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How does blockchain Technology help to make pharmaceutical cold chain reliable?

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Abstract

Despite the growing trend of cold chain adoption in the pharmaceutical industry, its capacity to ensure reliability, transparency, and trust throughout the chain system remains a challenging issue. Blockchain, in this regard, offers an effective solution to the issue, as it provides immutable records and enhanced security. This study, thus, investigates blockchain's potential to improve cold chain adoption in the pharmaceutical industry by examining public perceptions and professional insights. It employed the exploratory qualitative approach, which combined a literature review, a public survey of 113 respondents, and in-depth interviews with executives of the blockchain-enabled cold chain companies. Survey results present that public trust in vaccine and medicine distribution could be achieved through the provision of transparency, regulatory insight, product quality, monitoring systems, and technological solutions, which are offered by blockchain technology. Expert interviews, meanwhile, reveal that blockchain supports real-time tracking, quality assurance, compliance, and automation. These data collection processes revealed that integration with existing systems and regulatory compliance remained pressing concerns in the adoption of blockchain in the pharmaceutical industry. These findings outline that blockchain has the potential to enhance reliability, transparency, and trust in the pharmaceutical cold chain adoption, thus highlighting its suitability for education, policy support, and further research.

Keywords: blockchain, cold chain, pharma supply chain

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1. Introduction

Blockchain is a modern, revolutionary computer technology used for various purposes across different sectors to ensure transparency, trustworthiness, efficiency, and other key aspects. Its base algorithmic system is popular for its exceptional automation and safety. However, it is its irreversibility protection against human interruption and interference through its inside users or outside system hackers that makes it more unique.

Besides many other areas, blockchain has proved its efficiency in systemic process traceability through its hashed (chains and blocks) with irreversible and unbreakable nodes. The pharmaceutical cold chain is one example of how this technology can benefit society, as it offers transparency, trust, and most importantly, reliability in the value and supply chain of vital and sensitive pharmaceutical products, such as vaccines, blood, etc.

This paper clarifies the effectiveness of blockchain technology in ensuring reliability in the pharmaceutical products' cold chain. In this context, a fundamental research question was developed: what are the challenges and limitations in the implementation of blockchain technology in pharmaceutical cold chains, and how can these challenges and limitations be overcome? The study adopts an exploratory qualitative approach, combining a critical literature review with a pre-designed public survey and in-depth expert interviews with executives of blockchain-enabled cold chain companies. This approach enables a comprehensive understanding of public perceptions, operational challenges, and practical benefits of blockchain technology in pharmaceutical cold chains.

Previous studies have already extensively examined the potential benefits of blockchain technology in supply chain management (Hübschke et al., 2025). In particular, public trust in blockchain-based medicine and vaccine distribution, as well as professional insights into practical adoption challenges and strategies, are underexplored. This study addresses these gaps through a public survey and expert interviews, offering a comprehensive understanding of blockchain's role in enhancing reliability in pharmaceutical cold chains. Blockchain is increasingly recognized for its potential to improve pharmaceutical cold chain management, yet practical adoption challenges continue to exist, indicating a clear need for further empirical investigation (Bamakan et al., 2021).

That said, pharmaceutical supply chains, especially cold chains, have a high priority from a management perspective. They are complex and sensitive systems that directly impact public health and people's lives and therefore need to be managed effectively. This study is highly relevant because it investigates a forward-looking technology (Blockchain) in a health-critical application field (Bamakan et al., 2021). An analysis of more than 150 blockchain implementations across 25 countries, based on interviews with over 200 supply chain and technology leaders, shows that overall supply chain costs are reduced by 20–30%, while traceability improves by 75% (Immidi, 2024).

This paper is organized as follows: Section 2 reviews the literature, Section 3 presents the methodology, Section 4 discusses the findings, and Section 5 concludes.Blockchain is a modern, revolutionary computer technology used for various purposes across different sectors to ensure transparency, trustworthiness, efficiency, and other key aspects. Its base algorithmic system is popular for its exceptional automation and safety. However, it is its irreversibility

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2. Literature Review

Pharmaceutical supply chains face critical challenges affecting their security, authenticity, traceability, and safety. One of those challenges is the significant public health issue emerging from counterfeit medicines in the global pharmaceutical supply chain (Sarkar, 2023). These medicines have been more prevalent worldwide, particularly in low- and middle-income

countries, causing nearly USD 30 billion-worth of damage annually. They can include toxic substances and be transported across borders without quality control, potentially leading to severe side effects, including death. (Pascu et al., 2020). This highlights the importance of transparency and visibility in the digital pharmaceutical supply chain, which is addressed through the development of new pharmaceutical drug traceability systems (Sarkar, 2023). The global Pharma Track-and-Trace Solutions market was valued at USD 4,345.21 million in 2025, and has a compound annual growth rate of 15.5%. In 2024, more than 180,000 packaging lines worldwide were equipped with serialization systems, compared to 142,000 in 2022 (Market Growth Reports, 2025). Traditional pharmaceutical supply chain systems are often vulnerable to data tampering, leading to distrust among stakeholders. Moreover, these systems are not yet able to ensure secure and complete documentation throughout transportation and storage (Sarkar, 2023).

Drugs move between manufacturers, distributors, repackagers, wholesalers, and subcontractors within the pharmaceutical supply chains before reaching the patient. As one of the world's most complex supply chains, the pharmaceutical sector is highly susceptible to opaque processes (Kayhan, 2022). Maintaining the correct temperature for medications, thus, represents a complex and challenging task in the pharmaceutical cold chain. Deviations from the recommended storage temperatures can compromise the quality and effectiveness of medications, posing health risks to patients, such as reduced therapeutic effect, toxic degradation products, or adverse side effects. In addition, economic losses arising from medications are rendered unusable (Ferraz et al., 2025). In this context, a major challenge for the pharmaceutical supply chain is parallel trade, where medicines are purchased in one country at lower prices and sold in another country at higher prices. This practice complicates traceability, causes shortages, increases the risk of counterfeit medicines, and leads to price and cost calculation opacity, thereby undermining the overall safety and efficiency of the supply chain (Nolen & Balling, 2021).

The limited traceability of medicinal products represents a key challenge for supply chain security. This is particularly the case for biologics, where full traceability down to the batch number is often not achieved, delaying the identification and recall of defective products. Conventional linear barcodes only capture static information and do not allow for the automatic electronic recording of dynamic data such as batch or expiry numbers. Studies from Italy, the Netherlands, and the EudraVigilance database indicate that while product names are generally recorded correctly in adverse drug reaction reports, batch numbers are poorly captured (5–21 %). This is partly due to missing or insufficient barcodes on primary packaging (Klein & Stolk, 2018). A key challenge in pharmaceutical supply chains is limited visibility, as manufacturers, distributors, and pharmacies often operate with fragmented systems and poor data sharing. This hinders real-time tracking, delays decision-making, and increases the risk of disruptions (Gorani, 2024). Compliance with strict regulations from the U.S. Food and Drug Administration and the European Medicines Agency poses a major challenge for pharmaceutical supply chains, as rules vary significantly across regions. Violations can result in fines, product recalls, and reputational damage, as well as increased costs and time-to-market, ultimately affecting patient access to medications (Gorani, 2024).

It should be noted that the global pharmaceutical industry is one of the most highly regulated sectors worldwide, exposing pharmaceutical companies to a complex web of regulatory

challenges that differ greatly across regions (Navigating Regulatory Challenges in Global Pharmaceutical Supply Chains, 2025). Unfortunately, traditional forecasting methods, which are mostly based on historical sales data, often fail to capture sudden shifts in demand or emerging health risks, potentially leading to stockouts, excessive inventory, and direct financial losses (Gorani, 2024). In the pharmaceutical industry, demand forecasting frequently depends on simple statistical methods that use historical data, yet fail to capture the complex influences of economic conditions, regulatory changes, market competition, special contracts, and media impact (Bilal et al., 2024).

Another challenge in the pharmaceutical supply chain concerns quality assurance (QA). The primary goal of this process is to ensure product integrity, requiring medications to adhere to strict safety, efficacy, and quality standards throughout the entire supply chain. Upholding compliance with these standards is complex, as multiple stakeholders are involved (Gorani, 2024). Analysis of 163 drugs that experienced shortages between 2013 and 2017 revealed that 62 % of these shortages were linked to manufacturing or product quality issues (U.S. Food and Drug Administration, 2019). Globalization becomes the next challenge that pharmaceutical supply chains must address. It not only offers benefits, such as cost reduction and increased efficiency, but also introduces risks. Cross-border supply chains can be significantly disrupted by geopolitical tensions, trade disputes, and natural disasters (Gorani, 2024). Nearly 80 % of global supply chain leaders report having faced major supply chain disruptions in the past year, with external factors such as geopolitical tensions and regulatory changes being key contributors to these risks (Narayan et al., 2023).

Given the challenges described (i.e., limited traceability of medicines, lack of visibility across fragmented systems, risks of counterfeit drugs, quality assurance issues, and difficulties in maintaining regulatory compliance), the need for innovative systems that can improve the security, transparency, and efficiency of pharmaceutical supply chains becomes more paramount. This is where blockchain technology comes in; a technology characterized by properties such as irreversibility, immutability, transparency, decentralization, enhanced traceability, and autonomy (Sarkar, 2023; Bali et al., 2022).

Blockchain is an ordered sequence of blocks that are resistant to modification, carry a timestamp, and are connected through cryptographic hashes (Bali et al., 2022). A key component of blockchain is the common shared ledger, which enables every node (every participant in the network) to possess its own copy of all transactions (Bapatla et al., 2022). A blockchain sequence operates according to a consensus mechanism, with no central authority regulating the exchange between supply chain stakeholders. That said, all nodes must agree on a common protocol for updating the ledger to maintain a consistent state. Blocks are only added to the blockchain once a majority of nodes have given their approval (Puthal et al., 2018).

According to a market trend report by SNS Insider Pvt Ltd. (2025), the global blockchain in supply chain market is projected to grow significantly, from USD 3.96 billion in 2025 to USD 95.52 billion by 2033, reflecting the increasing demand for transparency and traceability in supply chains.

Blockchain technologies offer a solution to the aforementioned challenges in pharmaceutical supply chains by monitoring temperature through sensors, proactively identifying hazards,

and thus enhancing drug safety (Sarkar, 2023). The term “cold chain” refers to the handling of medicines and vaccines that require special temperature-controlled conditions. For temperature-sensitive pharmaceutical products, continuous surveillance should be performed throughout the entire drug’s life cycle, including storage in warehouses, transportation, packaging, handling at pharmacies and healthcare facilities, and the final dispensing to patients. One possible approach to ensuring temperature control and environmental monitoring in the pharmaceutical cold chain is to combine Internet of Things (IoT) and blockchain technology by deploying end nodes, consisting of sensors and actuators, near pharmaceutical shipments during transport. These end nodes are responsible for the continuous monitoring of the environmental conditions surrounding the medications. The internet-enabled end nodes transmit the collected data to the edge devices, with significantly larger storage capacities, and subsequently forward the data to the cloud for further processing.

If deviations from the recommended ranges are detected during the predefined checks of the environmental data received by the edge nodes, these deviations are reported to both the blockchain and the cloud. The blockchain creates an immutable record of the events, while the cloud provides real-time alerts and enables the participating entities in the supply chain to respond promptly. The cloud layer processes data from edge devices, generates real-time alerts, and enables supply chain participants to control the actuators of the end nodes to maintain the recommended environmental conditions. The blockchain layer creates an immutable record of all deviations and uses the PoAh consensus mechanism to enable near real-time processing with low computational overhead (Bapatla et al., 2022). By tracking drug temperatures across all stages of the supply chain and recognizing early detection of temperature deviations, damage to pharmaceutical quality can be reduced, thereby minimizing resource waste (Sarkar, 2023; Bamakan et al., 2021). IoT devices are inherently vulnerable to manipulation and cyberattacks. Therefore, the use of a decentralized blockchain, which is considered autonomous and trustworthy, is necessary to enhance security and strengthen coordination among stakeholders in the pharmaceutical supply chain (Bamakan et al., 2021).

Thanks to blockchain's decentralized structure, every supply chain participant can access the same tamper-proof data. This high level of transparency improves the traceability of medicines, helps prevent fraud, and supports adherence to regulatory requirements (Wang, 2024). Blockchain reduces the risk of counterfeit drugs by recording each transaction and the movement of medicines from the manufacturer to the end user in an immutable manner. Key details, such as batch numbers, production dates, and expiration dates, are captured at the time of manufacturing. Every participant in the supply chain logs the handling of the medicines, including storage conditions and transportation records. This extensive and immutable record ensures the provenance of medications can be verified at any time and facilitates the rapid identification of counterfeit products (Wang, 2024).

The use of blockchain technology in the pharmaceutical supply chain guarantees that genuine medications reach authorized stakeholders at every transfer point. The so-called Medledger records all verified and authenticated transactions. This secure data foundation provided by the blockchain enables collaboration among stakeholders in the pharmaceutical supply chain, even when they have varying levels of trust (Sarkar, 2023), by allowing continuous, permitted

monitoring of product quality, which improves operational efficiency and reduces costs (Bamakan et al., 2021).

The requirement for accurate reporting and record-keeping in pharmaceutical supply chains poses a challenge. Automating these documentation processes through blockchain helps ensure compliance with these regulations. Self-executing contracts, commonly known as smart contracts, encode the terms directly into the code, allowing automatic verification of compliance and ensuring that all parties adhere to legal requirements (Wang, 2024).

The weaknesses of traditional demand forecasting approaches, particularly fragmented data structures, delayed information flows, overstocking or stockouts, and reliance on centralized systems, can be mitigated by blockchain technology. The real-time and tamper-proof data access enabled by blockchain enables more accurate predictions, as it uses up-to-date, complete, consistent, and reliable data (Barati, 2025). Put differently, blockchain allows for real-time tracking of inventory (Zhou, 2024). In demand forecasting, the need for intermediaries who collect, process, and validate data is reduced or removed by the decentralized structure of blockchain. Direct interactions between participants accelerate the flow of information and enable faster updates to forecasts (Barati, 2025).

The use of blockchain in supply chains enhances their resilience (i.e., the ability to withstand and recover from disruptions) by facilitating data transparency and traceability, risk management and emergency response, inventory and logistics management, as well as collaboration across the supply chain (Zhou, 2024).

Certain restrictions are inherent to the core features of blockchain technology. Due to its high energy requirements and the need to repeatedly propagate transaction information across the entire network, blockchain technology faces scalability limits as the number of users increases (Chang et al., 2022). Supply chains must process thousands of transactions per second and large amounts of data, whereas blockchain systems like Gcoin can handle only around one million transactions per day, thereby delaying transaction validation. The complex, decentralized structure of medical supply chains, requiring multiple nodes per transaction, intensifies scalability concerns (Islam et al., 2025). The immutability and security of the blockchain protect data once it has been recorded from subsequent manipulation. However, information can already be incorrect or tampered with at the point of entry, as the blockchain does not perform active verification when data is first submitted. Allowing all users to access the activity history in the distributed ledger unavoidably impacts privacy. Although the immutability of blockchain data is an advantage, it can constrain business processes, for example, in transaction processing, when product returns or refunds become problematic due to the unchangeable nature of the information (Chang et al., 2022). High investment and operational costs, such as maintenance and external consulting, hinder the widespread adoption of blockchain in the pharmaceutical sector (Islam et al., 2025).

3. Research Methodology

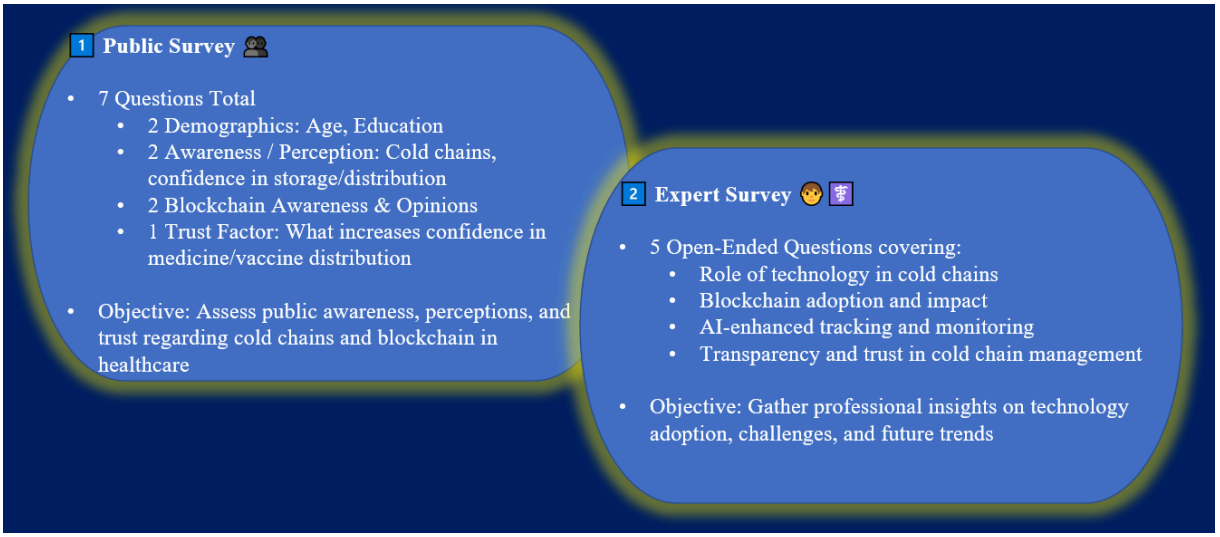
In light of the aforementioned research question, a pre-designed questionnaire was virtually distributed to a targeted diverse group of responders. The purpose is to gather insights on public awareness, perceptions, and attitudes toward pharmaceutical cold chains, which has

helped to create more specific questions for interviews with executives of blockchain-enabled cold chain companies.

Subsequently, an expert interview questionnaire was developed to reach executives of blockchain-enabled cold chain companies to gain in-depth insights into their implementation strategies, operational challenges, and the practical advantages of blockchain technology utilization in ensuring reliability, safety, efficiency, etc., along the process.

Furthermore, a suitable number of available online/offline literature was reviewed with a critical analysis and critical comparison to clarify the findings of the interviews. Figure 1 provides an overview of the research methodology, with a particular focus on the public and expert survey.

Figure 1: Research Methodology



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4. Research Findings

Of the 113 survey respondents, two of the seven questions were open-ended: “What would increase your trust in medicine or vaccine distribution?” and “What are your thoughts or concerns about the use of blockchain technology in healthcare or medicine logistics?”. These responses were analyzed qualitatively using thematic analysis, which revealed several main themes. Regarding trust in medicine and vaccine distribution, respondents emphasized the importance of transparency and regulatory oversight, confidence in manufacturer and supplier quality, proper storage and monitoring, technological solutions such as blockchain, and social validation through positive experiences. With respect to blockchain in healthcare logistics, key themes included transparency and security benefits, privacy and cost concerns, lack of understanding and adoption barriers, positive expectations, and the potential for global coordination. The following bullet points illustrate these main themes with selected participant responses.

“ What would increase your trust in medicine or vaccine distribution?”

Transparency & Oversight

“Transparency, more information.”

“A regulatory body ensuring strict oversight.”

Reputation & Quality

“Trusted manufacturers and suppliers.”

“Tamper-evident packaging and open batch-testing.”

Storage & Monitoring

“Better cold storage and visible expiry dates.”

“Real-time supply chain tracking.”

Technology & Communication

“Blockchain and automated monitoring.”

“Clear info on vaccine ingredients and side effects.”

Social Proof

“Many positive experiences.”

“Proven safety and positive reviews.”

“ What are your thoughts or concerns about blockchain in healthcare logistics?”

Transparency & Security Benefits

“Improves traceability of medicines.”

“Immutable ledger reduces counterfeit risks.”

Privacy & Cost Concerns

“Risk of unauthorized data access.”

“High implementation costs and complexity.”

Lack of Understanding & Adoption

“I don’t understand blockchain well.”

“Will companies actually adopt it?”

Positive Expectations

“Could improve healthcare quality.”

“Helps reduce waste and shortages.”

Global Coordination

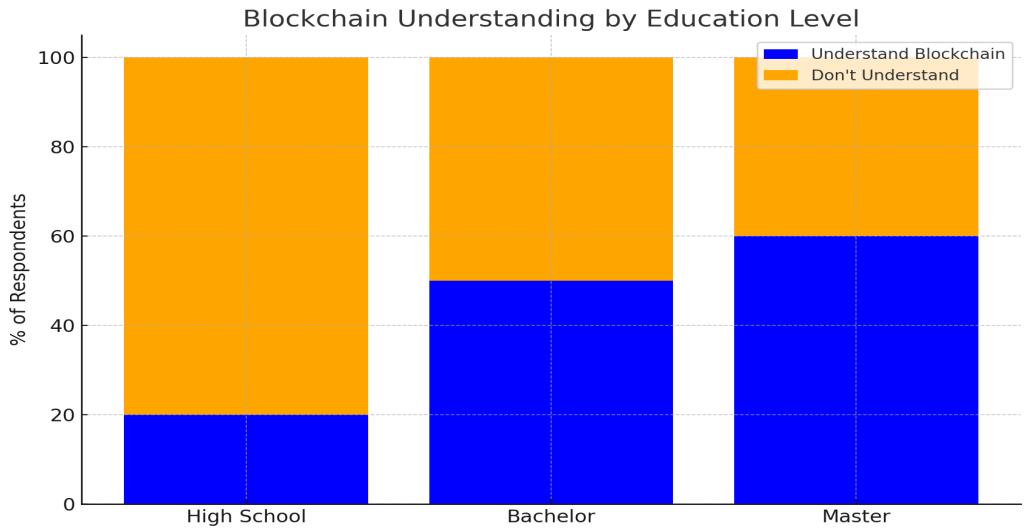
“Unifies fragmented systems internationally.”

“Supports fair access during crises.”

In addition to the open-ended questions, several closed questions were included in the public survey to quantitatively assess respondents’ perceptions and attitudes.

As shown in Figure 2, respondents’ understanding of blockchain appears to increase with higher education levels. Only 20% of high school respondents reported understanding blockchain, whereas approximately 50–60% of respondents with a Bachelor’s or Master’s degree demonstrated a clear understanding.

Figure 2: Blockchain Understanding by Education Level



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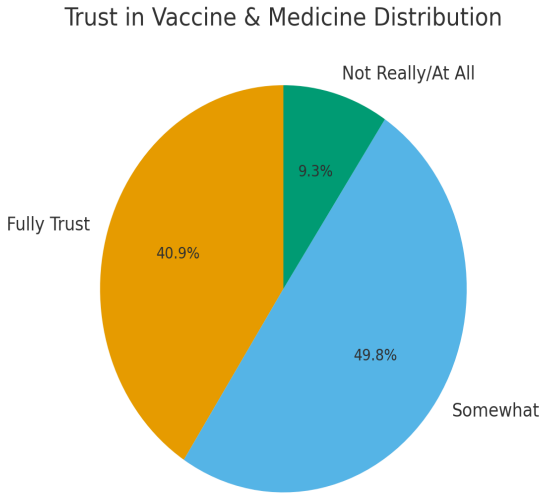
As illustrated in Figure 3, approximately 41% of respondents reported fully trusting vaccine distribution, while nearly 50% indicated that they only somewhat trust it. This trust gap highlights the need for greater transparency in the distribution process.

Figure 3: Trust in Vaccine & Medicine Distribution



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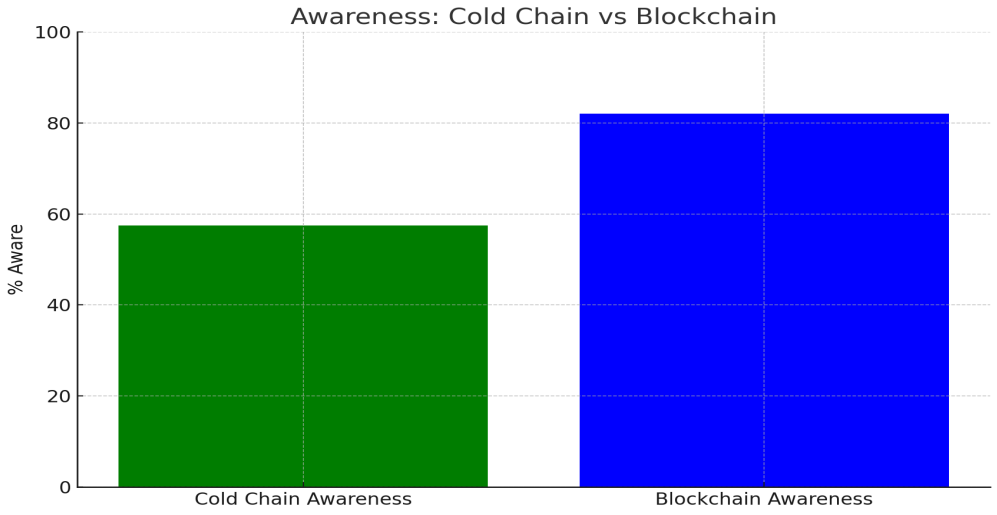
As shown in Figure 4, awareness of blockchain among respondents (82%) is notably higher than awareness of cold chain logistics (57.5%). This highlights an educational opportunity to emphasize the role of blockchain in enabling transparent and reliable supply chains.

Figure 4: Awareness: Cold Chain vs Blockchain



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Expert interview responses

The following summarizes the key insights obtained from expert interviews with executives and professionals involved in blockchain-enabled pharmaceutical cold chains. Responses were analyzed qualitatively, and the main themes are presented below.

"Could you please share your insight about the role of technology in the pharmaceutical cold chain?"

- Transparency & Traceability: IoT sensors, barcodes, and blockchain create immutable records of lot history, supplier verification, and storage conditions.
- Quality & Compliance: QA and regulatory processes are supported via blockchain and smart contracts for lot release, anti-counterfeit measures, and market-specific regulations.
- Real-Time Monitoring & Inventory:
    - Tracks time, temperature, location, and inventory.
    - AI can analyze real-time data from IoT sensors to predict bottlenecks, anticipate disruptions, and optimize logistics, enhancing reliability of the pharmaceutical cold chain.
- Automation & Collaboration: Smart contracts enable finance, reimbursements, recalls, clinical trial coordination, and decision-making for personalized medicine and shipment allocation.

"What do you think about the usage of blockchain technology in the pharmaceutical cold chain?"

- Adoption & Potential: Blockchain should become standard in pharma for transparency, immutability, security, and traceability; already used by major and smaller companies. Platforms like MediLedger, Hyperledger, and PharmaLedger InVis are operational internationally.
- Integration Challenges: Effective implementation requires combining blockchain with IoT, APIs, smart contracts, and possibly AI, while ensuring data integrity and security.
- Barriers to Adoption: Challenges include confusion with cryptocurrencies, unclear ROI, regulatory hurdles, compliance concerns, and hesitancy to be first movers in a heavily regulated industry.

4. Conclusion

This study demonstrates that blockchain technology holds significant potential to transform the reliability and transparency of pharmaceutical cold chains, a critical segment of global healthcare logistics. By ensuring that medicines and vaccines are stored, transported, and distributed under optimal conditions, blockchain provides a robust framework for traceability, authenticity, and trust throughout the supply chain.

The research highlights that blockchain-driven solutions can address major challenges such as security breaches, counterfeit products, and temperature deviations by enabling:

- End-to-end traceability through immutable, timestamped records.
- Tamper-proof data and decentralized verification eliminate single points of failure.
- Real-time temperature and logistics monitoring integrated with IoT sensors.
- Automated responses via smart contracts enhance operational reliability and efficiency.

Survey findings from both the public and experts reveal a growing awareness of blockchain (82%), though full understanding and trust remain limited. While only 41% fully trust current vaccine distribution systems, most respondents believe that transparency-enhancing technologies such as blockchain could increase confidence in pharmaceutical logistics. This trust gap underscores the need for education and practical demonstrations of blockchain's value in real-world healthcare systems.

Moreover, expert insights confirm that blockchain can reduce overall supply chain costs by up to 30% and improve traceability by 75%, aligning with global trends in technology adoption. However, successful implementation faces notable barriers, including high costs, limited throughput, data integration issues with IoT, and the requirement for cross-stakeholder collaboration, particularly in developing regions.

In summary, blockchain represents a forward-looking, high-impact technology capable of redefining how pharmaceutical cold chains operate. By securing data integrity, enabling visibility across all stakeholders, and fostering accountability, blockchain can not only improve efficiency but also enhance public trust in the safety and authenticity of medicines and vaccines. To fully realize this potential, future efforts should focus on:

- Strengthening education and awareness among industry stakeholders and the public,
- Advancing scalable blockchain frameworks compatible with IoT, and
- Encouraging international collaboration to standardize blockchain adoption in healthcare supply chains.

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