of transparency in supply chains; however, they continually treat blockchains as a homogeneous “Black Box,” failing to account for the underlying cryptographic and consensus mechanisms that are producing those solutions (Lohmer et al. 2022). This Architecture Paradox is most clearly articulated in the inability of the literature to provide solutions to the Scalability Trilemma – the intrinsic structural trade-offs among decentralized globality, network security, and network scalability. Both (Vilkov and Tian 2023; Kuzior and Sira 2022) have noted that although traditional Proof-of-Work (PoW) consensus methods ensure very secure networks, their large-scale, energy-intensive computational requirements produce extreme delays in processing transactions. To summarize the opposite side of the argument – Alternative architectures such as Proof of Stake (PoS) or Proof of Authority (PoA) will allow for higher transaction throughput; however these architectures are based on permissioned consortiums so they sacrifice pure decentralized characteristics (Gamboa-Cruzado et al. 2025). The architecture paradox is a result in proposed supply chain frameworks which assume infinite scalable networks without considering the algorithms used to support them. (Tharatipyakul and Pongnumkul 2021;

Pearson et al. 2019), have pointed out that using standard consensus protocols to force volatile, high frequency logistics data into an enterprise wide network will create network congestion and will also be difficult to integrate with ERP systems. Most of the current literature ignores the specific complexities associated with each algorithm (i.e., $O(N)$ time complexity for validating all messages in a broad consensus protocol) and thus propose theoretical models that do not meet the real-time requirements of modern cyber-physical supply chains.

3.3 Technical Benchmarks for High-Volume Transactions

In order for conceptual models to be converted into applicable industrial implementations, the literature will need to provide quantifiable technical implementation standards for large-scale commercial exchanges. The authors of both (Safeer et al. 2024; Varriale et al. 2021), emphasize that the conversion from theoretical application to operational realization of technology is often limited due to the lack of empirical analysis on ledger scalability, latency, and cost-effective operations within a real world environment. In addition, high throughput environments which include smart e-commerce logistics require benchmarking that goes beyond mere security claims. As an example of this, (Harish et al. 2023) demonstrate that a viable blockchain framework - such as a Proof-of-Authority (PoA)-based Lightning Network (LF) architecture - must be tested using strict metrics in terms of throughput (i.e. approximately 45 TPS) and near-real time latency for ingestions of data from IoT sensors. Implementations which overcome these limitations caused by the algorithms used for bottleneck control require the abandonment of monolithic network designs and replace them with digital asset tokenized structures, layer-2 local execution pipeline processing and dynamic routing structures that allow for trade-offs in computational overhead vs. cryptographic integrity (Al-Banna et al. 2023; Vilkov and Tian 2023). Tokenization is particularly suited to uniquely map tangible assets to their corresponding digital representations; in addition to creating the possibility that traceable data will flow without congestion into the master ledger (Harish et al. 2023). The development of the necessary standards also should be informed by the practical social realities of technological adoption. In this regard, (Yavaprabhas et al. 2025), identified two types of blockchain use contexts. A voluntary type of blockchain implementation would foster an organic trust transfer from the technology to supply chain partners, whereas a mandatory type of implementation (which often are required by powerful e-commerce platforms) require the inherent transparency of the system as a means to create partner trust over time. Therefore, it can be

reasonably concluded that there exists a need for a comprehensive quantitative assessment to identify which aspects of the relevant socio-technical and algorithmic benchmark have been either addressed or ignored in recent research. As such, this provides the essential base line for the subsequent bibliometric analysis.

4. Research Methodology

To provide a reliable systematic review with reproducibility and transparency in data collection for literature mapping, we applied PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) 2020 as the guiding methodology (Page et al. 2021). The methodological structure includes data extraction and then a bibliometric mapping.

4.1 Data Source and PRISMA Extraction Protocol

Data extraction utilized Scopus and the Core Collection of Web of Science (WoS), two of the most comprehensive scientific databases. Selection of these databases was based on their strong coverage of high impact literature in computer science, industrial engineering and supply chain management. Dual authoritative databases are recommended highly in bibliometric research to reduce bias from relying on one database and broaden coverage (Yubo et al. 2023). To capture intersections of e-commerce, logistics and consensus architectures a specialized Boolean string was formulated (see Table 1). Search was very strictly limited to peer reviewed journal articles and conference papers published in English between 2020 and 2026. This time period was chosen strategically to capture evolution of literature following global supply chain disruptions of 2020 which increased demand for scalable digital infrastructure. Initial database query returned a total of 772 raw records: 442 from Scopus and 330 from WoS. In the Identification Phase, 226 duplicates were removed from the 546 identified documents, and thus there were 546 documents to screen. In the Screening Phase, all 546 of those screened based on titles and abstracts against the strict inclusion/exclusion criteria. Any paper that was not directly related to a specific type of E-commerce supply chain architecture with an implementation of a consensus mechanism for blockchain technology as well as specifically, the use of cryptocurrency trading and/or public governance, were excluded. The screening phase resulted in elimination of 274 research papers, and 4 grey literature papers. Of the remaining 268 research papers, each underwent a full-text evaluation to ensure sufficient technical detail; 22 of those were eliminated due to low-quality, and lack of validation metrics. A total of 246 manuscript documents made up the final data set for this study as shown in (fig.1).

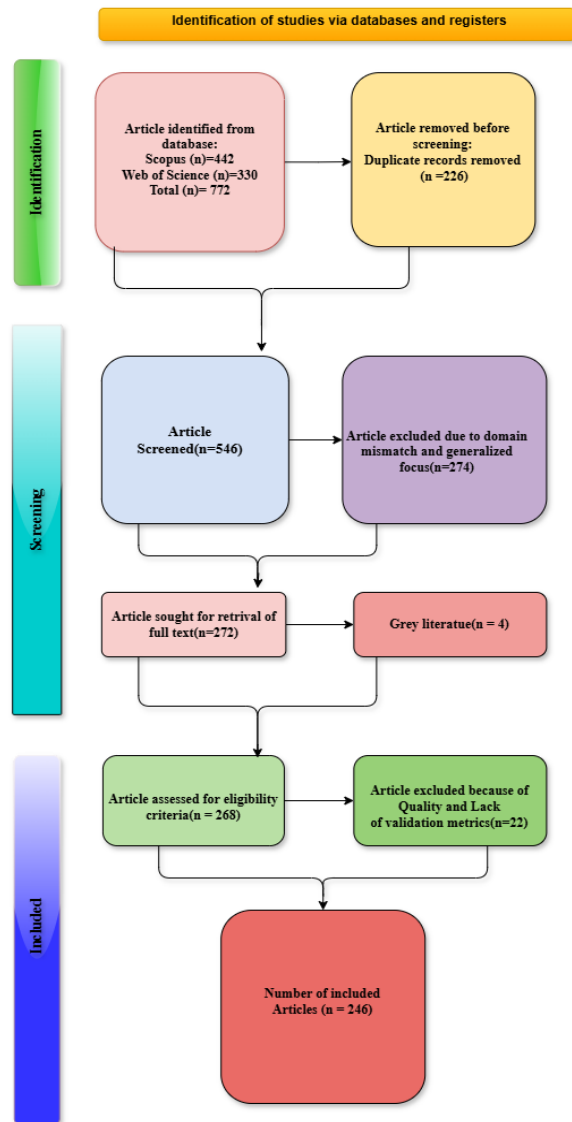


Fig 1. PRISMA Flow Diagram

Table 1 Database Search Strategy and Filtering Criteria

Database	Search Query / String	Parameters & Filtering Criteria
Scopus	TITLE-ABS-KEY (("blockchain*" OR "distributed ledger" OR "smart contract*" OR "consensus mechanism*" OR "consensus protocol*") AND ("e-commerce" OR "electronic commerce" OR "e-business") AND	Years: 2020– 2026 Document Type: Article (ar), Conference Paper (cp)

Database	Search Query / String	Parameters & Filtering Criteria
Web of Science(Core Collection)	(("supply chain*" OR "logistic*" OR "infrastructure")) AND PUBYEAR > 2019 AND PUBYEAR < 2027 AND (LIMIT- TO(DOCTYPE,"ar") OR LIMIT- TO(DOCTYPE,"cp")) AND (LIMIT- TO(LANGUAGE,"English")) TS=(("blockchain*" OR "distributed ledger" OR "smart contract*" OR "consensus mechanism*" OR "consensus protocol*") AND ("e-commerce" OR "electronic commerce" OR "e-business") AND ("supply chain*" OR "logistic*" OR "infrastructure"))	Language: English Years: 2020– 2026 Document Type: Article, Proceeding Paper Language: English

4.2 Bibliometric Software and Framework Modeling Approach

The robust metadata for the 246 completed records that were extracted with PRISMA which included cited references, authors' keywords and institutional affiliations was exported from PRISMA as a BibTeX file. The quantitative bibliometric mapping of the data was conducted using two software tools: Bibliometrix R-package (utilizing the Biblioshiny web interface) and VOSviewer.

The VOSviewer was used to create and represent spatial networks such as country collaboration networks and representations of keyword clusters based on the occurrences of keywords together. These representations utilized fractional counting to normalize document weights where there were multiple authors (Kuzior and Sira 2022). Science mapping was done by exporting all of the metadata (authors, affiliations, citation information, and keywords) after retrieval and deduplication. The VOSviewer software was used to map global collaborations (Section 5.2) and analyze co-occurrences among keywords (Section 6.1). A keyword threshold was applied (a minimum frequency

of five), reducing the 1,306 raw author keywords to 42 core nodes that were then grouped into clusters to visually represent the intellectual structure of IoT hardware convergence. A thematic evolution analysis was performed to show how author keywords changed over time during the years from 2020 to 2026. Empirical gaps and architectural barriers that were found using the quantitative mapping methods described above were then synthesized with data collected through qualitative research to help guide the design of the high-throughput conceptual framework proposed in Section 7.

5 Empirical Bibliometric Results

5.1 Macro Production Analysis and Growth Trajectory

As evidenced by the Annual Scientific Production Growth Chart as shown in Fig. 2(Annual Scientific Production), the trend of blockchain consensus architecture, e-commerce and logistics research is increasing at an exponential rate from 2020 through 2026. In addition, analyzing the last remaining pristine dataset consisting of 246 articles demonstrates that the scientific communities' focus has quickly transitioned away from peripheral theoretical explorations and toward foundational infrastructure development. Concurrently with this development, global e-commerce volume has grown significantly; therefore, the global footprint for malicious network actor attacks has also expanded. Therefore, researchers are now focused on using blockchain as not only a conceptual ledger, but as an integral architectural component for enhancing SCR against sophisticated cybercrime and data manipulation (Bayramova et al. 2021). The literature clearly demonstrates that there exists a pressing scientific need to transition from vulnerable data silos to tamper-resistant, distributed networks.

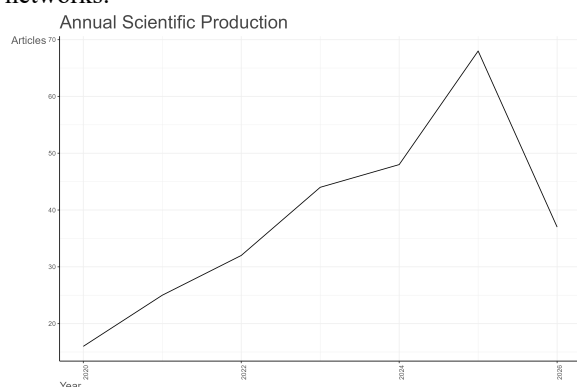


Fig. 2 Annual Scientific Production

The relationship between the current trajectory of increased production and the industrial transformation to both the industry 4.0 paradigm, and the developing Industry 5.0 principles based on resilience and humanity; represents an important opportunity for the

development of optimized Blockchain Consensus Protocols within Industry 4.0. These protocols have been studied for their ability to provide the necessary secured, low latency interoperability to support interconnection of IoT sensors, big data analytics and other related components(Werbińska-Wojciechowska and Winiarska 2023). As such, the clear indications of bibliometrics indicate that as e-commerce logistics continues to grow in size, it will continue to drive the increasing scientific need to resolve the Scalability-Security Tradeoff Trilemma associated with growing use of blockchain technology.(Chauhan and Rani 2026)

5.2 Global Collaboration and Institutional Network Analysis

Blockchain Logistics has now moved beyond speculative theoretical models to be applied as an actual architectural model. To accomplish this will require significant, cross-country resource mobilization. Analysis of the metadata of the manuscripts selected for inclusion using VOSviewer demonstrates that there is a strongly connected global research system. This is evident in the Spatial Country Collaboration Map (Fig.3 - Network Visualization) where of 65 countries identified, 22 countries were found to have had at least five papers published and grouped into seven unique collaborative networks. The visualization shows that the major structural components of the global research production are China, USA, India, and UK. While China is a large centralized node and has other countries grouped with it in cluster two (Canada, Australia, Hong Kong), this indicates an effort by the government to aggressively advance its domestic digital economy through integration of Blockchain and IoT technologies into very advanced manufacturing and logistics supply chains (Zhao et al. 2023; Kumar et al. 2022).

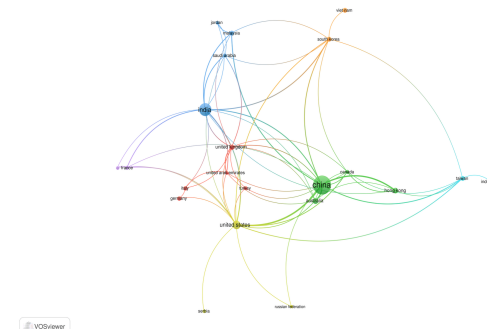


Fig 3. Spatial Country Collaboration Map (Network Visualization)

On the other hand, the European countries have a strong influence on leadership in terms of the UK, Germany and Italy (Cluster 1) that are well-established for their cooperative relationships with key countries in the Middle East such as UAE and Turkey. The high density of this Euro-Asia cooperation network is

strategic due to the fact that today's global supply chain networks operate globally across borders. Therefore it is critical for cross border industry and academia collaborations to develop common standards based architectures to mitigate cyber threats and operational interruptions (Bayramova et al. 2021). In addition to this, the map displays how newly developed or "emerging" economic systems are being integrated into the "core" development process. In example, India is a part of Cluster 3 and has ties with all three countries in Cluster 3 (Malaysia, Saudi Arabia and Jordan) showing its role as a part of an intra-cluster connection. This strong participation by these developing countries shows that large-scale digital platforms and high throughput consensus algorithms can be successfully tested and deployed on other than the traditional Western based research pipeline (Acosta-Prado et al. 2024). Ultimately, this high density of international clusters supports an understanding that blockchain scalability and digital integration will require continued, inter-organizational knowledge exchange to be resolved. The global pipelines being built will move us toward the next stage in transitioning isolated, black box concepts into a global, interoperable standard for infrastructure (Assimakopoulos et al. 2025).

5.3 Source Impact and Core Citation Structures

The concentration of publishing outlets according to Bradford's Law of Scattering suggests that there exists an extremely high degree of centralization among the journal outlets which drive discussions of Blockchain for e-commerce supply chain management. There is a strong presence of the most impactful articles in operationally-oriented journals as well as strategic technology adoption journals with a high degree of centralization to primarily two journals: The Transportation Research Part E: Logistics and Transportation Review and the International Journal of Information Management. These extremely high degrees of centralization suggest that the intellectual foundations of this area have become strongly established at the intersection of applied logistics, data governance, and strategic technology adoption (Teixeira et al. 2025; Cerchione et al. 2026).

Table 2 Top 10 Most Globally Cited Documents with Annualized Citation Frequencies

Paper	Total Citations	TC/Year	Normalized TC
(Dutta et al. 2020)	914	130.6	5.925
(Wamba and Queiroz 2020)	306	43.7	1.984

Paper	Total Citations	TC/Year	Normalized TC
(Liu et al. 2020)	247	35.3	1.601
(Cai et al. 2020)	229	32.7	1.485
(Kamble et al. 2021)	209	34.8	4.369
(Chittipaka et al. 2023),	205	51.2	6.885
(Makhdoom et al. 2020)	205	29.3	1.329
(Niu et al. 2021)	190	31.7	3.972
(Ren et al. 2020)	120	17.1	0.778
(Liu et al. 2021)	113	18.8	2.362

This body of research has a strong structural foundation based on a small number of highly cited papers. As seen in Table 2, (Dutta et al. 2020), was the first paper to create a citation base that would act as the central hub or "anchor" in this area of study, earning an unprecedented total of 914 citations (130.6 citations per year). In addition, it provided the initial structure for the integration of blockchain technology into supply chains, transitioning the field from speculative theoretical models to practical network designs. Next in line are (Wamba and Queiroz 2020; Liu et al. 2020); these two papers form the second tier of structural support and have been cited in excess of 550 times. These two papers bridge empirical data on supply chain performance with theoretical drivers of blockchain adoption. Finally, using NTC will expose the rate at which newer framework ideas are being developed. (Chittipaka et al. 2023) has demonstrated the greatest relative effect in this dataset (NTC = 6.88, with 51.2 references per year). The increased reference frequency is indicative of a rapid and up-to-date movement towards developing resilient models for supply chain disruption as well as mitigating its effects in new e-commerce systems in the wake of pandemic-related disruption (Mohammed et al. 2023; Radu et al. 2026). Similarly, (Kamble et al. 2021) also demonstrated strong NTC (NTC = 4.36), furthering the discussion on traceability, and smart contracts. Ultimately, it is the foundational works that are determining how the discipline will evolve. These seminal works provide the necessary theoretical frameworks which will be needed for transforming existing opaque and opaque supply chain systems to

develop transparent and decentralized supply chain systems that operate via algorithms (Elmatsani et al. 2026; Hübschke et al. 2025).

6. Thematic Evolution and Gap Identification

Transitioning from basic citation metrics to the conceptual foundation of the area, this part describes how the intellectual clustering in blockchain logistics was identified by using keyword co-occurrence networks; strategic thematic maps and longitudinal evolutionary diagrams. We then map these into research areas with significant gaps for the period 2020 through 2026.

6.1 Intellectual Clustering and IoT Convergence

In order to delineate the conceptual boundary of Blockchain Logistics and move from foundational citation-based metrics to thematic evolution a Keyword Co-Occurrence Analysis was performed. The Keyword Occurrence Network Graph (fig.4) illustrates that of the 1306 unique Author Keywords; 42 met the minimum number of occurrences of Five. The Refined Network clearly identifies the unique Intellectual Clusters primarily based on the convergence of Decentralized Ledger Technologies (DLTs) with Physical Hardware Architectures.

Resolving the "Oracle Problem" and Hardware Integration The most highly interconnected group of nodes in the graph shows how the Internet of things (iot), Radio Frequency identification (rfid), and Blockchain technologies can be integrated for a strong and efficient Supply chain. Traditionally the key vulnerability in all blockchain enabled supply chain networks was what is known as the "Oracle Problem". This refers to the process that occurs when physical items are logged into the Digital Ledger by hand. This creates a large bottleneck in both physically and digitally tracking goods (Dutta et al. 2020). A number of terms appear very frequently together, including "Smart Contracts", "RFID", and "Sensor Data Integrity", showing that researchers are working hard to develop ways of bridging the hardware-software gap. Autonomous Hardware Sensors, RFID Tags, etc., track movement of Physical Assets. Once an asset moves it automatically executes Smart Contracts which provide Real Time, Tamper Proof, Provenance of Data (Cai et al. 2020; Ren et al. 2020).

Traceability and Smart Contract Execution A single unit of a tightly linked sub cluster will be focused on providing end-to-end traceability and performing autonomously as an individual system. Directly integrating IOT sensor network into blockchain smart contract allows securing data integrity throughout physical environment and all the way through to the digital ledger (Kamble et al. 2021). Provenance tracking automation becomes the most important factor in improving overall performance of the supply chain. Hardware convergence has moved

out of theoretical speculation with real-world measurable operational improvements (Wamba and Queiroz 2020)

Big Data Analytics as a Mediating Layer

Furthermore, a secondary cluster illustrates how crucial big data analysis will be in the cyber-physical architecture. Nodes are near one another for "big data", "ecommerce" and "traceability", this shows that simply producing large amounts of unprocessed raw sensor data is pointless unless there is a means of advanced analytics to process high velocity input. As an example, in current logistics big data is used by parsing the enormous volumes of telemetry generated from Internet of Things (IoT) sensors. Blockchain technologies provide the means to ensure the security and auditable history of the resulting insight (Chittipaka et al. 2023; Liu et al. 2020; Talwar et al. 2021).



Fig. 4 Keyword Co-occurrence Network Visualization
Edge Computing, Latency, and Anti-Counterfeiting

The final step in our analysis shows how a new paradigm for networks will enable rapid acceleration from the periphery of a few key concepts ("edge computing", "real time monitoring" and "anti-counterfeiting") which are becoming increasingly important as the community moves toward decentralized local processing of data. Edge computing processes data from IoT sensors closer to where it was generated, dramatically reducing latency that hinders large-scale use cases with high throughput (Niu et al. 2021) while also providing real-time verified monitoring that enables effective anti-counterfeiting by blocking false information prior to recording it on an immutable blockchain-based ledger (Liu et al. 2021; Makhdoom et al. 2020). Together these results indicate that the academic discourse surrounding cyber physical systems have clearly moved toward practical applications, using the digital-physical tracking bottleneck as an opportunity to converge three major technologies: IoT sensors to automatically collect data, Big Data analytics to process collected data, and blockchain technology to create permanent records of transactions (Adamashvili et al. 2024; Etemadi et al. 2021).

6.2 Strategic Thematic Mapping and Longitudinal Shifts

To assess the level of thematic-maturity of the structure of blockchain technology in the context of supply chain-logistics, a strategic-diagram analysis was performed. The "Thematic-Strategic Diagram" (Fig. 5) illustrates an analytical approach to categorize the conceptual framework into four quadrants (Motor; Niche; Basic; and Emerging) based on keyword-density, and centrality. High-level concepts such as traceability and transparency have historically been dominant in the motor theme categories and thus were responsible for many of the initial adoption efforts in this area (Queiroz et al. 2020). However, strategic mapping indicates that basic traceability is now developing into a fundamental/basic theme. Consequently, the emerging motor themes are very specific technical constructs (e.g., smart contract algorithms; IoT hardware convergence; and performance metrics related to consensus mechanisms) which are directing the current direction of research (Lohmer et al. 2022). The proportionate distribution across these quadrants represents a matured field that has clearly transitioned from speculative theoretical development regarding supply chains, to applied design architecture and implementation-based frameworks.

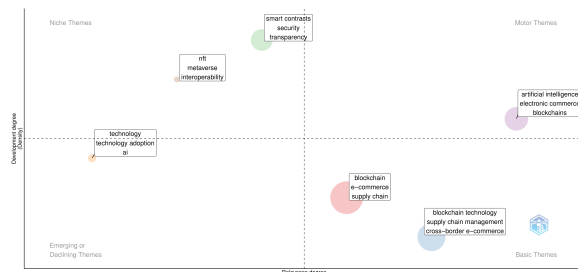


Fig.5 Thematic Strategic Diagram

Structural maturation is also demonstrated by a longitudinal examination of how keyword trends evolve over time during the 2020–2026 timeframe. According to the "Thematic Evolution Sankey Diagram", reproduced here verbatim as Figure 6, there has been a significant shift in the way that researchers have historically discussed the potential for Distributed Ledger Technology. In early literature, authors were very interested in the "Hype" around Blockchain as an idealized technological solution for supply chains that would be able to track products using decentralized methods, and ultimately provide a level of trust in transactions without needing third-party intermediaries (Qureshi et al. 2025). Throughout the longitudinal study period, the early general themes narrowed down and evolved into specialized disciplines related to the technical applications of Distributed Ledger Technology. The "Sankey Diagram" demonstrates how the broader conceptual

areas identified in earlier research studies provided a foundation for the development of advanced engineering techniques associated with optimizing blockchain systems, as well as the successful integration of earlier concepts with current technological solutions including Cyber Physical Systems, Interoperability Platforms, and Algorithmic Governance Models (Agrawal et al. 2023). The evidence in the literature supports the bibliometric transition from concept-based tracking to optimized engineering. Recent "state-of-the-art" frameworks are focused upon implementing smart contract technology to enable automated collaborative resource sharing, transaction validation, and mitigation of cyber security risks (Etemadi et al. 2020; Barbosa et al. 2022). Unlike previous applications that logged the history of products through their supply chains using only provenance, current solutions include algorithmic optimization for execution of smart contracts on public ledgers such as Ethereum, and/or tailoring Hyperledger Fabric architectures for use in complex logistics systems that span multiple borders (Dasaklis et al. 2022). Additionally, the long-term evolution of blockchain technologies has included an increased integration with both Big Data and IoT. The goal of this integration is to address the digital-physical bottleneck problem, i.e. verifying the authenticity of real-time sensor data inputs into a system, while reducing the adverse environmental impacts and high computational cost previously required to implement prior consensus algorithms (Qureshi et al. 2025; Lohmer et al. 2022).

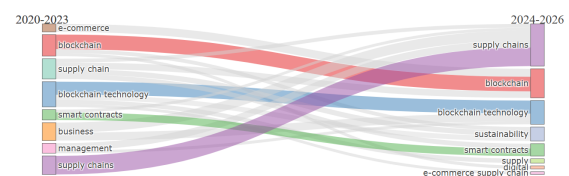


Fig.6 Thematic Evolution Sankey Diagram

Finally, as well, the latest evolutionary nodes for optimum blockchain technology are developing toward complex sustainability directions. The Thematic Mapping shows Smart Contract Logic is now being used in Closed Loop Supply Chain Systems and Circular Economy Frameworks specifically for the Agri-Food Industry (Dieguez-Santana et al. 2025). As a result, the industry has moved from just tracking products through an automated ledger system to creating an Algorithmic Enforcement System that can enforce multiple Tier Sustainable Development Goals (Dieguez-Santana et al. 2025). Therefore, both the Strategic Map and Longitudinal Streams confirm the Blockchain Logistics Domain has reached Structural

Maturity. The discussion has shifted from High Level Speculative Traceability to Rigorous Applied Engineering of Secure Interoperable and Sustainable Cyber Physical Systems.

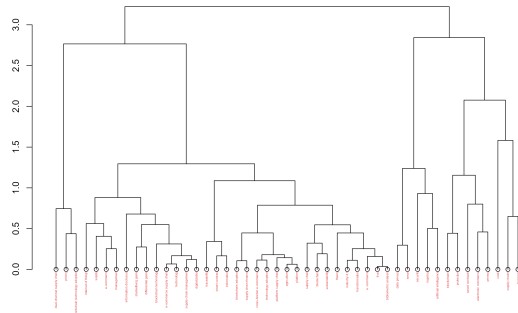


Fig. 7 Hierarchical Clustering Dendrogram of Core Thematic Nodes

To prove or disprove the theoretical limits of these seven clusters using a mathematical model, I created an HCD using MCA (multiple correspondence analysis) to create the dendrogram shown below (figure 7). The dendrogram shows how close in distance each of the theme groups are from one another, unlike a flat network visualization which simply displays the relationships between themes. The diagram also shows when in time the various groupings were first formed by showing how far apart they are on the tree; early branching shows a very close relationship between two particular terms ("smart contract" and "RFID") indicating that this relationship has been around for some time at the intersection of hardware and software. As you move further down the hierarchy, these individual sub-branching groupings merge together into larger, separate branches; thus, providing objective evidence to support the seven-cluster classification as observed in the network graph.

7 Proposed Conceptual Framework: High-Throughput Architecture

Our bibliometric study found that the $O(N)$ algorithmic bottlenecks can be resolved with the development of new, high-performance conceptual frameworks for cyber-physical supply chain management. The proposed framework is to utilize a bifurcation in an architecture that utilizes real-time trust evaluation to determine which network(s) will provide validated data. This provides secure routing of telemetry as well as near instantaneous $O(1)$ execution time for trusted transactions.

7.1 Synthesis of Extracted Bibliometric Bottlenecks

Although the Bibliometric Analysis in Section 5 illustrates a substantial move towards Applied Blockchain Engineering, the Literature simultaneously reveals a major Technical Barrier: that Consensus Mechanisms are unable to Scale for High-

Throughput Supply Chain Environments. The Main Architectural Bottleneck is the Algorithmic Complexity of Distributed Validation. Traditional Ledger Setups utilizing Standard Proof of Work (PoW), Broad Byzantine Agreements, etc. have Computational Overhead and Transaction Latency that scales Unfavorably with Network Size (Gu et al. 2023; Awan et al. 2022). These Mechanisms have an Inherent $O(N)$ Algorithmic Limitation; as the Number of Participating Nodes (N) increases, the Message Complexity, Validation Time and Storage Requirements all Grow Proportionally, ultimately resulting in System Congestion and Slower Processing Speeds (Sun et al. 2023).

The empirical assessment of previous approaches indicates that the major obstacle in terms of scalability limits the capability for integrating large volumes of high-velocity data streams including, but not limited to, real time IoT sensor telemetry, ERP transactions, etc. (Dasaklis et al. 2022). The extremely high volume of transactions generated by these types of networks will lead to a very significant overload of the traditional ledger leading to increased latency and a drastic increase in the cost of operations (Abiodun et al. 2024; Ellahi et al. 2023). Moreover, since every transaction is processed through the same $O(N)$ resource intensive validation pipeline regardless of the reliability of the node which submitted it, there is an artificially imposed limit on the system's throughput. Therefore, turning theoretical traceability into applicable real time logistics structures demands an immediate structural paradigm shift. To overcome this computational bottleneck, we need to transition from uniform network-wide consensus mechanisms to localized dynamic $O(1)$ execution pipelines.

7.2 Formal System Design and Dynamic Trust Routing Layer

To address the $O(N)$ time complexities of typical distributed ledger architectures presented in Section 7.1, as an alternative, scalable structural paradigm for achieving higher throughput is proposed. Rather than requiring every transaction from the supply chain to undergo identical network-wide validation procedures, a bifurcated model is introduced (see Fig. 8), which dynamically directs data flow (i.e., telemetry or smart contracts) using a self-governing Dynamic Trust Routing Engine, depending upon the submitting node's past history of reliability (Truong et al. 2021). The removal of a single, "one size fits all" consensus methodology reduces the burden of computationally verifying trusted cyber physical inputs. Additionally, integrating Multi-Agent Systems (MAS) within the routing layer allows decentralized coordination mechanisms to be employed, enabling the network to respond to changing supply chain topology

fluctuations while maintaining its scalability characteristics (Arévalo et al. 2025).

The Trust Oracle is a localised trust management system (TMS) that operates at the heart of this framework to autonomously assess node behaviour (Caldarelli 2022). As stated by (Liu et al. 2023), it is crucial that IoT networks have decentralised TMSs so they can identify malicious nodes and maintain secure and heterogeneous environments without being reliant on centralised verification bottlenecks. For each participant, the oracle calculates a continuous, dynamic trust score (T_s) based on previous metrics (veracity of sensors, rates of forwarding messages, latency of responses) to determine how trustworthy participants are. This process is governed by an operational logic represented within Table 3 which acts as the routing matrix for the framework. High trust scores are accumulated by nodes who act in accordance with honest behaviour; conversely, nodes that spread anomalous data or suffer delays when sending data will see their trust scores rapidly decrease, thus effectively segregate malicious participants from the majority of other network participants (Kaur et al. 2021). Any transactions sent by highly trusted nodes (i.e. $T_s \geq 0.85$) are routed into "Path A", a special, low-latency transaction pipeline. Due to the previously established reliability of these nodes, there is no computational need to force their data to pass through a global BFT agreement (Zhong et al. 2023). Therefore, Path A uses localised Smart Contracts combined with ZKP.

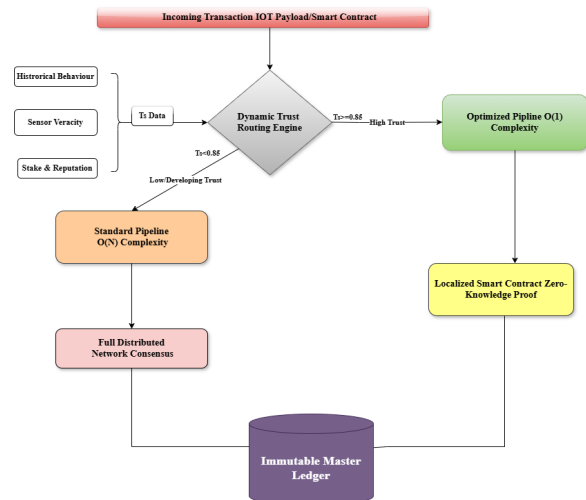


Fig 8. Architecture of the Bifurcated Conceptual Framework

It is proven in (Zhang et al. 2023; CR et al. 2025) how Zero-Knowledge Proofs enable a user to prove the integrity of a transaction to the entire network without having to reveal the underlying payload data for said transaction. The validation of the integrity of each

transaction is thus reduced to a constant amount of time which is defined as $O(1)$. Therefore, the $O(1)$ environment will provide the ability to rapidly process large amounts of IoT stream data. This means that the immutable and transparency of key agri-food or manufacturing supply chain traceability metrics can be maintained with no negative impact on the processing of transactions through the Master Ledger (Demestichas et al. 2020; Melesse and Orrù 2025).

Table 3- Trust-Based Routing Pipelines and Verification Complexity

Trust Tier	Score Range (T_s)	Routing Assignment	Computational Complexity	Verification Mechanism
Tier1 (High Trust)	$0.85 \leq T_s \leq 1.0$	Direct $O(1)$ Pipeline	$O(1)$ (Constant Time)	Localized Smart Contract / Zero-Knowledge Proof
Tier2 (Developing Trust)	$0.50 \leq T_s < 0.85$	Hybrid / Shared Route	$O(\log N)$ or $O(\sqrt{N})$	Partial Network Consensus / Committee Verification
Tier3 (Low/Zero Trust)	$0.20 \leq T_s < 0.50$	Standard Mainnet Pipeline	$O(N)$ (Linear Time)	Full Distributed Network Consensus (e.g., PBFT, PoW)
Tier4 (Malicious)	$T_s < 0.20$	Quarantine / Blocked	N/A (Transaction Dropped)	Flagged by Intrusion Detection System (IDS)

As clearly depicted in 2, The Trust Score T_s , determines the route that is to be taken through the Network. In doing so, it isolates $O(1)$ architectures from $O(N)$ pipelines, thus, it mitigates a large portion of the bibliometric bottleneck created as described in section 7.1

On the other hand, transactions generated by new (unverified), unknown (low-trust), or untested nodes ($T_s < 8.85$), will be sent to “path b,” the standard consensus path. The main difference in this path is that the default behavior of the system will be to operate in a completely trustless environment. For this reason, all of these messages require full validation using one of several multi-node consensus protocols used throughout the network in order to protect the integrity of the data (Zhong et al. 2023). As such, Path B will have the same $O(N)$ cost for sending messages as well as the corresponding latency. However, due to the fact that this pathway represents an essential cryptographic defense mechanism against intrusion and/or manipulation of the data produced by unverified entities (Abiodun et al. 2024); it does provide a means to isolate the energy consumption costs (and resulting carbon footprint) that were previously seen as barriers to widespread adoption of large-scale blockchains (Jiang et al. 2022). Additionally, by dynamically isolating the overhead associated with the $O(N)$ messages; there is no need for unverified nodes to incur these costs. Instead, once they generate successful transactions on Path B, their value of T_s increases over time until they qualify for the optimized $O(1)$ path (Truong et al. 2021). Therefore, this dynamically routing mechanism operates as a ‘Trust Building Machine’ in the Supply Chain Ecosystem (Yavaprabhas et al. 2023). By separating the computational workloads of the two paths, the proposed architecture separates the $O(N)$ consensus penalty into only those nodes at the edge of the network which are currently untrusted. At the same time, it allows honest participants to achieve $O(1)$ transaction finality. Thus, combining local execution with continuous trust assessment, creates a scalable and theoretically sound foundation able to accommodate high volumes of data as found in modern cyber-physical supply chain systems.

8. Discussion and Future Frontiers

This section provides a context to our proposal of the dual system of our framework by looking at it from the perspective of cyber-physical supply chain literature. We begin with an evaluation of the trust routing model for resolving the blockchain trilemma in industry. Then we will analyze the social technological aspects of this architecture, and show that this architecture is aligned with SDG 9.

8.1 Overcoming the Blockchain Trilemma in Industry

The need for extreme flexibility to handle extremely large, constantly changing volumes of orders and very high frequency data flows in smart e-commerce logistics is a major driver of the required extreme agility (Kalkha et al. 2023). In addition to providing the ability to provide significant levels of traceability and security via distributed ledger integration, such an integration also presents a critical structural limitation referred to as the blockchain scalability trilemma. The blockchain scalability trilemma is defined as the fact that all decentralized networks are limited by their inherent inability to provide simultaneous, maximum degrees of scalability, security and global decentralization (Pennino et al. 2022). As a result of this trilemma, standard homogeneous blockchains are severely constrained by transaction latency and low throughput making these systems inadequate for the real time needs of dynamic e-commerce supply chains (Vilkov and Tian 2023; Gurzhii et al. 2022). According to (Dasaklis et al. 2022), forcing large amounts of industrial data into standard on-chain consensus mechanisms results in significant network congestion which ultimately requires alternative architectures that can support both high performance and strong cryptography.

The bifurcated architecture presented in this research effort is designed to structurally resolve the scalability bottleneck in IIoT applications by replacing a fixed and single consensus model with a flexible routing-based trust model. Achieving scalable performance in IIoT applications will require the use of dynamic optimization techniques that allow for continuous trade-offs between throughput, latency, security and decentralization (Liu et al. 2019). However, when trusted interactions have relaxed requirements for global decentralization, the architecture allows for significantly increased processing speeds without compromising total system integrity.

More specifically, the path a dynamic routing layer validates through lightweight constant time execution pipelines validated telemetry. In this way, the local processing enables the same level of scalability as that achieved using off-chain scaling techniques and therefore eliminates both network congestion and the large amounts of computation needed when running a global consensus algorithm (Pennino et al. 2022; Dasaklis et al. 2022). Meanwhile, the path b ensures the integrity of volatile/unknown data feeds, by validating each feed with other peers within the network, which ultimately ensures that the basic security of the network has never been compromised. Overall, it demonstrates an application of advanced optimization techniques (Liu et al. 2019) that shows how the blockchain trilemma can be solved in practical

applications of logistics. The architecture successfully separates computational delays from untrusted peripheral networks while providing the necessary level of safety for digital transformation (Gurzhii et al. 2022) along with the increased transaction speed of modern ecommerce (Kalkha et al. 2023).

8.2 Socio-Technical Alignment with Sustainable Industrialization (SDG 9)

The bifurcated, high-performance structure of the new system developed in section 6 is a major social technological component to support the realization of Sustainable Development Goal 9 (SDG 9) which is focused on promoting sustainable industrialisation and developing resilient infrastructures. According to (Jiang et al. 2022) Blockchain provides the foundation upon which SDG 9 can be achieved through providing secure automation of industrial processes and facilitating the creation of transparent, cyber resilient industrial systems. In order to create these types of resilient systems; modern supply chain architectures must have seamless integration capabilities to enable real time IoT telemetry without data silo's or significant latency issues. Directly addressing this need is our real-time $O(1)$ execution pipeline. Consistent with this finding is (Takawira and Duri 2026) who demonstrated how effectively combining IoT with blockchain enables raw data visibility to become a measurable and verifiable form of computational trust.

In addition to improving performance in regards to latency, distributed ledger technology also improves the Key Performance Indicators (KPI's), which are necessary for a strong supply network. As (Marinagi et al. 2023) stated, using a variety of new technologies such as blockchain increases a company's resilience by increasing KPI's such as visibility, agility and secure information exchange. The verification of telemetry is processed instantly, so the proposed framework can provide real-time regulatory compliance and auditing automatically. Through ongoing data integrity the proposed framework will mitigate endogenous risk in supply chains, therefore; companies will be able to quickly identify and eliminate fraudulent activity, counterfeit products and cyber attacks (Rauniyar et al. 2023). According to (Ellahi et al. 2023) as well as others, by utilizing both decentralized ledgers and IoT based systems it creates an unalterable and transparent audit record that clearly shows accountability of all parties involved within a large scale business relationship. Ultimately, the architecture, through resolution of the typical hindrance to decentralized ledgers of algorithmic latency, provides a high-velocity digital base for all of modern industry. The architecture is able to reconcile performance requirements with the socio-technical aspects of SDG 9 (build resilient infrastructure),

providing an applicable model for sustainable supply chain transparency and fraud-resistance in a highly resilient manner.

9. Conclusion

This paper analyzed theoretically proven e-commerce supply chain application concepts (proofs-of-concepts) using blockchain technology as they are converted into actual business use cases for scalable applications. We demonstrated how our answers to the research questions helped us map the overall structural maturation of this domain. In answering RQ1, our bibliometric analysis clearly showed an exponential increase in activity between 2020 and 2026 that indicates a significant transition away from purely theoretical proofs-of-concept toward practical application of cyber-physical systems through blockchain. In answering RQ2, we were able to identify a densely connected international collaborative structure among countries including China, the United States, India, and the United Kingdom which is driving the development of these technologies at an accelerated rate. Development of applied technical models was key here. Regarding RQ3 thematic mapping showed a decisive pivot: literature has matured beyond generic discussions of traceability and now prioritizes specialized consensus architectures and convergence of IoT hardware along with empirical benchmarking performance. Regarding RQ4, friction in algorithms, latency of data and the trilemma of scalability emerged as defining unresolved bottlenecks for future smart logistics infrastructure. To overcome these limitations this paper proposed a novel hybrid architecture bifurcated that uses Dynamic Trust Routing Engine. Routing trusted telemetry through localized $O(1)$ pipelines and restricting heavy $O(N)$ consensus to unverified data resolves scalability trilemma. Despite these contributions this study has specific methodological limitations. The bibliometric dataset was derived solely from the Scopus and Web of Science databases. This has provided a highly credible set of peer reviewed sources but has by definition excluded important gray literature and corporate whitepapers that may be proprietary or un-indexed industrial pilot reports. Future research is needed to empirically test the proposed hybrid approach. We recommend using discrete event simulation modeling to test the proposed architecture with high frequency ecommerce data streams. Simulation parameters for discrete event models would need to include, stochastic transaction arrival rate (to simulate volatile OMNI-CHANNEL traffic) as well as dynamic variables which affect the decay of trust scores, localized execution queue lengths and comparative latency in achieving consensus. These empiric tests will clearly

demonstrate the systems ability to provide continuous support for Smart Logistics.

10. Declarations

- **Author contribution:**
R.Y.: Conceptualization, Methodology, Investigation, Data Curation, Formal Analysis, Visualization, Writing - Original Draft. **P.D.:** Supervision and Project Administration, Review & Editing. **S.U.:** Validation, Formal Analysis, Writing - Review
- **Funding:** This research received no external funding.
- **Conflicts of Interest:** The authors declare no conflicts of interest.
- **Data Availability Statement:** No new data were created or analyzed in this study.

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