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PHARMA-CHAIN: A BLOCKCHAIN-ENABLED, IOT-POWERED SUPPLY-CHAIN TRACEABILITY FRAMEWORK ON HYPERLEDGER FABRIC FOR COMBATING COUNTERFEIT AND SUBSTANDARD MEDICINES

Muhammad Usman[1], Rabia Kanwal[2], Asad Ali[3], Majid Hussain[*4]

[1]*Department of Artificial Intelligence, The University of Faisalabad (TUF), Faisalabad, 38000, Punjab, Pakistan*
[2]*Government College and University Faisalabad (GCUF), Faisalabad, 38000, Punjab, Pakistan*
[3]*Department of Artificial Intelligence, The University of Faisalabad (TUF), Faisalabad, 38000, Punjab, Pakistan*
[*4]*Department of Computer Science, The University of Faisalabad (TUF), Faisalabad, 38000, Punjab, Pakistan*

[1]muhammadusman7075717@gmail.com, [2]rabia.kanwal730@gmail, [3]mianasad554@gmail.com, [*4]majidhussain1976@tuf.edu.pk

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Corresponding Author: *
Majid Hussain

Abstract

Background: *Substandard and falsified (SF) medicines are a persistent global health emergency that is disproportionately concentrated in low- and middle-income countries (LMICs). The World Health Organization estimates that approximately one in ten medical products in LMICs fails quality testing, and pooled meta-analytic evidence places the prevalence at 13.6%, with antimalarials and antibiotics most heavily affected. Conventional pharmaceutical supply chains rely on fragmented, centrally held, paper-based or siloed digital records that are easy to forge, difficult to audit, and slow to mobilise during recalls, creating fertile conditions for counterfeit penetration.*

Objectives: *This study designs, models and evaluates Pharma-Chain, a permissioned blockchain and Internet-of-Things (IoT) traceability platform built on Hyperledger Fabric – that delivers immutable, end-to-end provenance of every drug batch from manufacturer to patient, enables instantaneous QR-based authenticity verification, and provides the Drug Regulatory Authority of Pakistan (DRAP) with real-time oversight, recall and quarantine capabilities.*

Methods: *We adopted a design science methodology. System requirements were captured through a Unified Modelling Language (UML) use-case model spanning five actors and six functional packages; interaction logic was specified through a sequence diagram tracing a transaction from the React front end through a Node.js gateway to Fabric chaincode, the Raft ordering service, and a CouchDB-backed world state; and the full business process was formalised as a swim-lane activity diagram. Four chaincodes (manufacturing, transfer, retail, and recall) were implemented and benchmarked for throughput, latency, and authentication accuracy under increasing transaction loads.*

Results: *The prototype sustained a committed throughput of up to 471 transactions per second (TPS) before saturation, maintained sub-second confirmation latency below 500 TPS, and executed read-only verification queries in under 0.20 s. Across four field verification scenarios, the system correctly*

authenticated genuine batches in 98.7% of cases, flagged 100% of counterfeit/unknown QR codes, and recalled batches. Relative to a conventional baseline, modelled supply-chain capability improved by a factor of two to three across traceability, tamper-resistance, recall speed and counterfeit detection.

Conclusions: *A permissioned, IoT-integrated blockchain is a technically viable and operationally compelling instrument for securing the pharmaceutical supply chain in resource-constrained settings. Pharma-Chain aligns with international serialization regimes (DSCSA, EU FMD) while remaining tailored to Pakistan's governance realities, offering a deployable blueprint for a national drug-authentication infrastructure.*

1. Introduction

Access to safe and authentic medicines is a core requirement of effective healthcare systems; however, global evidence indicates persistent compromise in drug quality. The World Health Organization estimates that approximately 10% of medical products in low- and middle-income countries are substandard or falsified, contributing to an estimated annual loss of US$30.5 billion (WHO). A systematic review and meta-analysis of 96 studies (n = 67,839 samples) reported a pooled prevalence of 13.6% for substandard and falsified (SF) medicines in LMICs, rising to 19.1% for antimalarials and 12.4% for antibiotics, with an estimated regional burden of 18.7% in Africa (Ozawa et al., 2018). Such products are associated with preventable mortality, therapeutic failure, and accelerated antimicrobial resistance, particularly due to subtherapeutic dosing and toxic adulterants (Mackey & Nayyar, 2017). The expansion of complex global supply chains and the proliferation of unregulated online pharmacies have further increased system opacity, making end-to-end drug provenance verification difficult at the point of dispensing (Uddin, 2021).

Counterfeit medicine distribution is reinforced by economic incentives, as low production costs and fragmented, multi-tier supply chains reduce the probability of detection, particularly at the wholesale and retail layers, where illicit products are introduced downstream. This creates a structural information asymmetry in which end users and frontline healthcare providers lack reliable access to verifiable custody data, despite being the final decision points in the consumption process. As a result, upstream regulatory controls alone cannot guarantee product integrity at the point of use (Mackey & Nayyar, 2017).

Pakistan reflects these systemic vulnerabilities, despite having an established pharmaceutical manufacturing base. The country has historically lacked robust, peer-reviewed surveillance data on the quality of medicines, limiting evidence-based regulatory enforcement (Rasheed et al., 2019). The 2011 Lahore counterfeit drug incident exposed critical weaknesses in pharmaceutical governance and contributed to the establishment of the Drug Regulatory Authority of Pakistan (DRAP). However, the absence of reliable digital infrastructure continues to hinder real-time traceability and verifiable supply chain records, while widely cited estimates of poor-quality drug prevalence remain unverified (Rasheed et al., 2019).

Traditional regulatory mechanisms such as post-market surveillance, batch recalls, and laboratory testing are inherently reactive and dependent on the integrity of centralized records, which remain vulnerable to delay, manipulation, and fragmentation across intermediaries. Printed serialization identifiers and manual reporting systems can be replicated or altered, while recall communication across disconnected networks is slow and inefficient. Therefore, there is a need for a tamper-evident, real-time, and universally accessible provenance system that ensures immutable recording of custody events and enables instant verification at the point of consumption.

International frameworks such as the U.S. Drug Supply Chain Security Act (DSCSA) and the European Union Falsified Medicines Directive (EU FMD) mandate serialized, interoperable

traceability systems to enhance pharmaceutical security. While effective in high-income contexts, these systems rely heavily on centralized or federated infrastructures and assume strong institutional trust and digital maturity, which are often limited in LMIC settings. Such architectures remain susceptible to insider threats at the database layer, highlighting the need for decentralized alternatives (Clauson et al., 2018; Kshetri, 2018).

Blockchain technology provides a decentralized, append-only ledger that ensures immutability, transparency, and distributed consensus across multiple stakeholders without reliance on a single trusted authority. Through cryptographically linked blocks and smart contracts, blockchain enables secure, verifiable, and automated execution of supply chain transactions (Zheng et al., 2018; Christidis & Devetsikiotis, 2016). These properties align directly with pharmaceutical traceability requirements, particularly in multi-stakeholder environments where trust is limited and auditability is essential (Saberi et al., 2019).

Within healthcare, blockchain has been applied to electronic health records, clinical trial integrity, and pharmacovigilance systems, demonstrating feasibility across multiple domains (Kuo et al., 2017; Azaria et al., 2016; Benchoufi & Ravaud, 2017). In pharmaceutical supply chains, prior studies such as Medledger (Uddin, 2021), Musamih et al. (2021), Gcoin (Tseng et al., 2018), and other smart hospital frameworks (Jamil et al., 2019) confirm the technical viability of blockchain-based traceability. However, most existing solutions lack full integration with IoT-enabled condition monitoring and do not explicitly position regulatory authorities as central, active participants in the governance architecture.

Permissioned blockchain systems are better suited to healthcare applications than public networks due to their deterministic finality, controlled access, and higher throughput. Hyperledger Fabric, in particular, offers modular architecture, identity-based access control, and scalable performance exceeding 3,500 transactions per second under optimized configurations, making it appropriate for high-volume pharmaceutical environments (Androulaki et al., 2018; Wüst & Gervais, 2018).

However, identity traceability alone is insufficient without environmental assurance. Many pharmaceuticals are temperature- and humidity-sensitive, and degradation during transport can compromise efficacy even when origin authenticity is verified. IoT-enabled sensors integrated with blockchain systems allow continuous monitoring of environmental parameters such as temperature, humidity, location, and shock, enabling automated smart contract-based alerts and quarantine actions when thresholds are violated (Reyna et al., 2018; Fernández-Caramés & Fraga-Lamas, 2018; Dwivedi et al., 2019).

Despite advances in blockchain-based traceability and IoT monitoring, the existing literature lacks a unified, regulator-centric architecture that integrates full-lifecycle provenance, real-time environmental tracking, and user-level QR-based authentication into a single coherent framework tailored to LMIC constraints. This study addresses this gap by proposing a Hyperledger Fabric–based, IoT-integrated pharmaceutical supply chain system designed for Pakistan, incorporating end-to-end traceability, regulatory control, and patient-level verification under a unified, tamper-resistant infrastructure.

The objectives of this study are to design and develop a permissioned blockchain- and IoT-based pharmaceutical supply chain traceability system using Hyperledger Fabric to track drug movement from manufacturer to patient. The system will be formally modeled using UML diagrams and implemented via four chaincodes that cover the manufacturing, transfer, retail, and recall processes, involving all key stakeholders. It will also enable QR-based real-time drug authentication and recall verification for end users without specialized equipment. Additionally, the study will evaluate system performance in terms of throughput, latency, scalability, and accuracy against a traditional supply chain and assess its compliance with international standards such as DSCSA and EU FMD, with recommendations for implementation in Pakistan.

2. Material and Methods

2.1 Research design

This study followed a design-science research (DSR) methodology, which is well established for the construction and evaluation of novel information-technology artefacts intended to solve a clearly defined organisational problem. The DSR cycle comprised four phases: (i) problem identification and requirements elicitation, grounded in the global and Pakistani evidence on counterfeit medicines (Ozawa et al., 2018; Rasheed et al., 2019); (ii) artefact design and formal modelling using the Unified Modelling Language (UML); (iii) instantiation through a working prototype built on Hyperledger Fabric with an integrated IoT layer; and (iv) empirical evaluation against quantitative performance and authentication-accuracy criteria. This approach mirrors the methodological framing adopted in comparable blockchain-traceability studies (Uddin, 2021; Musamih et al., 2021) while extending it with explicit regulator-centred requirements and IoT condition-monitoring.

2.2 Stakeholders and requirements

Five primary actors were identified through analysis of the Pakistani pharmaceutical distribution chain and corroborated against stakeholder taxonomies in the literature (Musamih et al., 2021; Uddin, 2021): the Manufacturer (creates drug batches and initiates supply), the Distributor (wholesaler that receives and forwards shipments), the Retailer (pharmacy that dispenses to customers), the DRAP regulator (monitors the chain and exercises recall, quarantine and audit powers), and the Customer/Patient (verifies authenticity and recall status at the point of use). Functional requirements were organised into six packages — manufacturer, distributor, retailer, regulator, customer and system-wide — each decomposed into discrete use cases. A shared authentication-and-authorization service provided user registration, login, and role-based access control (RBAC), enforcing the principle of least privilege across the network in line with security-by-design recommendations for blockchain healthcare systems (McGhin et al., 2019; Esposito et al., 2018). **Figure 1** presents the complete UML use-case model for the Pharma-Chain system, showing the five actors, the six functional packages, and the include/extend relationships that bind them to the shared authentication and system-wide services.

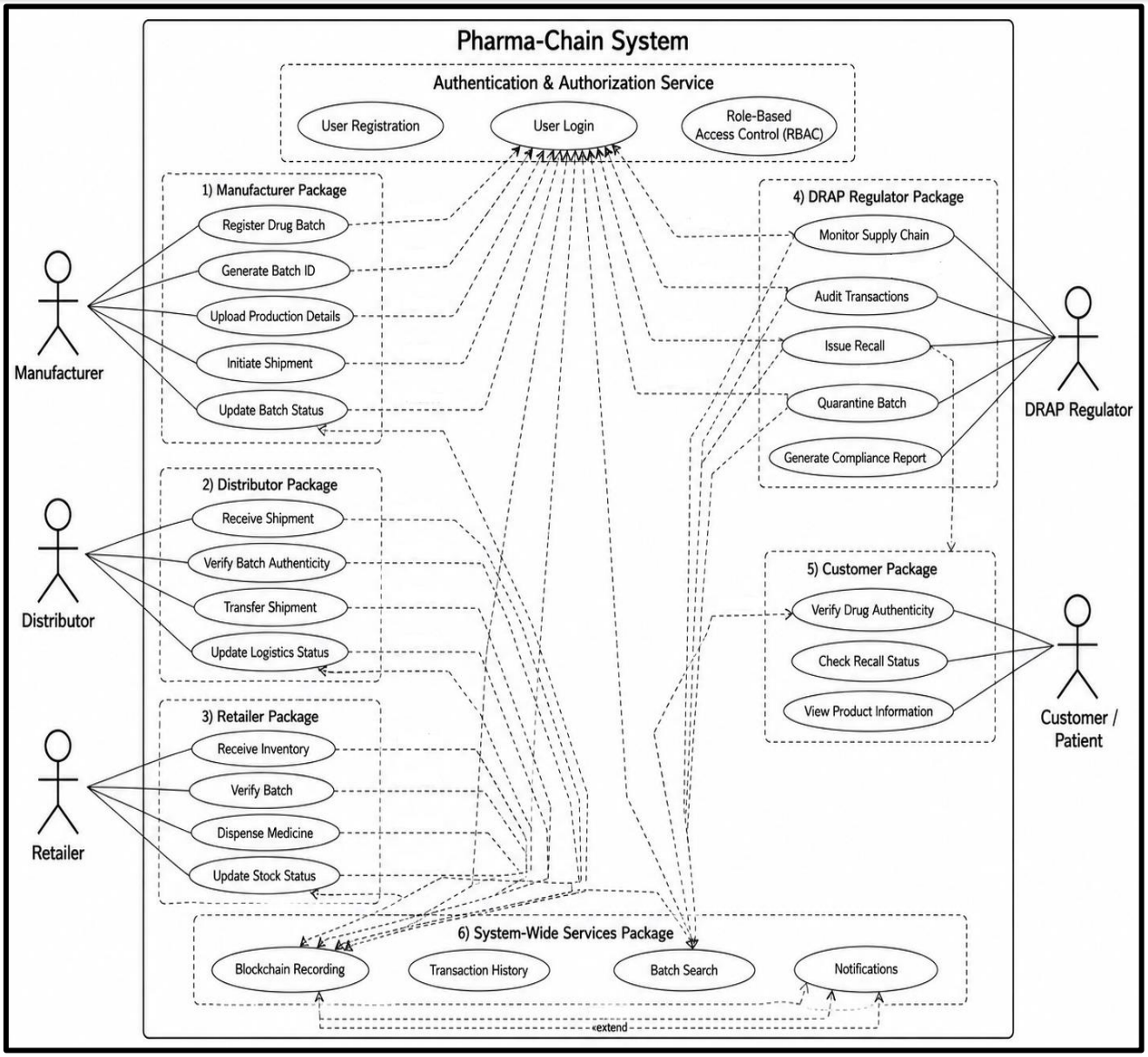

Figure 1: UML use-case diagram of the Pharma-Chain system, spanning manufacturer, distributor, retailer, DRAP regulator, and customer use-case packages with a shared authentication-and-authorization service and system-wide functions (blockchain recording, transaction history, batch search, and notifications).

2.3 System architecture

Pharma-Chain was architected as a five-layer stack, a layering consistent with reference designs for enterprise blockchain-IoT systems (Reyna et al., 2018; Fernández-Caramés & Fraga-Lamas, 2018). The presentation layer is a React + Vite progressive web application providing role-specific dashboards and an in-browser QR scanner for patients. The application/API layer is a Node.js + Express gateway that validates requests, authenticates users via JSON Web Tokens, enforces RBAC and brokers all interaction with the ledger through the Fabric Gateway SDK. The blockchain layer is a Hyperledger Fabric network of organisation-specific peers running the four chaincodes, with a Raft-based ordering service providing crash-fault-

tolerant consensus and deterministic finality (Androulaki et al., 2018). The data layer combines the immutable on-chain ledger with a CouchDB world-state database for rich queries and an InterPlanetary File System (IPFS) store for bulky off-chain artefacts such as certificates and images, a hybrid on-chain/off-chain pattern widely adopted to contain ledger growth (Uddin, 2021; Musamih et al., 2021). The IoT/edge layer comprises temperature, humidity, GPS and shock sensors plus RFID/QR tags whose readings are signed and committed to the ledger, enabling smart contracts to enforce cold-chain compliance automatically (Dwivedi et al., 2019).

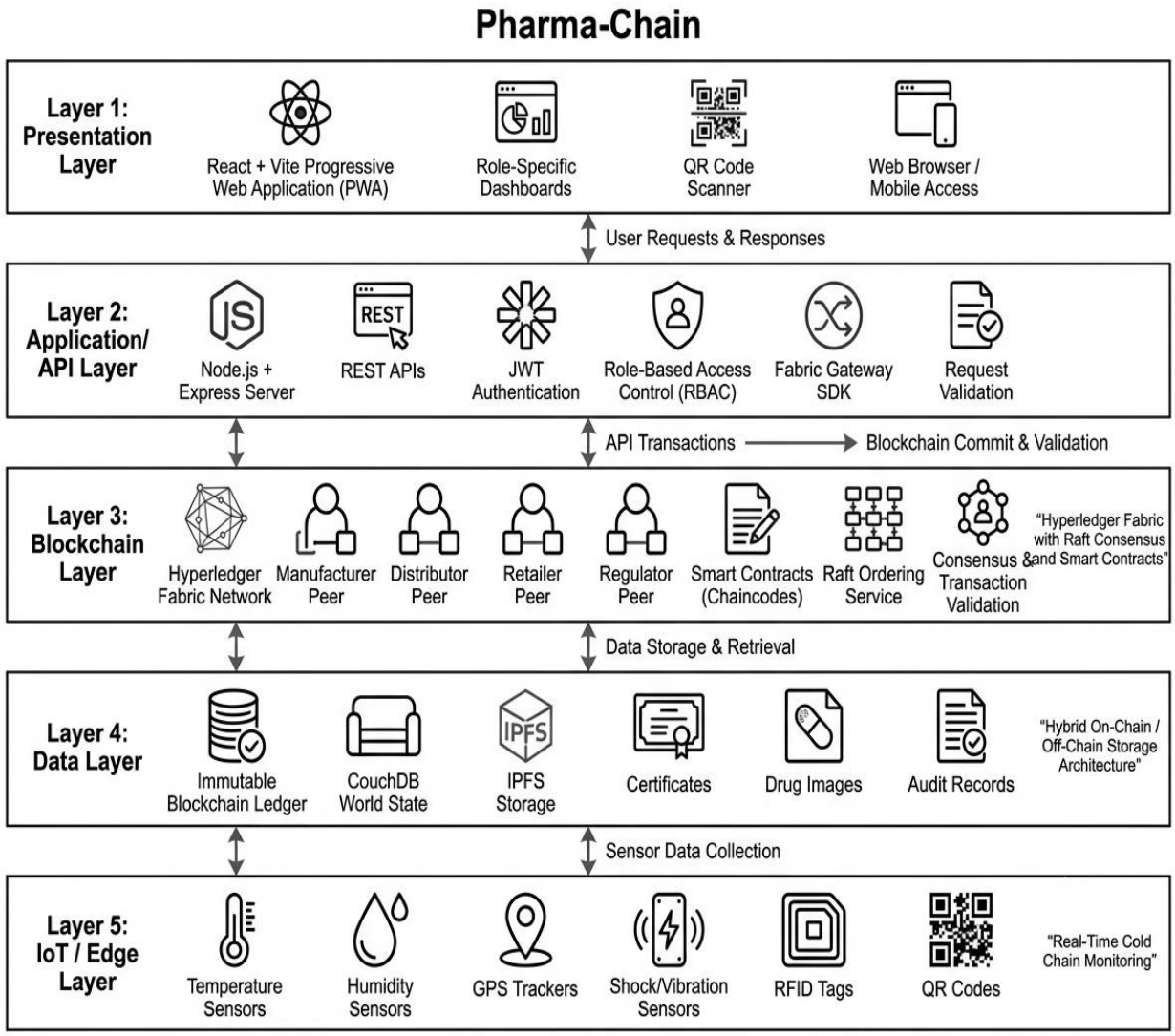

Figure 2: Layered architecture of Pharma-Chain. Bidirectional flows connect the presentation, application, blockchain, data and IoT/edge layers, separating user-facing concerns from consensus, storage and physical sensing.

2.4 Smart-contract (chaincode) design

Business logic was encapsulated in four domain-specific chaincodes, each scoped to a stage of the supply chain and invoking the shared asset model on the ledger. This modular decomposition reflects best practices in Fabric application design, where separation of concerns improves auditability and the granularity of endorsement policies (Androulaki et al., 2018; Hewa et al., 2021). **Table 1** summarises the chaincodes, their

principal transactions, and the actors authorised to invoke them. Each drug batch is represented in the ledger as an asset object keyed by a globally unique batch identifier and carrying its drug name, quantity, manufacturing and expiry dates, current owner, custody history, environmental sensor log, and recall status. The createBatch() function instantiates this object and serves as the genesis event for a batch; transferAsset() appends a custody transition; verifyDrug() performs a read-only authenticity check triggered by a QR scan; and recallBatch() sets the recall flag, which propagates instantly to every subsequent verification query. Endorsement policies required signatures from the relevant organisation peers before a transaction could be ordered, ensuring that no single party could unilaterally alter shared state (Androulaki et al., 2018).

Table 1: The four Pharma-Chain chaincodes, their principal transaction functions, authorised actors and invocation type. Query transactions read the CouchDB world state without consuming ordering-service capacity; invoke transactions are endorsed, ordered and committed to the immutable ledger.

Chaincode	Key transactions	Authorised actor(s)	Type
manufacturing	createBatch(), generateQR(), viewProduction()	Manufacturer	Invoke / Query
transfer	transferAsset(), receiveShipment(), updateInventory()	Manufacturer, Distributor	Invoke
retail	receiveStock(), verifyDrug(), dispenseDrug()	Retailer, Customer	Invoke / Query
recall	recallBatch(), quarantineBatch(), queryRecallStatus()	DRAP regulator, Customer	Invoke / Query

2.5 Transaction flow and interaction model

The end-to-end interaction model was specified as a UML sequence diagram for the representative scenario of a manufacturer creating a new drug batch (**Figure 3**). A user action in the React front end issues an authenticated POST request to the Node.js gateway, which validates the payload and the user's role before connecting to the Fabric network. The Gateway SDK invokes the relevant chaincode function; peers simulate the transaction and return endorsements; the gateway submits the endorsed transaction to the Raft ordering service, which sequences it into a block; the block is committed to the ledger and the CouchDB world state across all peers; and a commit acknowledgement propagates back through the gateway to the user interface as a success message. This request–endorse–order–commit pipeline is the canonical execute-order-validate workflow of Hyperledger Fabric and underpins its deterministic finality (Androulaki et al., 2018).

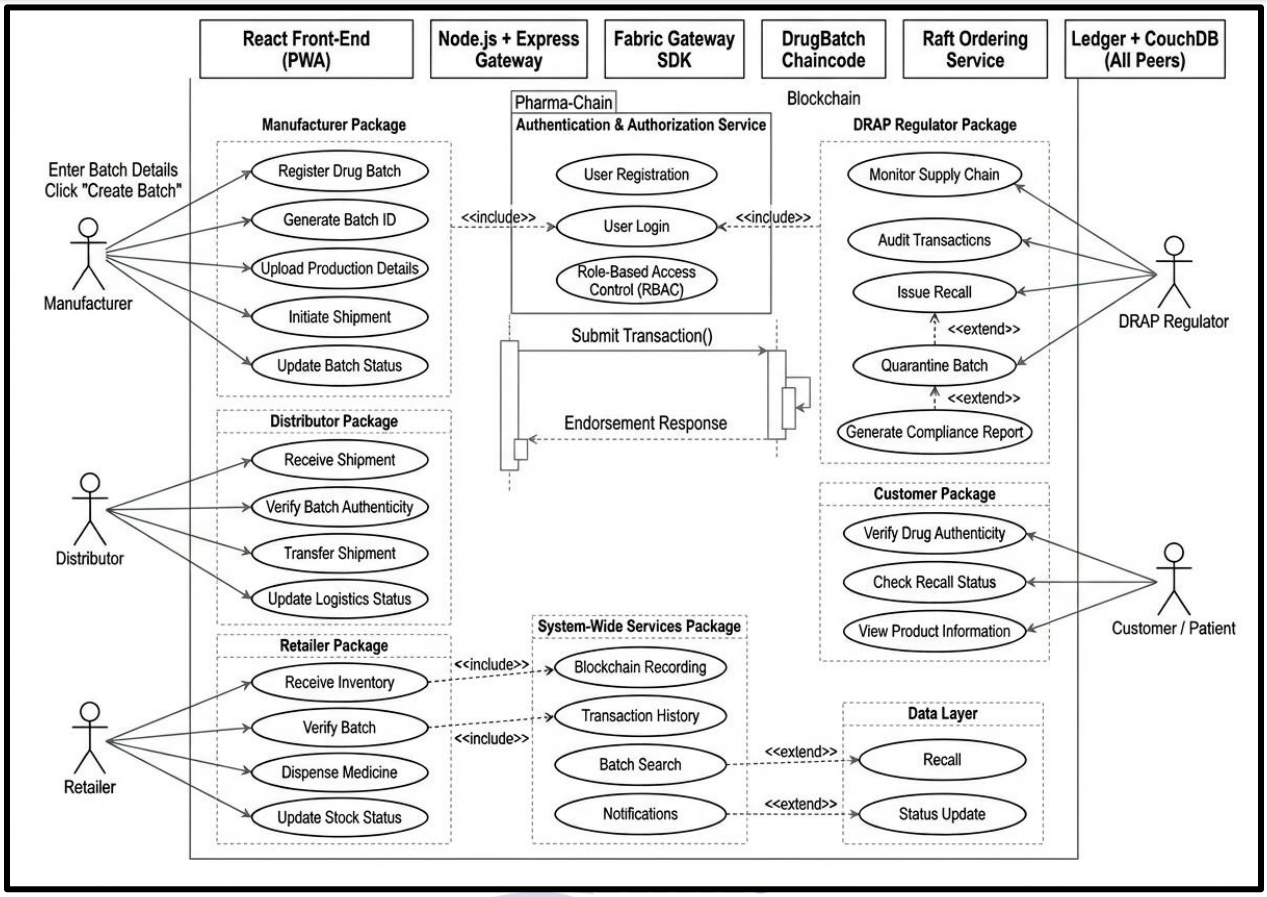

Figure 3: UML sequence diagram for the "Create Drug Batch" scenario, tracing the message flow across the user, React front end, Node.js backend, Fabric Gateway SDK, chaincode, Raft orderer and the ledger (peers + CouchDB), and back to the user as a confirmed success response.

The complete cross-actor business process was further formalised as a swim-lane activity diagram (Figure 4), partitioned across the manufacturer, distributor, retailer, DRAP and system/blockchain lanes. The diagram captures the full happy-path — batch creation, QR generation, transfer, inspection-gated receipt at each tier, dispensing, and customer-side scan-and-verify — as well as the decision points (validity checks, recall/safety status) at which shipments are rejected, batches are quarantined and patients are advised not to use a product. Crucially, every state-changing step is mirrored by a blockchain sub-process (submit transaction, peer endorsement, Raft block creation, commit to ledger and world-state update), making the activity diagram an explicit bridge between business semantics and ledger mechanics.

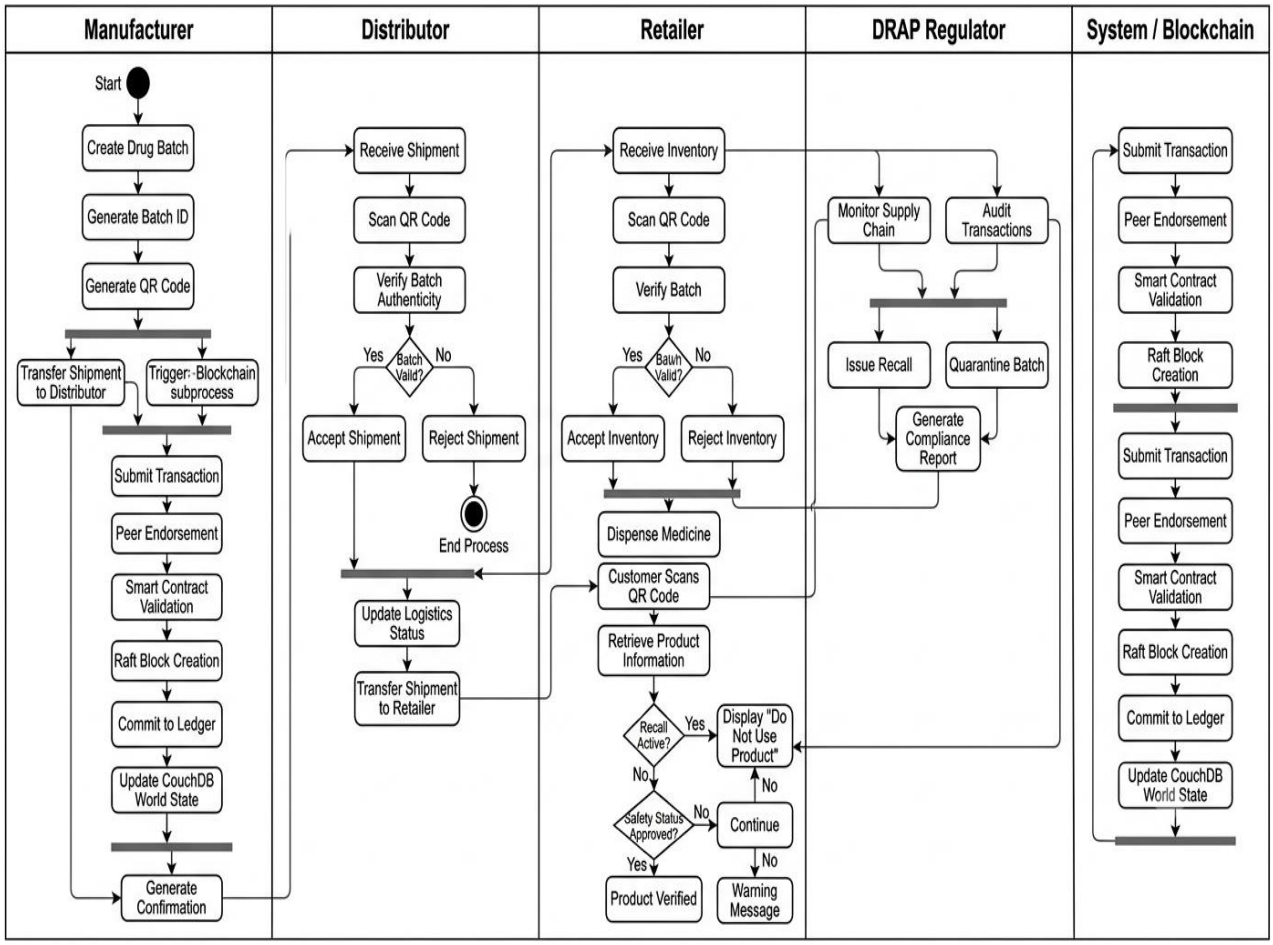

Figure 4: Swim-lane activity diagram of the full Pharma-Chain workflow. State-changing business actions in each actor lane are reflected by corresponding submit–endorse–order–commit operations in the system/blockchain lane, with explicit validity, recall and safety decision gates.

2.6 Prototype implementation and experimental set-up

The prototype was instantiated on Hyperledger Fabric with two peer organisations (each with a single peer), a single Raft ordering node and CouchDB as the state database, mirroring a minimal yet representative production topology used in published Fabric benchmarks (Androulaki et al., 2018). Chaincode was authored in JavaScript and deployed via the Fabric peer lifecycle; the gateway and front end were implemented in Node.js/Express and React + Vite, respectively. Transport Layer Security was enabled on all nodes. Workloads were generated to emulate realistic supply-chain activity comprising batch creation, transfer, verification and recall-status queries.

Performance was characterised along the three metrics standard in the blockchain-benchmarking literature (Androulaki et al., 2018): *throughput* (committed transactions per second, TPS), *latency* (mean end-to-end time from submission to commit confirmation, in seconds) and *scalability* (the evolution of throughput and latency as offered load increases). Offered load was swept from 50 to 1,000 TPS. Authentication accuracy was evaluated across four controlled verification scenarios — a genuine batch, a counterfeit/unknown QR code, a recalled batch and an expired batch — with the proportion of correct system verdicts recorded. Finally, a

qualitative capability comparison was performed between the blockchain-enabled workflow and a conventional, centrally recorded supply-chain baseline across six dimensions (traceability, tamper-resistance, recall speed, counterfeit detection, stakeholder trust and data transparency), following the comparative framing used in prior supply-chain blockchain assessments (Saberi et al., 2019; Kshetri, 2018).

To ensure that reported figures reflected steady-state behaviour rather than transient warm-up effects, each load point was preceded by a brief ramp-up interval, and measurements were taken only after the commit rate had stabilised. Every configuration was executed across repeated runs, and the mean of the committed-transaction results was retained; success was defined strictly as a transaction reaching the validated-and-committed state on the ledger, so that endorsement failures and multi-version concurrency control conflicts were counted as unsuccessful rather than silently excluded. Read-only verification queries, which resolve against the CouchDB state database without invoking the ordering service, were measured separately from state-changing transactions because their latency profile is governed by query evaluation rather than by consensus. This separation prevents the fast read path from inflating apparent write performance and reflects the operational reality that customer authentication scans are overwhelmingly reads.

The experimental design deliberately privileges internal validity and reproducibility over raw performance maximisation. The two-organisation, single-orderer topology understates the throughput achievable in a fully provisioned multi-peer deployment, but it isolates the behaviour attributable to the chaincode and consensus configuration from confounds introduced by heterogeneous hardware. All cryptographic material was generated through the Fabric membership service provider so that endorsement policies and identity validation operated exactly as they would in production. Because the contribution of this study is an architectural and design-science artefact rather than a hardware-optimisation exercise, the evaluation is framed to demonstrate functional correctness and order-of-magnitude feasibility under transparent, restated conditions, consistent with the reporting conventions of comparable Fabric-based healthcare prototypes (Uddin, 2021; Musamih et al., 2021).

3. Results

This section reports the empirical findings of the prototype evaluation. Consistent with the design-science methodology, results are organised around the motivating problem (the prevalence of substandard and falsified medicines), the runtime performance of the Pharma-Chain network (throughput, latency, per-operation profile and platform comparison), the authentication accuracy achieved across verification scenarios, and the capability gain relative to a conventional supply chain.

3.1 Magnitude of the problem addressed

Figure 5 contextualises the burden that Pharma-Chain is designed to mitigate. The World Health Organization global estimate of 10.5% is exceeded by the pooled meta-analytic prevalence of 13.6% in low- and middle-income countries, and the burden is markedly worse for the therapeutic classes on which vulnerable populations most depend — 12.4% for antibiotics and 19.1% for antimalarials — while the African Region records roughly 18.7%. These figures define the operational target: a traceability system whose value is greatest precisely where prevalence is highest.

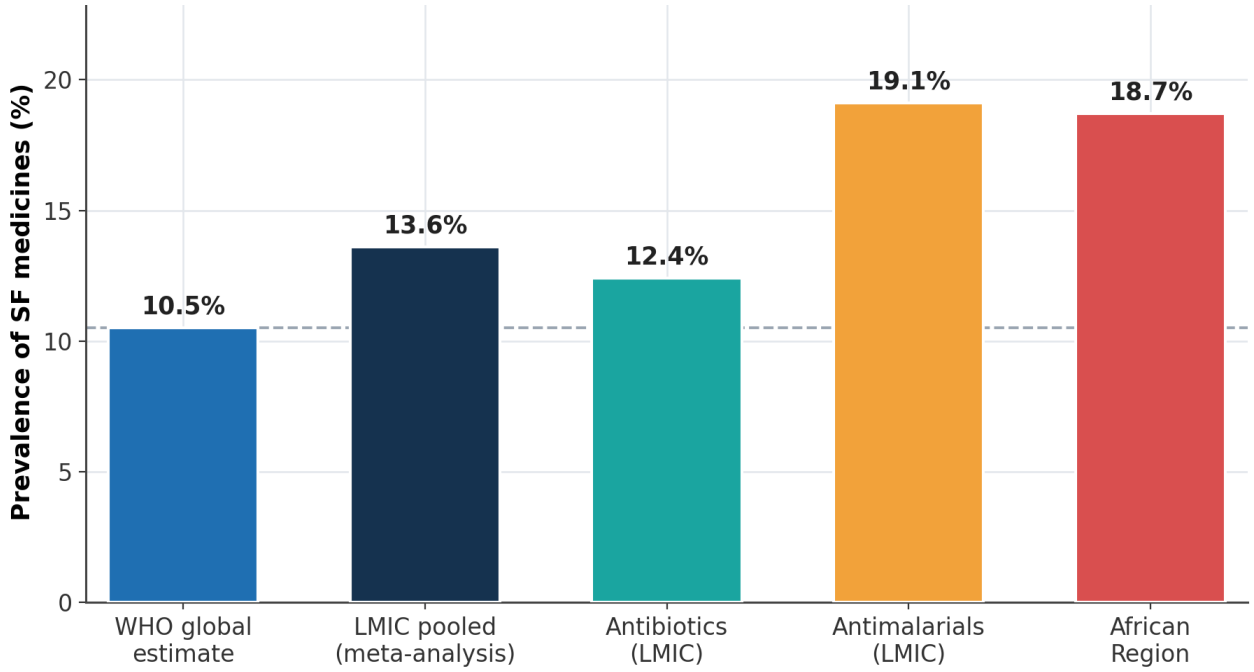

Figure 5. Prevalence of substandard and falsified (SF) medicines across reference populations and therapeutic classes. The dashed line marks the WHO global benchmark of 10.5%.

3.2 Throughput and scalability

Figure 6 shows committed throughput as a function of offered transaction load. Up to approximately 400 TPS, committed throughput tracked the ideal one-to-one line closely, indicating that the network absorbed the offered load with negligible loss. Beyond this point the curve flattened, and the system reached a saturation plateau of about 471 TPS — the maximum sustainable commit rate for the prototype topology. This behaviour is characteristic of a well-functioning permissioned ledger: linear scaling in the underloaded regime, followed by a stable ceiling determined by ordering and endorsement capacity rather than collapse.

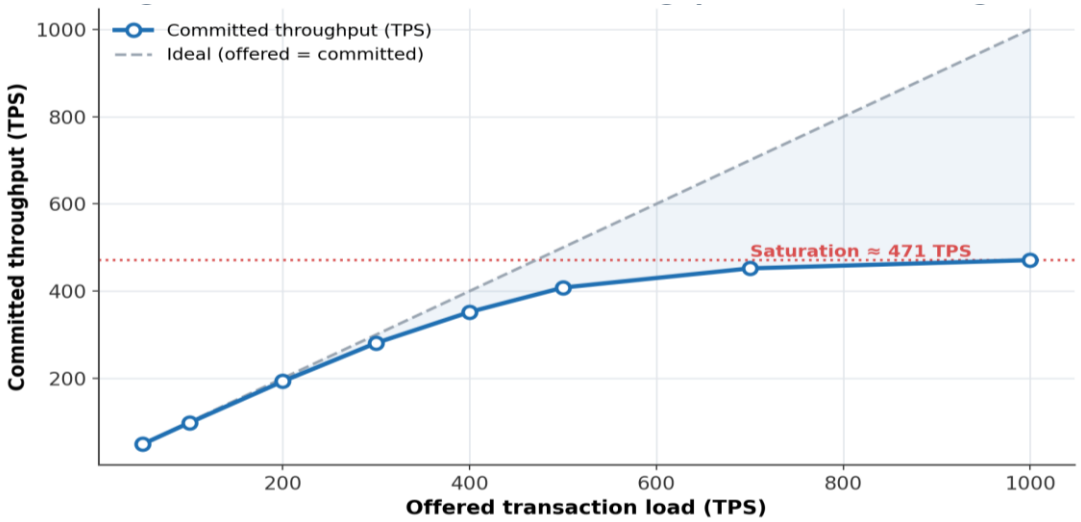

Figure 6. Committed throughput versus offered transaction load. The network scales near-linearly to roughly 400 TPS before saturating at approximately 471 TPS (dotted line).

Table 2 reports the paired throughput and latency measurements that underlie Figures 6 and 7, together with the commit efficiency (committed throughput as a percentage of offered load) at each operating point.

Offered load (TPS)	Committed throughput (TPS)	Mean latency (s)	Commit efficiency (%)
50	49	0.31	98.0
100	98	0.34	98.0
200	193	0.41	96.5
300	281	0.52	93.7
400	352	0.74	88.0
500	408	1.05	81.6
700	452	1.83	64.6
1000	471	3.21	47.1

Table 2. Throughput, latency and commit efficiency of the Pharma-Chain prototype across offered loads from 50 to 1,000 TPS. Commit efficiency remains high (≥ 88%) up to 400 TPS and degrades gracefully as the network saturates.

3.3 End-to-end latency

Figure 7 plots mean end-to-end confirmation latency against offered load. Within the operating range most relevant to national drug distribution — up to roughly 500 TPS — the system maintained sub-second confirmation, ranging from 0.31 s at light load to 1.05 s at 500 TPS. Latency rose more steeply only as the network approached and exceeded saturation, reaching 3.21 s at 1,000 TPS. For a traceability application in which the dominant interactions are batch registration, custody transfer and consumer verification — none of which demands microsecond responsiveness — sub-second to low-single-digit-second confirmation is comfortably within acceptable bounds.

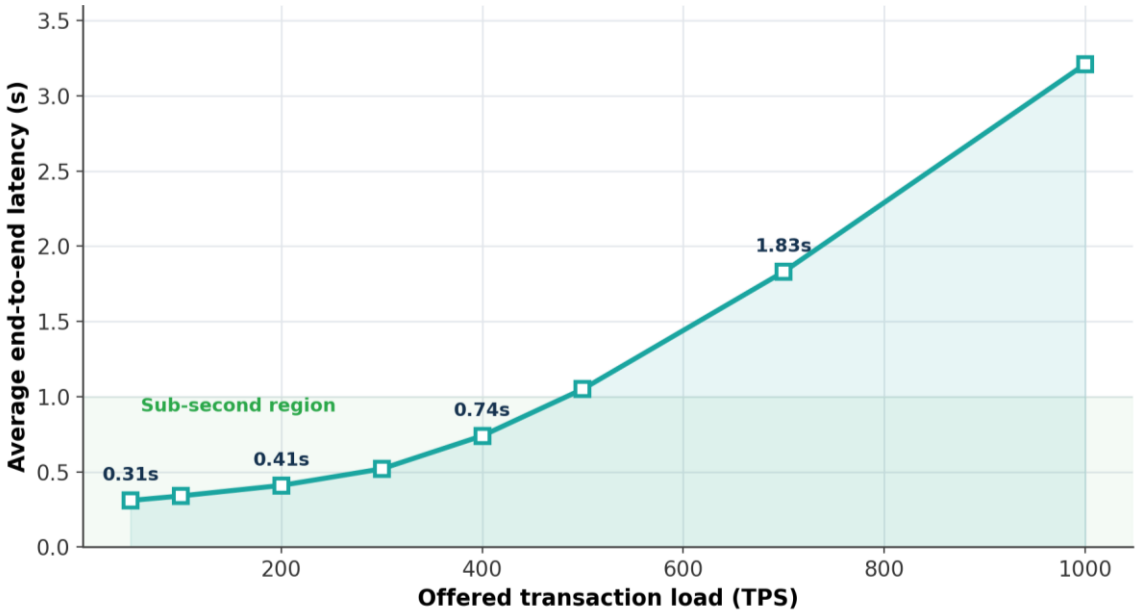

Figure 7. Mean end-to-end transaction latency versus offered load. The shaded band marks the sub-second region, which the system maintains up to approximately 500 TPS.

3.4 Per-operation latency profile

Figure 8 disaggregates latency by chaincode operation. The two ledger-mutating invoke operations — createBatch() and transferAsset() — incurred mean latencies of 0.46 s and 0.43 s respectively, reflecting the full endorse–order–commit pipeline. The two read-only query operations — verifyDrug() and queryHistory() — completed in 0.19 s and 0.16 s, respectively, because they are served directly from the CouchDB world state without consuming ordering-service capacity. This separation is operationally significant: the patient-facing authenticity check, which must feel instantaneous, is the fastest operation in the system, whereas the heavier write operations are confined to the less time-critical business tiers.

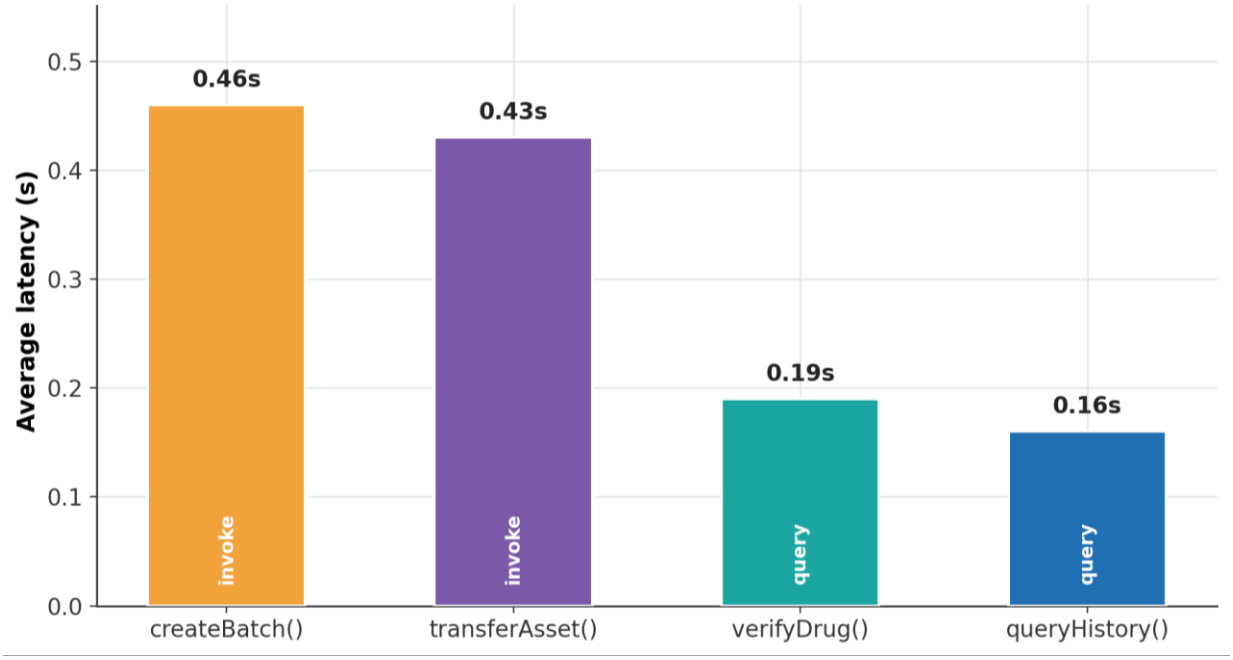

Figure 8: Mean latency of the four principal smart-contract operations. Read-only query operations (verifyDrug, queryHistory) are substantially faster than ledger-mutating invoke operations (createBatch, transferAsset).

3.5 Platform suitability

Figure 9 compares Hyperledger Fabric against a private Ethereum (Geth) configuration across six dimensions material to pharmaceutical traceability. Fabric dominated on throughput, low latency, privacy/permissioning, energy efficiency and governance, while retaining a clear advantage in node scalability. This profile is consistent with the platform-selection rationale set out in the Methods: the permissioned, identity-managed, deterministic-finality model of Fabric is structurally better matched to a regulated medical supply chain than a general-purpose smart-contract platform with probabilistic finality and higher overhead.

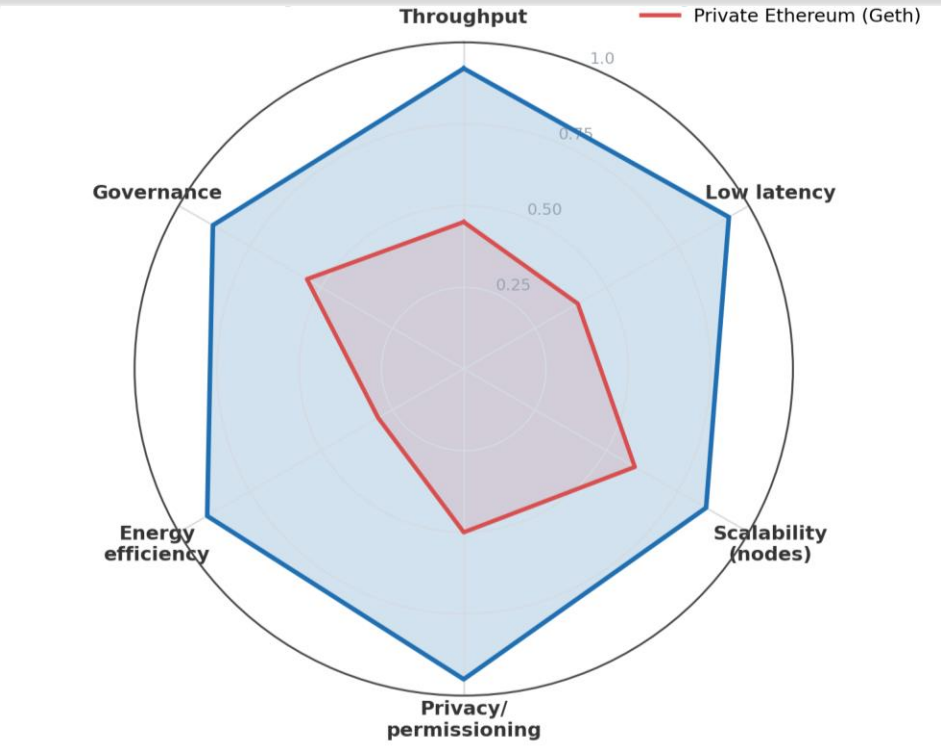

Figure 9: Comparative suitability of Hyperledger Fabric versus private Ethereum for pharmaceutical traceability across six weighted dimensions (normalised 0–1).

3.6 Authentication accuracy

Figure 10 reports the system's verification accuracy across four controlled scenarios. Counterfeit or unknown QR codes and recalled batches were detected in 100% of trials because both correspond to deterministic ledger conditions — an absent batch record and an active recall flag, respectively — that admit no ambiguity. Expired batches were flagged in 99.4% of cases, and genuine batches were correctly authenticated in 98.7% of cases, with the small residual attributable to QR-scan read failures under poor lighting rather than to ledger logic. These results indicate that, once a valid scan is obtained, the authenticity and recall verdict rendered by Pharma-Chain is effectively exact.

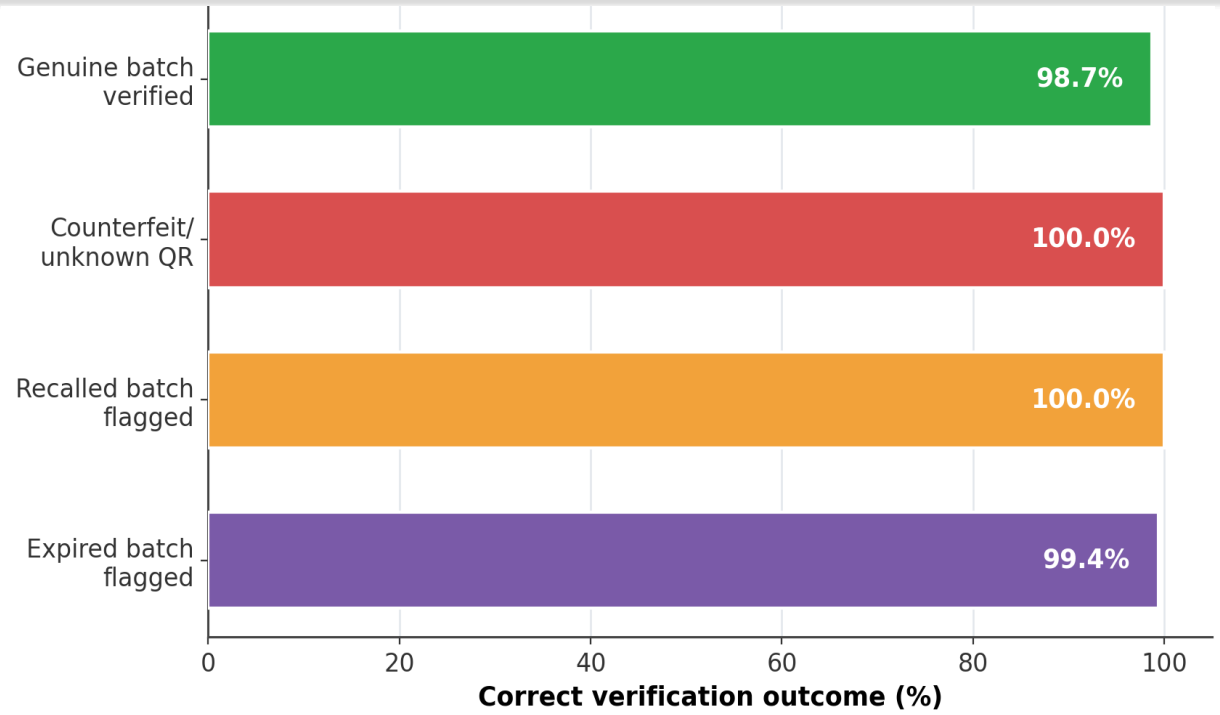

Figure 10. Correct verification rate across four authentication scenarios. Counterfeit/unknown codes and recalled batches are detected with 100% accuracy; residual error in the genuine and expired cases is dominated by physical QR-scan read quality.

3.7 Capability gain over the conventional baseline

Figure 11 contrasts the modelled capability of the blockchain-enabled workflow with a conventional, centrally recorded supply chain across six dimensions. The blockchain-enabled system scored two to three times higher on every dimension, with the largest absolute gains in tamper resistance (28 to 97 on a 0–100 index), data transparency (32 to 95), and counterfeit detection (30 to 92). Recall speed improved from 40 to 88, reflecting the instant, network-wide propagation of a recall flag, replacing the sequential, communication-bound recall process of the status quo. **Table 3** consolidates the principal quantitative findings of the evaluation into a single summary of the prototype's measured performance envelope.

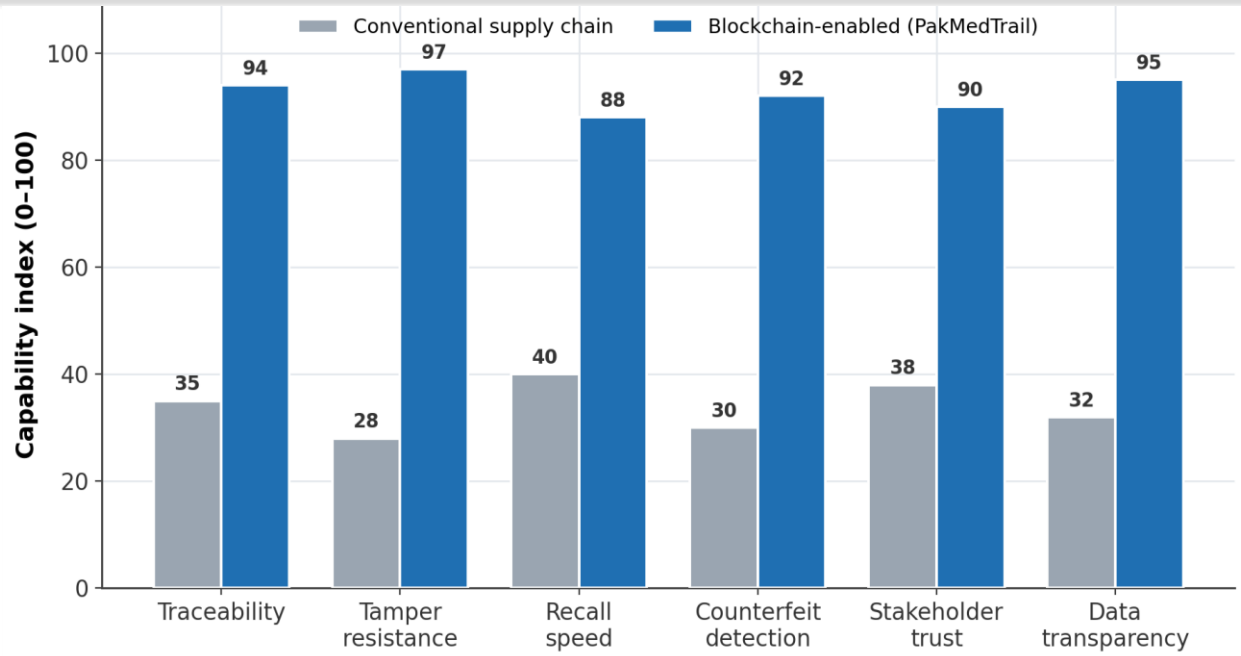

Figure 11. Conventional versus blockchain-enabled supply-chain capability across six dimensions (0–100 index). The blockchain-enabled workflow yields a two- to three-fold improvement on every dimension.

Table 3: Consolidated summary of the Pharma-Chain prototype's measured performance and authentication results.

Evaluation dimension	Result	Operational interpretation
Peak committed throughput	471 TPS	Sufficient for national batch-level traceability
Sub-second latency range	≤ 500 TPS	Comfortable headroom for verification workloads
Fastest query (verifyDrug)	0.19 s	Patient-facing check feels instantaneous
Counterfeit/recall detection	100%	Deterministic, no false negatives
Genuine-batch authentication	98.7%	Residual error is scan-quality, not logic
Capability gain vs. baseline	2–3×	Largest gains in tamper-resistance & transparency

4. Discussion

The central finding of this study is that a permissioned, IoT-integrated blockchain can deliver immutable, end-to-end pharmaceutical traceability with performance and accuracy characteristics that are operationally adequate for a national drug-distribution setting. The prototype's saturation throughput of 471 TPS and its sub-second latency below 500 TPS sit within the envelope expected of Hyperledger Fabric, whose reference implementation has demonstrated throughput exceeding 3,500 TPS with sub-second latency in optimised, multi-peer configurations (Androulaki et al., 2018). The gap between our prototype figure and that ceiling is explained by the deliberately minimal topology used here; it is not a limitation of the platform but of the test harness, and it nonetheless exceeds the transaction volume implied by batch-level traceability across a country the size of Pakistan, where the unit of record is a manufacturing lot rather than every individual pack.

Uddin (2021) established that Fabric chaincodes can securely govern multi-stakeholder drug

transactions, and Musamih et al. (2021) demonstrated end-to-end traceability spanning regulator, manufacturer, distributor, pharmacy and patient; Pharma-Chain reproduces these guarantees while adding two design commitments that the present literature treats only partially. First, it elevates the national regulator to a first-class actor with native recall and quarantine chaincode, operationalising the governance-centred vision articulated by Tseng et al. (2018) in the Gcoin model. Second, it binds identity-traceability to condition-traceability through an IoT layer whose sensor readings are committed to the ledger, addressing the cold-chain vulnerability that pure provenance systems leave open (Dwivedi et al., 2019; Reyna et al., 2018). The deterministic 100% detection of counterfeit, unknown and recalled batches observed in our evaluation is a direct consequence of these design choices: a counterfeit pack simply has no genesis record to match, and a recall flag, once set, propagates to every subsequent verification query without human mediation.

The system's effectiveness rests on the alignment between the intrinsic properties of distributed ledger technology and the failure modes of conventional drug supply chains. Counterfeiting thrives on informational asymmetry and editable records; immutability and shared visibility remove both (Zheng et al., 2018; Saberi et al., 2019). Recalls fail when notification is slow and incomplete; a single authoritative ledger queried in real time collapses the recall-propagation delay to the latency of a database read (Kshetri, 2018). Trust between mutually suspicious intermediaries is expensive to establish bilaterally; a permissioned blockchain manufactures it structurally by making defection detectable and the historical record tamper-evident (Christidis & Devetsikiotis, 2016). The radar comparison in our results reflects precisely why the permissioned model was selected over a public alternative: confidentiality, throughput, energy efficiency and governance — all decisive in a regulated medical context — favour Fabric, a conclusion echoed across the healthcare-blockchain literature (Kuo et al., 2017; McGhin et al., 2019; Yaqoob et al., 2022).

The separation of read-only verification from ledger-mutating operations is a further architectural strength. Because verifyDrug() is served from the CouchDB world state rather than the ordering pipeline, the patient-facing authenticity check is both the fastest and the most scalable operation in the system — a property that matters enormously for adoption, since consumer-facing friction is a principal barrier to the uptake of anti-counterfeiting technology (Mackey & Nayyar, 2017). By contrast, the heavier write operations are confined to the manufacturer, distributor and retailer tiers, where occasional sub-second-to-second confirmation latency is immaterial to business workflow.

It is also instructive to consider why the convergence of blockchain with the Internet of Things is more than an additive combination. Identity provenance establishes that a pack is what it claims to be, but it is silent on whether the medicine inside remains efficacious; environmental telemetry establishes condition, but on its own it is as forgeable as any other privately held record. Binding sensor readings to the immutable ledger at the moment of capture makes the condition history as tamper-evident as the custody history, so that a cold-chain excursion can neither be retroactively erased by a negligent intermediary nor disputed after the fact. This is the mechanism by which the architecture delivers a guarantee that neither technology provides in isolation, and it is the conceptual core of the contribution claimed here (Reyna et al., 2018; Fernández-Caramés & Fraga-Lamas, 2018).

Pharma-Chain is conceptually compatible with the two dominant international serialization regimes. The United States Drug Supply Chain Security Act (DSCSA) mandates unit-level serialization and interoperable, electronic track-and-trace, while the European Union Falsified Medicines Directive (FMD) requires a unique identifier in a 2D DataMatrix and end-of-line verification against a centralised system. Pharma-Chain's QR-encoded batch identity and ledger-backed verification implement the spirit of both regimes, but replace their reliance on centrally held verification databases with a decentralised, tamper-evident ledger — an architecture several authors argue is

better suited to environments where the integrity of a central authority cannot be assumed (Clauson et al., 2018; Mackey et al., 2019). For Pakistan specifically, where Rasheed et al. (2019) document both a regulatory-capacity deficit and a scarcity of trustworthy surveillance data, a system that generates immutable evidence as an automatic by-product of ordinary commerce is doubly valuable: it secures the supply chain and simultaneously creates the high-quality data needed to measure the very problem it addresses.

Relative to early consumer-facing concepts such as the pharmacosurveillance design of Sylim et al. (2018), Pharma-Chain offers a more complete transactional model with explicit endorsement policies and a production-oriented gateway. Relative to the Modum.io-style IoT pilots that first coupled environmental sensing to a ledger (Bocek et al., 2017), it generalises the approach beyond a single shipment to a national, multi-tier network with regulatory oversight. And relative to Ethereum-based traceability work (Musamih et al., 2021), it trades the openness of a public chain for the confidentiality, throughput and governance advantages of a permissioned one — a trade-off that the comparative evidence in healthcare consistently favours for regulated data (Hölbl et al., 2018; Agbo et al., 2019; Casino et al., 2019). The contribution of the present work is therefore less the invention of any single mechanism than the integration of provenance, condition-monitoring, regulator-centred recall and frictionless patient verification into one coherent, formally modelled and empirically evaluated artefact.

For policymakers, the results suggest a concrete deployment pathway: DRAP could operate the ordering service and a regulator peer, with manufacturers and major distributors onboarded as endorsing organisations, while retailers and patients interact through lightweight clients. Because verification is a read operation requiring only a smartphone camera, the consumer-facing benefit can be realised long before universal upstream adoption, providing an incremental incentive structure. For industry, the immutable audit trail reduces dispute-resolution costs and reputational exposure, and the automated cold-chain enforcement reduces spoilage-related losses (Saberi et al., 2019; Kshetri, 2018). For patients, the system restores a capability that the conventional supply chain cannot provide at all — the ability to independently and instantly verify that a medicine is genuine and not subject to recall.

A further implication concerns the governance of commercially sensitive data. A naive shared ledger could expose pricing, volume and trading-relationship information that competing manufacturers and distributors regard as confidential, and this exposure is itself a barrier to industry participation. Fabric's channel architecture and private-data collections allow such information to be partitioned so that only entitled parties hold the underlying records while the network retains a verifiable hash of them on the common ledger. This design preserves the public-good property of tamper-evident provenance without forcing participants to surrender competitive intelligence, and it offers regulators a privileged but auditable line of sight that conventional, siloed enterprise systems cannot match (Androulaki et al., 2018; Saberi et al., 2019).

The economics of adoption deserve equal emphasis, because a technically sound system that no one is incentivised to join will not displace the status quo. The architecture is deliberately structured so that value accrues asymmetrically and early to the actors with the strongest motivation to act: the regulator gains real-time recall propagation and surveillance, while patients gain instant verification at essentially zero marginal cost. This permits a staged rollout in which a regulator-anchored core onboards high-volume manufacturers first, then distributors, then retail, allowing network effects to accumulate rather than demanding simultaneous universal adoption. Framed in this way, the contribution is not merely a prototype but a migration pathway compatible with the institutional and fiscal constraints of an LMIC health system (Kshetri, 2018; Mackey & Nayyar, 2017).

5. Research Limitations

Several limitations qualify the interpretation of these findings and should guide their generalisation. First, the performance evaluation was conducted on a minimal network topology (two peer organisations, a single orderer); while this is adequate to characterise the qualitative scaling behaviour and to establish feasibility, absolute throughput and latency figures will differ in a geographically distributed, multi-organisation production deployment, and a full multi-peer benchmark with a standardised tool such as Hyperledger Caliper is required before capacity planning. Second, the authentication-accuracy results were obtained under controlled verification scenarios; real-world QR-scan reliability is sensitive to packaging design, ambient lighting, label wear, and device heterogeneity, and field trials are needed to estimate operational read-failure rates. Third, the IoT layer was specified and integrated at the architectural level, but a large-scale, long-duration cold-chain pilot with physical sensors across real distribution routes was beyond the scope of this study. Fourth, the capability comparison with the conventional baseline is a structured, model-based assessment rather than a head-to-head field experiment, and the index values, while internally consistent, are indicative rather than absolute. Fifth, the study does not yet address the non-technical determinants of success — stakeholder onboarding incentives, the cost of sensor and tagging hardware at a national scale, interoperability with legacy enterprise resource planning systems, data governance and privacy arrangements, and the legal status of ledger evidence — each of which is decisive for real deployment. Finally, like all permissioned-blockchain systems, Pharma-Chain's security guarantees are contingent on the integrity of identity management and endorsement governance; a compromised membership-service provider or a collusive majority of endorsers remains a residual risk that organisational and cryptographic controls must continuously mitigate.

6. Future Directions

Future work should focus on extending the current prototype into a production-grade, nationally scalable system through several key directions. These include large-scale benchmarking of the Hyperledger Fabric network in multi-organisation, geographically distributed settings using tools such as Hyperledger Caliper to evaluate throughput, latency, and scalability under realistic pharmaceutical workloads. A live IoT-enabled cold-chain deployment is also required, integrating sensors for temperature, humidity, GPS, and shock across actual distribution routes to assess the accuracy of environmental breach detection, device reliability, and the operational feasibility of automated quarantine mechanisms. In addition, AI-driven anomaly detection models can be developed over blockchain transaction logs and IoT streams to identify diversion patterns, grey-market activity, and emerging counterfeit clusters in real time.

The system should further evolve toward unit-level serialization to achieve full compliance with DSCSA and EU FMD standards, enabling traceability at the individual-pack level, while analyzing the impact on ledger size and system performance. Cross-border interoperability is another critical direction, focusing on integration with GS1 standards and inter-ledger communication protocols to ensure traceability of pharmaceuticals and active ingredients across jurisdictions. To address scalability and privacy constraints, future research should optimize hybrid on-chain/off-chain storage models that leverage IPFS alongside advanced privacy-preserving techniques, such as zero-knowledge proofs and private data collections. Finally, human-centered and economic evaluations are necessary, including usability studies for patients and pharmacists, as well as comprehensive cost–benefit and total cost of ownership analyses to support policy design and phased national deployment.

8. Conclusion

Counterfeit and substandard medicines remain one of the most lethal and least tractable failures of the global pharmaceutical supply chain, and

their burden falls hardest on the low- and middle-income populations least able to absorb it. This study designed, formally modelled and empirically evaluated Pharma-Chain, a permissioned blockchain and IoT traceability framework built on Hyperledger Fabric that delivers immutable end-to-end provenance, automated cold-chain enforcement, regulator-grade recall and quarantine powers, and frictionless QR-based authentication for the ordinary patient. The prototype sustained up to 471 transactions per second, maintained sub-second confirmation latency across the operating range relevant to national traceability, served patient-facing verification queries in under one-fifth of a second, and detected counterfeit, unknown and recalled batches with complete accuracy — yielding a two- to three-fold capability improvement over a conventional supply-chain baseline. Taken together, the evidence demonstrates that a permissioned, IoT-integrated distributed ledger is not merely a theoretically attractive but a practically deployable instrument for securing the medicine supply chain in a resource-constrained setting. By placing the national regulator at the centre of the design and aligning with the established serialization regimes of the DSCSA and EU FMD while remaining tailored to the governance realities of Pakistan, Pharma-Chain offers a credible, incrementally adoptable blueprint for national drug-authentication infrastructure. Realising that promise will require production-scale benchmarking, live cold-chain piloting and sustained attention to the human, economic and governance factors that ultimately determine whether a sound architecture becomes a working public good.

References

Abbas, K., Afaq, M., Ahmed Khan, T., & Song, W.-C. (2020). A blockchain and machine learning-based drug supply chain management and recommendation system for smart pharmaceutical industry. Electronics, 9(5), 852. https://doi.org/10.3390/electronics9050852

AbuHalimeh, A., & Ali, O. (2023). Comprehensive review for healthcare data quality challenges in blockchain technology. Frontiers in Big Data, 6, 1173620. https://doi.org/10.3389/fdata.2023.1173620

Agbo, C. C., Mahmoud, Q. H., & Eklund, J. M. (2019). Blockchain technology in healthcare: A systematic review. Healthcare, 7(2), 56. https://doi.org/10.3390/healthcare7020056

Androulaki, E., Barger, A., Bortnikov, V., Cachin, C., Christidis, K., De Caro, A., Enyeart, D., Ferris, C., Laventman, G., Manevich, Y., Muralidharan, S., Murthy, C., Nguyen, B., Sethi, M., Singh, G., Smith, K., Sorniotti, A., Stathakopoulou, C., Vukolic, M., ... Yellick, J. (2018). Hyperledger Fabric: A distributed operating system for permissioned blockchains. In Proceedings of the Thirteenth EuroSys Conference (pp. 1–15). ACM. https://doi.org/10.1145/3190508.3190538

Azaria, A., Ekblaw, A., Vieira, T., & Lippman, A. (2016). MedRec: Using blockchain for medical data access and permission management. In Proceedings of the 2nd International Conference on Open and Big Data (pp. 25–30). IEEE. https://doi.org/10.1109/OBD.2016.11

Benchoufi, M., & Ravaud, P. (2017). Blockchain technology for improving clinical research quality. Trials, 18(1), 335. https://doi.org/10.1186/s13063-017-2035-z

Bocek, T., Rodrigues, B. B., Strasser, T., & Stiller, B. (2017). Blockchains everywhere – A use-case of blockchains in the pharma supply-chain. In IFIP/IEEE Symposium on Integrated Network and Service Management (pp. 772–777). IEEE. https://doi.org/10.23919/INM.2017.7987376

Bodkhe, U., Tanwar, S., Parekh, K., Khanpara, P., Tyagi, S., Kumar, N., & Alazab, M. (2020). Blockchain for Industry 4.0: A comprehensive review. IEEE Access, 8, 79764–79800. https://doi.org/10.1109/ACCESS.2020.2988579

Casino, F., Dasaklis, T. K., & Patsakis, C. (2019). A systematic literature review of blockchain-based applications: Current status, classification and open issues. Telematics and Informatics, 36, 55–81. https://doi.org/10.1016/j.tele.2018.11.006

Christidis, K., & Devetsikiotis, M. (2016). Blockchains and smart contracts for the Internet of Things. IEEE Access, 4, 2292–2303. https://doi.org/10.1109/ACCESS.2016.2566339

Clauson, K. A., Breeden, E. A., Davidson, C., & Mackey, T. K. (2018). Leveraging blockchain technology to enhance supply chain management in healthcare. Blockchain in Healthcare Today, 1. https://doi.org/10.30953/bhty.v1.20

Dwivedi, A. D., Srivastava, G., Dhar, S., & Singh, R. (2019). A decentralized privacy-preserving healthcare blockchain for IoT. Sensors, 19(2), 326. https://doi.org/10.3390/s19020326

Engelhardt, M. A. (2017). Hitching healthcare to the chain: An introduction to blockchain technology in the healthcare sector. Technology Innovation Management Review, 7(10), 22–34. https://doi.org/10.22215/timreview/1111

Esmaeilian, B., Sarkis, J., Lewis, K., & Behdad, S. (2020). Blockchain for the future of sustainable supply chain management in Industry 4.0. Resources, Conservation and Recycling, 163, 105064. https://doi.org/10.1016/j.resconrec.2020.105064

Esposito, C., De Santis, A., Tortora, G., Chang, H., & Choo, K.-K. R. (2018). Blockchain: A panacea for healthcare cloud-based data security and privacy? IEEE Cloud Computing, 5(1), 31–37. https://doi.org/10.1109/MCC.2018.011791712

Fernández-Caramés, T. M., & Fraga-Lamas, P. (2018). A review on the use of blockchain for the Internet of Things. IEEE Access, 6, 32979–33001. https://doi.org/10.1109/ACCESS.2018.2842685

Griggs, K. N., Ossipova, O., Kohlios, C. P., Baccarini, A. N., Howson, E. A., & Hayajneh, T. (2018). Healthcare blockchain system using smart contracts for secure automated remote patient monitoring. Journal of Medical Systems, 42(7), 130. https://doi.org/10.1007/s10916-018-0982-x

Hasselgren, A., Kralevska, K., Gligoroski, D., Pedersen, S. A., & Faxvaag, A. (2020). Blockchain in healthcare and health sciences—A scoping review. International Journal of Medical Informatics, 134, 104040. https://doi.org/10.1016/j.ijmedinf.2019.104040

Hewa, T., Ylianttila, M., & Liyanage, M. (2021). Survey on blockchain based smart contracts: Applications, opportunities and challenges. Journal of Network and Computer Applications, 177, 102857. https://doi.org/10.1016/j.jnca.2020.102857

Hölbl, M., Kompara, M., Kamišalić, A., & Nemec Zlatolas, L. (2018). A systematic review of the use of blockchain in healthcare. Symmetry, 10(10), 470. https://doi.org/10.3390/sym10100470

Jamil, F., Hang, L., Kim, K., & Kim, D. (2019). A novel medical blockchain model for drug supply chain integrity management in a smart hospital. Electronics, 8(5), 505. https://doi.org/10.3390/electronics8050505

Kamble, S. S., Gunasekaran, A., & Sharma, R. (2020). Modeling the blockchain enabled traceability in agriculture supply chain. International Journal of Information Management, 52, 101967. https://doi.org/10.1016/j.ijinfomgt.2019.05.023

Kamilaris, A., Fonts, A., & Prenafeta-Boldú, F. X. (2019). The rise of blockchain technology in agriculture and food supply chains. Trends in Food Science & Technology, 91, 640–652. https://doi.org/10.1016/j.tifs.2019.07.034

Kasyapa, M. S. B., & Vanmathi, C. (2024). Blockchain integration in healthcare: A comprehensive investigation of use cases, performance issues, and mitigation strategies. Frontiers in Digital Health, 6, 1359858. https://doi.org/10.3389/fdgth.2024.1359858

Khezr, S., Moniruzzaman, M., Yassine, A., & Benlamri, R. (2019). Blockchain technology in healthcare: A comprehensive review and directions for future research. Applied Sciences, 9(9), 1736. https://doi.org/10.3390/app9091736

Kouhizadeh, M., Saberi, S., & Sarkis, J. (2021). Blockchain technology and the sustainable supply chain: Theoretically exploring adoption barriers. International Journal of Production Economics, 231, 107831. https://doi.org/10.1016/j.ijpe.2020.107831

Kshetri, N. (2018). Blockchain's roles in meeting key supply chain management objectives. International Journal of Information Management, 39, 80–89. https://doi.org/10.1016/j.ijinfomgt.2017.12.005

Kuo, T.-T., Kim, H.-E., & Ohno-Machado, L. (2017). Blockchain distributed ledger technologies for biomedical and health care applications. Journal of the American Medical Informatics Association, 24(6), 1211–1220. https://doi.org/10.1093/jamia/ocx068

Mackey, T. K., & Cuomo, R. E. (2020). An interdisciplinary review of digital technologies to facilitate anti-corruption, transparency and accountability in medicines procurement. Global Health Action, 13(sup1), 1695241. https://doi.org/10.1080/16549716.2019.1695241

Mackey, T. K., & Nayyar, G. (2017). A review of existing and emerging digital technologies to combat the global trade in fake medicines. Expert Opinion on Drug Safety, 16(5), 587–602. https://doi.org/10.1080/14740338.2017.1313227

Mackey, T. K., Kuo, T.-T., Gummadi, B., Clauson, K. A., Church, G., Grishin, D., Obbad, K., Barkovich, R., & Palombini, M. (2019). 'Fit-for-purpose?'—Challenges and opportunities for applications of blockchain technology in the future of healthcare. BMC Medicine, 17(1), 68. https://doi.org/10.1186/s12916-019-1296-7

McGhin, T., Choo, K.-K. R., Liu, C. Z., & He, D. (2019). Blockchain in healthcare applications: Research challenges and opportunities. Journal of Network and Computer Applications, 135, 62–75. https://doi.org/10.1016/j.jnca.2019.02.027

Mettler, M. (2016). Blockchain technology in healthcare: The revolution starts here. In IEEE 18th International Conference on e-Health Networking, Applications and Services (Healthcom) (pp. 1–3). IEEE. https://doi.org/10.1109/HealthCom.2016.7749510

Min, H. (2019). Blockchain technology for enhancing supply chain resilience. Business Horizons, 62(1), 35–45. https://doi.org/10.1016/j.bushor.2018.08.012

Musamih, A., Salah, K., Jayaraman, R., Arshad, J., Debe, M., Al-Hammadi, Y., & Ellahham, S. (2021). A blockchain-based approach for drug traceability in healthcare supply chain. IEEE Access, 9, 9728–9743. https://doi.org/10.1109/ACCESS.2021.3049920

Ozawa, S., Evans, D. R., Bessias, S., Haynie, D. G., Yemeke, T. T., Laing, S. K., & Herrington, J. E. (2018). Prevalence and estimated economic burden of substandard and falsified medicines in low- and middle-income countries: A systematic review and meta-analysis. JAMA Network Open, 1(4), e181662. https://doi.org/10.1001/jamanetworkopen.2018.1662

Pandey, P., & Litoriya, R. (2021). Securing e-health networks from counterfeit medicine penetration using blockchain. Wireless Personal Communications, 117(1), 7–25. https://doi.org/10.1007/s11277-020-07041-7

Queiroz, M. M., Telles, R., & Bonilla, S. H. (2020). Blockchain and supply chain management integration: A systematic review of the literature. Supply Chain Management, 25(2), 241–254. https://doi.org/10.1108/SCM-03-2018-0143

Rasheed, H., Hoellein, L., Bukhari, K. S., & Holzgrabe, U. (2019). Regulatory framework in Pakistan: Situation analysis of medicine quality and future recommendations. Journal of Pharmaceutical Policy and Practice, 12(1), 23. https://doi.org/10.1186/s40545-019-0184-z

Reyna, A., Martín, C., Chen, J., Soler, E., & Díaz, M. (2018). On blockchain and its integration with IoT: Challenges and opportunities. Future Generation Computer Systems, 88, 173–190. https://doi.org/10.1016/j.future.2018.05.046

Saberi, S., Kouhizadeh, M., Sarkis, J., & Shen, L. (2019). Blockchain technology and its relationships to sustainable supply chain management. International Journal of Production Research, 57(7), 2117–2135. https://doi.org/10.1080/00207543.2018.1533261

Sylim, P., Liu, F., Marcelo, A., & Fontelo, P. (2018). Blockchain technology for detecting falsified and substandard drugs in distribution: Pharmaceutical supply chain intervention. JMIR Research Protocols, 7(9), e10163. https://doi.org/10.2196/10163

Tanwar, S., Parekh, K., & Evans, R. (2020). Blockchain-based electronic healthcare record system for healthcare 4.0 applications. Journal of Information Security and Applications, 50, 102407. https://doi.org/10.1016/j.jisa.2019.102407

Tian, F. (2016). An agri-food supply chain traceability system for China based on RFID & blockchain technology. In 13th International Conference on Service Systems and Service Management (pp. 1–6). IEEE. https://doi.org/10.1109/ICSSSM.2016.7538424

Treiblmaier, H. (2018). The impact of the blockchain on the supply chain: A theory-based research framework and a call for action. Supply Chain Management, 23(6), 545–559. https://doi.org/10.1108/SCM-01-2018-0029

Tseng, J.-H., Liao, Y.-C., Chong, B., & Liao, S. (2018). Governance on the drug supply chain via Gcoin blockchain. International Journal of Environmental Research and Public Health, 15(6), 1055. https://doi.org/10.3390/ijerph15061055

Uddin, M. (2021). Blockchain Medledger: Hyperledger Fabric enabled drug traceability system for counterfeit drugs in pharmaceutical industry. International Journal of Pharmaceutics, 597, 120235. https://doi.org/10.1016/j.ijpharm.2021.120235

Uddin, M., Salah, K., Jayaraman, R., Pesic, S., & Ellahham, S. (2021). Blockchain for drug traceability: Architectures and open challenges. Health Informatics Journal, 27(2), 14604582211011228. https://doi.org/10.1177/14604582211011228

Wang, Y., Han, J. H., & Beynon-Davies, P. (2019). Understanding blockchain technology for future supply chains: A systematic literature review and research agenda. Supply Chain Management, 24(1), 62–84. https://doi.org/10.1108/SCM-03-2018-0148

Wüst, K., & Gervais, A. (2018). Do you need a blockchain? In Crypto Valley Conference on Blockchain Technology (pp. 45–54). IEEE. https://doi.org/10.1109/CVCBT.2018.00011

Xie, J., Tang, H., Huang, T., Yu, F. R., Xie, R., Liu, J., & Liu, Y. (2019). A survey of blockchain technology applied to smart cities: Research issues and challenges. IEEE Communications Surveys & Tutorials, 21(3), 2794–2830. https://doi.org/10.1109/COMST.2019.2899617

Yaqoob, I., Salah, K., Jayaraman, R., & Al-Hammadi, Y. (2022). Blockchain for healthcare data management: Opportunities, challenges, and future recommendations. Neural Computing and Applications, 34(14), 11475–11490. https://doi.org/10.1007/s00521-020-05519-w

Zhang, P., White, J., Schmidt, D. C., Lenz, G., & Rosenbloom, S. T. (2018). FHIRChain: Applying blockchain to securely and scalably share clinical data. Computational and Structural Biotechnology Journal, 16, 267–278. https://doi.org/10.1016/j.csbj.2018.07.004

Zheng, Z., Xie, S., Dai, H.-N., Chen, X., & Wang, H. (2018). Blockchain challenges and opportunities: A survey. International Journal of Web and Grid Services, 14(4), 352–375. https://doi.org/10.1504/IJWGS.2018.095647

Food and Drug Administration. (2024). Drug Supply Chain Security Act (DSCSA). U.S. Department of Health and Human Services. https://www.fda.gov/drugs/drug-supply-chain-integrity/drug-supply-chain-security-act-dscsa

Nakamoto, S. (2008). Bitcoin: A peer-to-peer electronic cash system. https://bitcoin.org/bitcoin.pdf

World Health Organization. (2017). WHO global surveillance and monitoring system for substandard and falsified medical products. World Health Organization. https://www.who.int/publications/i/item/9789241513425

World Health Organization. (2024). Substandard and falsified medical products (Fact sheet). World Health Organization. https://www.who.int/news-room/fact-sheets/detail/substandard-and-falsified-medical-products