

Original Research

Received 22 May 2026

Revised 13 July 2026

Accepted 26 July 2026

Natural Resources for Human Health 2026, Vol. 6 (13s): 918–935

KEYWORDS:

Pharmaceutical Supply Chain; Track-and-Trace Readiness; Digital Infrastructure; Data Governance; Serialization; Technology Adoption

Pharmaceutical Track-and-Trace Readiness in India: Assessing Digital Infrastructure, Data Governance and Serialization Capability across Supply-Chain Stakeholders

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ABSTRACT: Indian pharmaceutical supply chain is plagued with issues like counterfeit drugs, inadequate information systems and technological disparities among stakeholders in the supply chain. The present study measured the readiness of pharmaceutical track and trace system in India by looking into five factors namely; Supply-Chain Transparency, Product Authentication, Regulatory Compliance, Digital Infrastructure Readiness, Data Governance Readiness, and Serialization Capability and Technology Adoption Capability. The design used was quantitative research with primary data collected using a structured questionnaire from 200 stakeholders of the pharmaceutical supply chain. Data were analyzed using Pearson correlation and multiple regression analysis, both in the SPSS software. The correlation results showed that there were significant positive correlation among the variables Supply-Chain Transparency and Product Authentication and Regulatory Compliance. The results of the regression analysis revealed that Digital Infrastructure Readiness and Data Governance Readiness were significant predictors of Track and Trace Readiness, accounting for 51.9% of the variance in Track and Trace Readiness. The second regression model showed that Serialization Capability and Technology Adoption Capability also significantly affected Track-and-Trace Readiness, accounting for 17.8% of the variance. The results underlined the need to improve the technological infrastructure, data governance, and the ability to implement serialization capabilities and technology to enhance pharmaceutical traceability. The study offers viable implications for participating pharmaceutical companies and regulators in India to enhance end-to-end visibility, validation and regulatory adherence.

1. INTRODUCTION

Pharmaceutical supply chain (PSC) is a complex and interdependent supply chain of various stakeholders, processes and technologies that ensure safe and efficient delivery of medicines to the patients. It covers not only the acquisition of raw materials and active pharmaceutical ingredients, but also manufacturing, packaging, transportation and distribution, wholesale, retail and final consumption (Rajak, D. K., et.al., 2025). Medicines are a vital component of health and wellbeing, and the effectiveness and integrity of the supply chain is directly linked to patient safety. Yet there are a number of challenges along the pharmaceutical supply chain, such as counterfeit and substandard medicines, disruption of the supply chain, lack of transparency, regulatory flaws and illegal activities. These challenges can also affect the quality and credibility of

pharmaceuticals, resulting in substantial economic losses for pharmaceutical companies and health systems (Bapatla, A. K., et.al., 2024).

One of the biggest issues for the security of pharmaceutical products in the supply chain is counterfeit and substandard medicines. There can be vulnerabilities in the pharmaceutical distribution system that illicit manufacturers and other dubious operators can take advantage of to infiltrate legitimate supply chains with falsified products. These medicines can have wrong dosages, contain high or low levels of the active ingredients or even be made without containing any active ingredient at all. Use of the same however can lead to ineffective treatment, adverse reactions, and serious risks to patients (Rani, J., & Yadav, S. K. 2027). It has been estimated that around one in every 10 medical products sold in low and middle-income countries is substandard or fake. This illustrates that mechanisms are needed for identification, authentication and monitoring of pharmaceutical products during their transport from manufacturers to patients.

Another source of disruption is geopolitical conflict, natural disasters, production limitations, raw-material scarcity, and logistical challenges that can lead to a shortage of medicines and delays in providing critical treatments (Hamdi et al., 2024; Hupman et al., 2024). COVID-19 pandemic also caused a disruption in pharmaceutical production, transportation, distribution of vaccines, and the access to essential medical products, thus highlighting these structural vulnerabilities. Research on the pharmaceutical and healthcare supply-chain resilience showed that the pandemic exposed supply chains' vulnerabilities in absorbing, adapting and recovering from unexpected disruptions (Ivanov, 2021; Queiroz et al., 2022). These disruptions also emphasized the significance of visibility, coordination, the use of digital technologies, and resilience skills to ensure the continuity of pharmaceutical supply during crises (Hamdi et al., 2024; Shekoohi et al., 2026). As a result, there was a need for better communication across the pharmaceutical supply chain and greater coordination between its operational elements to keep the supply of essential medicines moving and ensure it is ready.

The lack of consistency in regulations and information systems can reduce the visibility and traceability of the pharmaceutical supply chain even more. Interoperability issues can arise due to differences in regulatory requirements, data standards and information sharing practices, which can make it more challenging for stakeholders to create a single view of the pharmaceutical product. Traceability systems could also help improve the monitoring of medical products from their source to their point of use, and aid in the timely detection and response to risks from falsified medical products, the World Health Organization (2025) reiterated. Fragmented tracking and a lack of information sharing can also help make it harder to identify the origin, location and movement of pharmaceutical products, whereas good tracking can help product verification, recalls and regulatory monitoring. Thus, increased regulatory coordination, digitalisation, information interoperability, and effective track and trace mechanisms are needed to enhance the visibility, security and product integrity of the pharmaceutical supply chain.

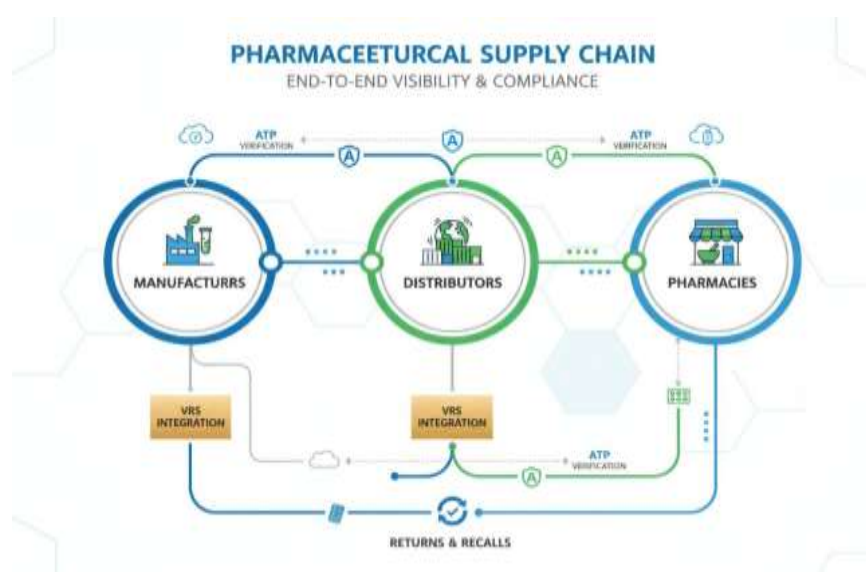


Figure 1: Pharmaceutical Supply-Chain Track-and-Trace Flow

Source: Adapted by the Author from GS1 US and relevant pharmaceutical track-and-trace literature.

1.1. Regulatory and Technological Framework for Pharmaceutical Track-and-Trace in India

The Indian pharmaceutical supply chain is regulated by a regulatory framework in which the Central Drugs Standard Control Organization (CDSCO) is the national regulatory authority for pharmaceuticals, cosmetics and medical devices, playing an important role. CDSCO has the regulatory responsibilities regarding the safety, quality and efficacy of pharmaceutical products. Hence, the regulatory environment is an essential building block of health systems' effective pharmaceutical traceability and ability to identify and track pharmaceutical products through the supply chain (Yadav, P., et.al., 2021).

The Drugs (Amendment) Rules, 2022, are some important developments in pharmaceutical traceability in India. The amendment added provisions relating to the implementation of QR codes on certain pharmaceutical products. Information that can be included in a QR code includes the Unique Product Identification Code (UPIC), Active Pharmaceutical Ingredient (API) name, brand name, manufacturer details and batch information. This data can help in eID and verification of pharmaceutical products and is a significant leap towards improving product traceability and serialization in India (Vadia, N., et.al., 2026). The requirements, however, imply that attention has to be given to whether pharmaceutical stakeholders have appropriate technological infrastructure and operational capacities to meet the requirements.

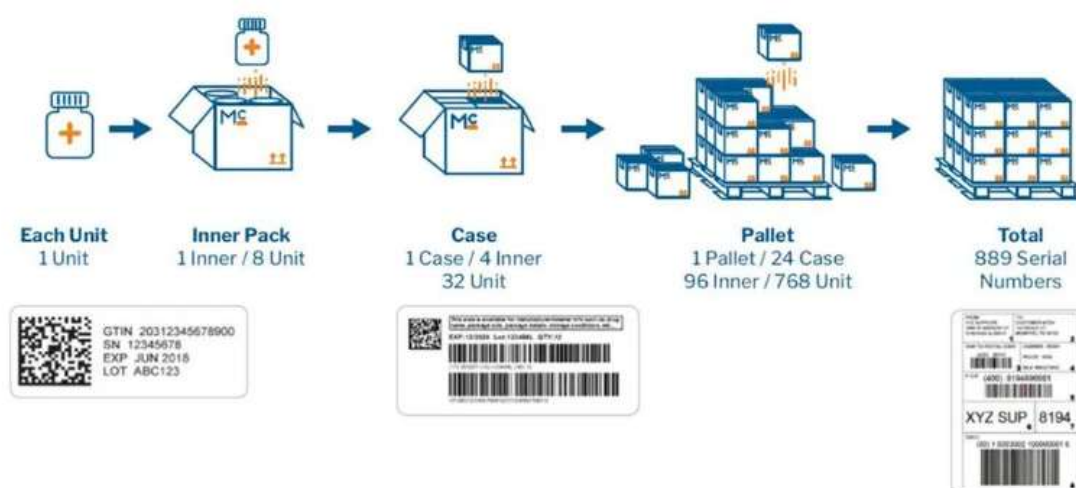


Figure 2: Serialization + QR Code + Product Authentication

Source: Adapted from McKesson Medical-Surgical, Drug Supply Chain Security Act (DSCSA) Overview & FAQ.

Serialization is crucial in a pharmaceutical track and trace system because it allows pharmaceutical products or packages to be given unique identification information. Serialization can provide information on individual products as well as track them across the supply chain, unlike systems based on general product or batch data. Research on pharmaceutical serialization has shown that unique identification can enhance the product level traceability and verification and supply chain visibility (Alhossainy et al., 2022; Kshetri, 2018). But manufacturers and other entities in the product value chain must have appropriate systems for creating, recording, scanning, storing and sharing product information, for effective serialization. QR codes or other identification technologies alone can also not ensure traceability if the stakeholders are not equipped with the necessary infrastructure, system integration and data-management capabilities (Pournader et al., 2020).

Track and trace technology can be used to enhance the visibility of the pharmaceutical supply chain, enabling all relevant parties to follow the medicines as they progress through the various steps in the supply chain. Traceability can help establish product authenticity, detect suspicious products, aid product recall and minimize possible counterfeit medicines entering legal supply. Studies on supply-chain traceability in the pharmaceutical industry have demonstrated that supply-chain information-

sharing mechanisms and product identification can enhance visibility and facilitate the detection of irregularities at various points in the supply-chain (Mackey & Nayyar, 2017; Tseng et al., 2021). Pharmaceutical track and trace in this context needs to be seen not only as a technological mechanism, but as a system, which includes product identification, data collection, information sharing, regulatory compliance and coordination of activities between actors in the supply chain.

Different technologies have been used to enhance pharmaceutical supply-chain transparency and traceability. These include Radio Frequency Identification (RFID), Near-Field Communication (NFC), Internet of Things (IoT), QR codes, barcode systems and cloud-integrated tracking platforms. Product information can be collected, transmitted and exchanged through such technologies, which could help in the manufacturing, transportation, storage and distribution of products (Aung & Chang, 2014; Haji, M., et.al., 2021). Blockchain has also been identified as a technology that can help bolster pharmaceutical traceability due to its features of transparency, decentralisation and immutability of records (Tseng et al., 2021). But rather than being the focus of the present study, blockchain technology should be considered one of multiple technological options.



Figure 3: Digital Technologies Supporting Track-and-Trace

Source: https://www.pharmatrax.net/smart-packaging-in-pharma-beyond-the-box/?utm_source=chatgpt.com

1.2. Readiness of Pharmaceutical Supply-Chain Stakeholders

The existence of regulatory requirements and technological solutions does not automatically ensure effective pharmaceutical track-and-trace. It is crucial that the stakeholders involved in the pharmaceutical supply chain (PSC) are prepared and ready for the successful implementation (Pagonidis, T., et.al., 2020). These stakeholders are pharmaceutical manufacturers, API suppliers, distributors, wholesalers, logistics suppliers, pharmacies and other concerned organizations. The technological, organisational and human capabilities of each stakeholder should be sufficient to create, record, exchange and verify information on pharmaceutical products (Kootstra, G. & Kleinhout-Vliek, T. 2021).

Digital infrastructure is thus an integral part of preparing for track-and-trace. For pharmaceutical companies, the right hardware and software solutions, bar code or QR-code scanners, information-management systems, stable connections, data-storage facilities, and suitable enterprise systems are crucial (Hassan, M. M., et al. 2020). The ability of different stakeholders to connect their systems is also crucial since pharmaceutical products flow through several organisations before reaching

patients. When systems are not integrated or not able to communicate, there is a chance of loss or difficulty in verifying product information (Ma, J.-Y. et. al, 2023). In this regard, the assessment of readiness of the digital infrastructure can be useful to identify whether there is the technological capacity among stakeholders to implement effective pharmaceutical traceability

Another key aspect of readiness is data governance. Track and trace systems create and share significant amounts of data on the product, manufacturer, batch numbers, serial numbers, and movement history, among other supply-chain data (Nabiyeva, A., & Wu, D. Z. Y. 2018). Data governance needs to have the proper tools and processes for data accuracy, consistency, security and availability, along with controlled sharing. Even with a sophisticated tracking technology, weak data-management practices can jeopardize the effectiveness of traceability. As a result, appropriate data collection, storage, access, sharing, protection and regulatory reporting policies and practices are needed among pharmaceutical stakeholders.

The ability to be serialized also is crucial. Stakeholders need to create or read unique product identifiers, scan QR codes or barcodes, keep track of product and batch information and incorporate serialization data into their current systems. Manufacturers may require to create and maintain information about the products; distributors, wholesalers and pharmacies may require the ability to scan and verify products as they pass through the supply chain (Alsamani, A., & Beckmann, A. 2026). However, technological differences of the various interested parties can lead to gaps within the overall traceability system.

The preparedness of stakeholders in the pharmaceutical supply-chain should therefore be evaluated beyond the availability of technology to also include capabilities for implementation, worker skills, organizational readiness, data management, interoperability of systems and regulatory compliance (Ma, J.-Y., et.al., 2023). Even if the manufacturer has the most sophisticated serialization system, a pharmaceutical company may not be able to establish end-to-end traceability if distributors, wholesalers or retailers do not use a system compatible with the manufacturer's system. Track-and-trace readiness is not the ability of one organisation but rather is a collective ability of the pharmaceutical supply chain.

Then, the present study can be directed towards evaluating the readiness of the pharmaceutical supply-chain players in India for effective implementation and operation of track and trace systems. Specific emphasis may be placed on digital infrastructure, data governance and serialization capability, and technological and organisational preparedness of various stakeholders. This type of evaluation can reveal any gaps between expectations and current implementation practices, and can serve as a foundation for enhancing the effectiveness, transparency and security of the pharmaceutical supply chain in India (O'Mahony, D., et.al., 2024).

2. BACKGROUND MATERIALS

2.1. Pharmaceutical Supply Chain, Product Tracking and Traceability

“Pharmaceutical supply chain (PSC) is a very complex chain of actors who work in the sourcing of pharmaceutical ingredients, in the manufacture, packaging, and distribution and delivery of medicines to the patients”. According to the study, the PSC comprises a diversified product mix, production methods and distribution channels, and has a multi-location (geographically distributed) chain with several actors involved throughout the chain. (Musamih, A., et.al., 2021) The actors can be suppliers, manufacturers, contract manufacturing and packaging companies, wholesalers or distributors, pharmacies, healthcare providers and patients. These interactions are complicated and present challenges in maintaining a continuous line of sight for pharmaceutical products and information throughout the supply chain (Sunny, J., et.al., 2020).

Particularly in the case of pharmaceuticals, the flow of information is as crucial as the flow of the product, with activities along the supply chain relying on timely exchange of product and transaction information. “The study identifies material flows, information flows and financial flows in the pharmaceutical supply chain and highlights the significance of information flow in mitigating risks in the pharmaceutical supply chain. Poor visibility of information may lead to problems verifying the authenticity and track of pharmaceutical products, making it more likely that counterfeit medicines will get into legitimate supply systems” (Nanda, S. K., et.al., 2023).

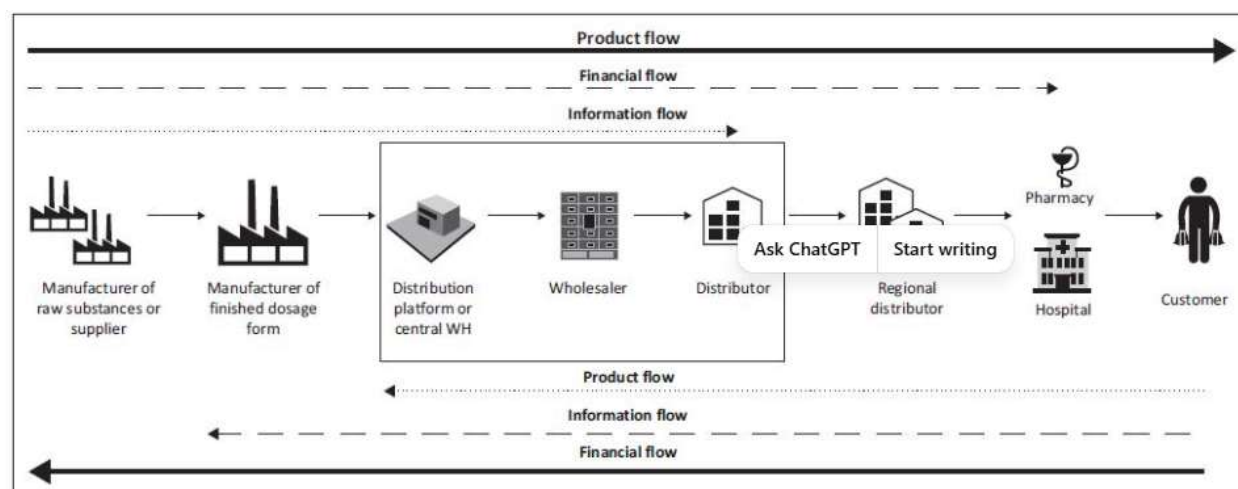


Figure 4: Material–Information–Financial Flow in Pharmaceutical Supply Chain

Source: https://jsaer.com/download/vol-9-iss-2-2022/JSAER2022-9-2-156-160.pdf?utm_source=chatgpt.com

A solution to this issue can be provided by Product tracking and tracing, which allow identifying the movement of pharmaceutical products throughout the supply chain both in the past and in the present. Track and trace is linked to the maintenance of transaction information, product history, product origin, and distribution information and changes of ownership in the study. The information can be used for product authentication and enhance pharmaceutical supply chain visibility (Panda, S. K., & Satapathy, S. C. 2024). Track and trace for the present study is thus seen not only as a technology application but as a capability which needs to be supported by the right infrastructure, reliable information and co-ordination of all the stakeholders involved.

2.2. Product Serialization and Digital Technologies for Pharmaceutical Traceability

Product serialization is a core element in pharmaceuticals' track-and-trace system. Serialization refers to the process of assigning a unique identifier to a pharmaceutical product or unit, allowing it to be traced and tracked in the supply chain. The study defines serialization as the method of assigning a unique identifier to help track and trace products. It also states that two dimensional bar codes can store information including Lot Number and Expiration Date, and standard GTIN, GLN and SSCC may be used to identify products, locations and shipping containers (Chiacchio, F., et.al., 2022).

Serialization is crucial because if a single product or batch is required to be verified, simple product or batch identification may be not enough to give clarity. The study emphasizes the difference between lot-level traceability and item level traceability and points out that product serialization is one of the crucial requirements to attain more detailed pharmaceutical traceability (Bapatla, A. K., et.al., 2024). In this study, serialization capability is defined as the ability of supply-chain participants to create, collect, read, store and employ unique product identifiers within the various steps of the supply chain.

Another way of pharmaceutical identification and tracking is Radio Frequency Identification (RFID). In comparison to the traditional bar code, RFID technology does not need to be scanned in line of sight and therefore can enable more automation in inventory management and product monitoring (Amin, M. R., et.al., 2025). The study covers a number of the uses of RFID technology including real-time tracking, incident reporting, product integrity and anti-counterfeiting. Another technology being suggested for the pharmaceutical applications is near field communication (NFC). It can be used for product authentication, inventory management, traceability and temperature monitoring, especially with high value pharmaceuticals.

2.3. Data Governance, Stakeholder Readiness and the Indian Regulatory Context

“Achieving effective track and trace in the pharmaceutical supply chain depends on the consistent flow of accurate product data between different players in the supply chain”. The study highlights the key challenges in the pharmaceutical supply chain such as information fragmentation, lack of standardisation, data security and regulatory compliance (Maurya, A. P., Suri,

P. K. 2026). There may be variations in data formats and communication protocols between different systems, posing a potential obstacle to data interoperability and limiting product tracking in real time. Thus, readiness for track and trace needs to go beyond the physical technologies and embrace the management and governance of the pharmaceutical supply-chain data.

Data governance for pharmaceutical traceability is the series of processes by which product data is created, documented, verified, saved, retrieved, distributed and secured. Master data for the product, vendor information, location information, inventory and logistics information and other supply-chain information may need to be shared between manufacturers, distributors, pharmacies, hospitals and regulatory authorities (Kaginalkar, A., et.al., 2023). The study case on supply-chain data systems illustrates the significance of having connected information about products, customers, vendors, locations, inventory and logistics.

Data quality and interoperability are especially critical since meaningful visibility through a track-and-trace system relies on the ability of data created at one point in the supply chain to be accurately interpreted and leveraged at another point in the chain (Amin, M. R., et.al., 2025). The study highlights that interoperability issues, delays and difficulties in tracking in real time can arise due to differences in data formats and communication protocols. Therefore, the present study considers the readiness for data governance as an essential component of readiness for track and trace in the pharmaceutical industry.

Therefore, the present study proposes to understand the readiness for track and trace in the Pharmaceutical industry in terms of three interconnected preparatory capacities: (i) Digital Infrastructure readiness, (ii) Data Governance readiness, and (iii) Serialization Capabilities. Digital infrastructure is the foundation of whether or not stakeholders have the hardware, software, connectivity and system integration they need to achieve traceability; data governance is the foundation of whether or not pharmaceutical information can be managed and transferred accurately, securely and consistently; and serialization capability is the foundation of whether or not individual pharmaceutical products can be uniquely identified and tracked across the supply chain. This combination of these capabilities decides how ready Indian stakeholders in the supply chain are to implement effective track and trace systems (Bapatla, A. K., et.al., 2024).

3. RELATED PRIOR RESEARCH

Theme 1: Pharmaceutical Track-and-Trace, Transparency, Product Authentication and Regulatory Compliance

The tracking and tracing systems for pharmaceuticals became more significant for enhancing medicines safety, visibility and supply chain transparency. Ozawa et al. (2018) discovered how common substandard and falsified medicines are, especially in low and middle income countries. Mackey et al. (2021) discovered that track-and-trace systems might facilitate to keep misrepresented products away from the correct pharmaceutical circulation. Saeed et al. (2022) also emphasized the need for greater pharmaceutical supply-chain transparency and accountability using digital technologies. Also, the WHO (2024) called for enhanced regulation and supply chain monitoring and oversight to combat falsified medicines. The results showed that tracking needed collaborative action and accurate data from various actors in the pharmaceutical value chain. Thus, preparedness in tracking and tracing was crucial for the enhancement of pharmaceutical transparency and regulatory control.

Pharmaceutical traceability was critical due to the need for correct identification of medicines as they traveled up and down the supply chain. Serialization allowed each individual pharmaceutical product, or package, to be identified with unique codes for verification and monitoring purposes. GS1 (2023) highlighted the need for traceability of pharmaceuticals, including the exchange of information between different parties, must be carried out by means of a serialised identification and serialised information exchange. (Mackey et al. 2021) found that the success of a track and trace system would be dependent upon the implementation conditions and stakeholders involved. (Saeed et al 2022) further identified product identification and traceability technologies as important mechanisms for increasing the accountability of the pharmaceutical supply-chain. WHO (2024) emphasized the importance of effective regulatory surveillance to ensure that patients are not exposed to falsified medicines. Therefore, product authentication, transparency and regulatory compliance all helped pharmaceuticals to be prepared for track-and-trace.

Theme 2: Digital Infrastructure, Data Governance, Serialization and Technology Adoption in Pharmaceutical Track-and-Trace

Digital infrastructure was the new technological platform needed to monitor pharmaceuticals' movement along the supply chain. Product identification, information collection and movement tracking might be assisted by QR codes, barcodes, RFID and NFC and IoT technologies. Saeed et al. (2022) pointed out that digital technologies are emerging as crucial tools to enhance pharmaceutical supply-chain transparency and monitoring. The study also mentioned QR codes, barcodes, RFID and NFC as methods of pharmaceutical tracking and tracing. GS1 (2023) also stressed that systems within the supply chain need to be interoperable for the exchange of serialized product information. The results indicated that in addition to technology availability, digital readiness was also dependent on connectivity, integration and interoperability. Thus, proper digital infrastructure was crucial for the implementation of pharmaceutical track and trace.

Data governance was also critical as track and trace systems demanded constant generation, storage and interchange of pharmaceutical data. Data could be fragmented and standards, communication systems incompatible, limiting visibility and effectiveness in tracking the supply chain. The study revealed three main challenges for pharmaceutical supply-chain information systems, namely information fragmentation, standardisation and data security and interoperability. In a similar vein, Saed et al. (2022) highlighted a link between digital technologies, transparency and governance in the pharmaceutical supply chain. GS1 (2023) emphasised the need for standardised information exchange for serialised traceability. Thus, the data governance, along with digital infrastructure and capabilities for serialization and technology, were essential for effective track and trace.

4. RESEARCH GAP AND PROBLEM STATEMENT

➤ Research Gap

The literature has already laid the groundwork for the significance of pharmaceutical track-and-trace systems, such as their ability to enhance product visibility, combat counterfeiting and bolster supply-chain oversight. (Ozawa et al. 2018) pointed to the large scale and economic impact of substandard and falsified medicines, and Mackey et al. (2021) illustrated how track-and-trace systems might reduce the likelihood of the entry of falsified medicines into legitimate drug distribution channels. (Saeed et al. 2022) also highlighted the importance of digital technologies for pharmaceutical supply chains for enhancing transparency and accountability. In GS1 (2023), the need for serialization and standardized exchange and/or interoperability of information for effective pharmaceutical traceability was emphasized. But the literature so far has concentrated on the advantages, technologies and implementation conditions of pharmaceutical track-and-trace and not on the empirical assessment of the readiness of various stakeholders in the pharmaceutical supply chain. However, there has been sparse research attention paid to the interaction between digital infrastructure readiness, data governance readiness, and serialization capability and technology adoption capability in explaining pharmaceutical track-and-trace readiness. In addition, there is a lack of empirical evidence to identify the association between supply chain transparency and product authentication and regulatory compliance in the Indian pharmaceutical setting. Hence, the present research tries to fill this gap by investigating these relationships and evaluating the effect of the Digital infrastructure, Data governance and capability of serialization and technology adoption on the readiness of the pharmaceutical track-and-trace among stakeholders of the supply chain in India.

➤ Problem Statement

Despite its pivotal position in ensuring availability, quality and safety of medicines, the pharmaceutical supply chain in India is still fraught with challenges around counterfeit and falsified products, limited product visibility, fragmented information systems, and challenges with maintaining end-to-end traceability. Pharmaceutical track and trace mechanisms, serialization systems, QR codes, barcodes, and other digital technologies are being increasingly touted as ways to enhance product identification and transparency within the supply chain but the presence of track and trace technologies doesn't necessarily mean that all stakeholders within the supply chain are ready to implement and operate that technology effectively. Track and trace may be hampered by differences in digital infrastructure, data-management practices, system interoperability, serialization capabilities and technological adoption. In addition, there are significant variations between pharmaceutical companies, distributors, wholesalers, pharmacies, hospitals and other stakeholders regarding their technological capabilities, data governance and organisational readiness. The literature has been mainly focussed on the benefits and technology possibilities of track-and-trace systems for pharmaceuticals, with relatively little empirical research interest in the readiness of stakeholders in India's pharmaceutical supply chain and what accounts for that readiness. More specifically, the contribution

of Digital Infrastructure Readiness, Data Governance Readiness, Serialization Capability and Technology Adoption Capability to the pharmaceutical track-and-trace readiness has been hardly explored. This is why it is essential to have an empirical assessment of pharmaceutical track-and-trace readiness in India that looks into the correlation between: Supply-Chain Transparency and Product Authentication and Regulatory Compliance, and the effectivity of the digital infrastructure, data governance, serialization and capabilities in adopting track-and-trace technology in the supply-chain of pharmaceutical products.

5. RESEARCH FRAMEWORK AND METHODOLOGY

➤ Research Framework

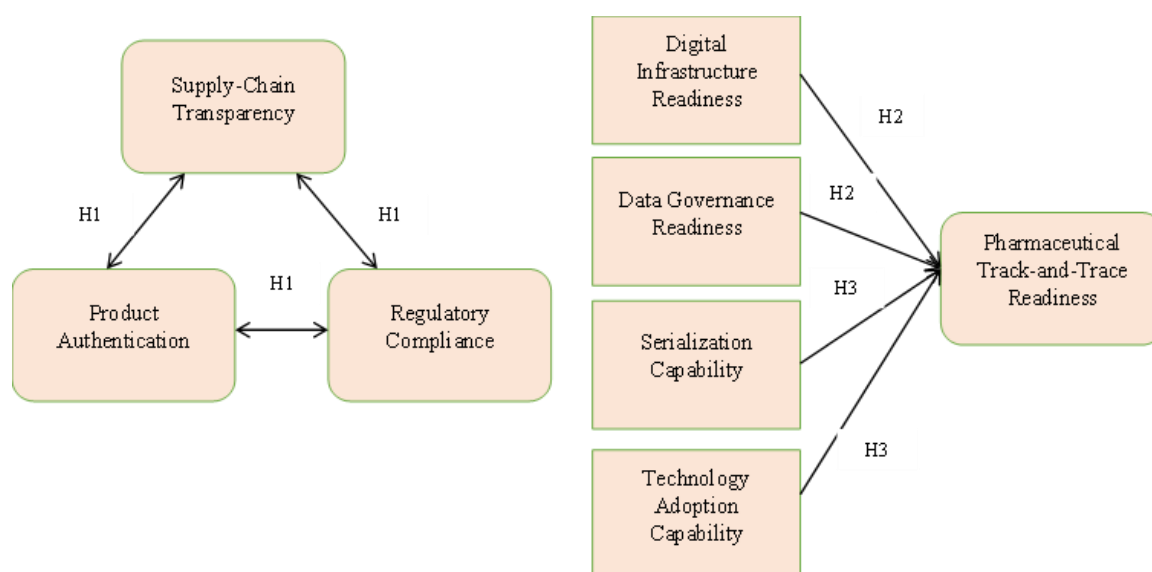


Figure 5: Research Framework

Source: Author own Collaboration

➤ Research Methodology

This study used a quantitative empirical research design to evaluate the preparedness of the stakeholders in the pharmaceutical track and trace in India. Primary data was collected from 200 respondents across various stakeholders in the pharmaceutical supply chain, such as manufacturers, distributors, wholesalers, retail pharmacies, hospitals/healthcare providers, logistics/transportation sector, regulatory/compliance, and IT/digital technology. The research instrument was a structured questionnaire consisting of constructs that were deemed important in the context of Supply-Chain Transparency, Product Authentication, Regulatory Compliance, Digital Infrastructure Readiness, Data Governance Readiness, Serialization Capability, Technology Adoption Capability, and Pharmaceutical Track-and-Trace Readiness. The characteristics and responses of the participants were summarised using descriptive statistics. The relationship between each of Supply-Chain Transparency, Product Authentication and Regulatory Compliance was explored using Pearson correlation analysis, and the role of Digital Infrastructure Readiness and Data Governance Readiness on Pharmaceutical Track-and-Trace Readiness was investigated by multiple regression analysis, as was the role of Serialization Capability and Technology Adoption Capability on Pharmaceutical Track-and-Trace Readiness. Data were analysed statistically with SPSS and the hypothesis testing was done based on the significance of the correlation and regression coefficients. The study therefore attempted to empirically measure the technological, data-related and serialization readiness of track and trace preparedness of pharmaceutical industry in India.

6. RESULTS AND ANALYSIS

Table 1: Demographic Characterstictis

S.NO.	Demographic Characterstictis		N	%
1	Gender	Male	103	51.5%
		Female	97	48.5%
2	Age Group	Below 25 years	54	27.0%
		25–34 years	41	20.5%
		35–44 years	44	22.0%
		45–54 years	33	16.5%
		55 years and above	28	14.0%
3	Educational Qualification	Diploma/Certificate	34	17.0%
		Undergraduate	32	16.0%
		Postgraduate	43	21.5%
		Professional Qualification	41	20.5%
		Doctorate	50	25.0%
4	Current Role in the Pharmaceutical Supply Chain	Manufacturer	28	14.0%
		Distributor	23	11.5%
		Wholesaler	24	12.0%
		Retail Pharmacy	12	6.0%
		Hospital/Healthcare Provider	32	16.0%
		Logistics/Transportation	23	11.5%
		Regulatory/Compliance	22	11.0%
		IT/Digital Technology	20	10.0%
		Other	16	8.0%
5	Years of Experience in the Pharmaceutical Industry	Less than 2 years	38	19.0%
		2–5 years	36	18.0%
		6–10 years	33	16.5%
		11–15 years	46	23.0%
		More than 15 years	47	23.5%
6	Size of the Organisation	Micro	37	18.5%
		Small	39	19.5%
		Medium	53	26.5%
		Large	34	17.0%
		Very Large	37	18.5%

The demographic data of the 200 respondents that were used in the study are displayed in Table 1. The gender distribution revealed that there were 103 male respondents (51.5%) and 97 female respondents (48.5%) which is almost equal. As per age group, maximum 27.0% respondents were below 25 years, 22.0% were in the age group of 35-44 years, 20.5% were in the age group 25-34 years and 16.5% were in the age group 45-54 years and 14.0% were in age group of 55 years and above. In terms of educational qualification, Doctorate was the largest group (25.0%), followed by postgraduate (21.5%), professionally qualified (20.5%), diploma/certificate (17.0%) and undergraduates (16.0%). As to their current jobs in the pharmaceutical supply chain, Hospital/Healthcare Providers represented the largest group (16.0%), followed by manufacturers (14.0%),

wholesalers (12.0%), distributors and Logistics/Transportation professionals (11.0% each), regulatory/compliance professionals (11.0%), IT/digital technology professionals (10.0%), other roles (8.0%) and retail pharmacy respondents (6.0%). As far as experience in industry, the respondents who had 11-15 years of experience were the next largest group (23.0%), followed by those who had more than 15 years of experience (23.5%) then those who had less than 2 years of experience (19.0%), 2-5 years of experience (18.0%) and 6-10 years of experience (16.5%). The medium-sized organisations had the largest number of respondents (26.5%), followed by the small organisations (19.5%), the micro organisations (18.5%) and the very large organisations (18.5%) and the large organisations (17.0%). In general, the sample comprised a cross-section of respondents by demographic, professional, experiential and organisational characteristics, and this offered adequate representation of the various stakeholders in the pharmaceutical supply chain to explore track-and-trace readiness.

Objective 1: To examine the relationship between Supply-Chain Transparency, Product Authentication, and Regulatory Compliance in pharmaceutical track-and-trace systems in India.

H1: There is a significant relationship between Supply-Chain Transparency, Product Authentication, and Regulatory Compliance in pharmaceutical track-and-trace systems in India.

Table 2: Descriptive Statistics

Descriptive Statistics			
	Mean	Std. Deviation	N
Supply-Chain Transparency	18.0000	3.83714	200
Product Authentication	16.3400	3.34820	200
Regulatory Compliance	16.6900	4.00426	200

Table 2 shows descriptive statistics for the responses on the Supply-Chain Transparency, Product Authentication, and Regulatory Compliance scales for 200 respondents. A medium level of perceived supply-chain transparency in the respondents was seen in the mean score of 18.00, which had a standard deviation of 3.837. The mean score for Product Authentication was 16.34 and the standard deviation 3.348, indicating a relatively low variation and moderate level of Product Authentication practices. Respondents generally indicated a positive level of regulatory compliance with a mean score of 16.69 and the highest standard deviation of 4.004, indicating that while general levels of compliance were positive, there was a certain degree of variation across respondents. Results showed that the highest mean score was for Supply-Chain Transparency and the lowest mean score was for Product Authentication compared to the three variables. The standard deviations indicated a moderate range of variation for participants' perception on the measured constructs.

Table 3: Correlations

Correlations				
		Supply-Chain Transparency	Product Authentication	Regulatory Compliance
Supply-Chain Transparency	Pearson Correlation	1	.389**	.273**
	Sig. (2-tailed)		.000	.000
	N	200	200	200
Product Authentication	Pearson Correlation	.389**	1	.247**
	Sig. (2-tailed)	.000		.000
	N	200	200	200
Regulatory Compliance	Pearson Correlation	.273**	.247**	1
	Sig. (2-tailed)	.000	.000	
	N	200	200	200

**, Correlation is significant at the 0.01 level (2-tailed).

Pearson correlation analysis results of the respondents (n = 200) are shown in Table 3. The findings revealed that there was a significant positive correlation between Supply-Chain Transparency and Product Authentication ($r = 0.389$, $p < 0.01$), which means that the higher the level of transparency in the supply chain, the higher the level of product authentication. Regulatory Compliance also showed a strong positive correlation with Supply-Chain Transparency ($r = 0.273$, $p < 0.01$), indicating that

the higher the transparency, the better the regulatory compliance. Moreover, the correlation between Product Authentication and Regulatory Compliance ($r = 0.247$, $p < 0.01$) was found to be significant and positive, suggesting that better practices in product authentication correlates with better practices in regulatory compliance. The 1% (two-tailed) significance level was achieved for all three relationships. The relationship between Supply-Chain Transparency and Product Authentication was found to be the strongest ($r = 0.389$), followed by the relationship between Supply-Chain Transparency and Regulatory Compliance ($r = 0.273$) and the relationship between Product Authentication and Regulatory Compliance was comparatively weaker ($r = 0.247$).

Objective 2: To assess the impact of Digital Infrastructure Readiness and Data Governance Readiness on Pharmaceutical Track-and-Trace Readiness among supply-chain stakeholders in India.

H2: Digital Infrastructure Readiness and Data Governance Readiness have a significant positive impact on Pharmaceutical Track-and-Trace Readiness among supply-chain stakeholders in India.

Table 4: Model Summary

Model Summary				
Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.720 ^a	.519	.514	2.57813
a. Predictors: (Constant), Data Governance Readiness, Digital Infrastructure Readiness				

Table 4 shows the model summary for the regression analysis of the effect of Digital Infrastructure Readiness and Data Governance Readiness on Pharmaceutical Track-and-Trace Readiness. The R value obtained for the model was found to be 0.720, which represents a strong positive correlation between the combination of the predictor variables and Pharmaceutical Track and Trace Readiness. The value of R Square was 0.519 which means that 51.9% of the variance in Pharmaceutical Track-and-Trace Readiness was explained together with Digital Infrastructure Readiness and Data Governance Readiness. The Adjusted R Square of 0.514 showed that the model continued to explain 51.4% of the variance after adjusting for the number of predictors included in the model. The standard error of the estimate was 2.57813, which meant that the average prediction error in the regression model was 2.57813. In general, the findings indicated that, Digital Infrastructure Readiness and Data Governance Readiness explained significantly variance in Pharmaceutical Track-and-Trace Readiness.

Table 5: ANOVA^a

ANOVA ^a						
Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	1412.744	2	706.372	106.273	.000 ^b
	Residual	1309.411	197	6.647		
	Total	2722.155	199			
a. Dependent Variable: Track-and-Trace Readiness						
b. Predictors: (Constant), Data Governance Readiness, Digital Infrastructure Readiness						

The ANOVA results used to determine the overall significance of the regression model as Digital Infrastructure Readiness and Data Governance Readiness are used to predict Pharmaceutical Track-and-Trace Readiness is provided in Table 5. The regression sum of squares was 1412.744 (2 degrees of freedom) and the residual sum of squares was 1309.411 (197 degrees of freedom). The obtained F-value was 106.273 with a significance value of 0.000 ($p < 0.001$). The significance value was less than 0.05, which means that the regression model was statistically significant, meaning that Digital Infrastructure Readiness and Data Governance Readiness taken together was a significant predictor of Pharmaceutical Track-and-Trace Readiness. Hence the model accounted for the variability in the dependent variable, at a statistically significant level. Thus, acceptance of

H2 validated the high positive effect of the Pharmaceutical Track-and-Trace Readiness among Indian supply chain stakeholders on the Pharmaceutical Track-and-Trace readiness of Digital Infrastructure Readiness and Data Governance Readiness.

Table 6: Coefficients^a

Coefficients ^a					
Model		Unstandardized Coefficients		Standardized Coefficients	t
		B	Std. Error	Beta	
1	(Constant)	3.752	1.028		3.651
	Digital Infrastructure Readiness	.334	.068	.295	4.942
	Data Governance Readiness	.497	.058	.513	8.606
a. Dependent Variable: Track-and-Trace Readiness					

Table 6 shows the regression coefficients for studying the effect of digital infrastructure readiness and data governance readiness on pharmaceutical track-and-trace readiness individually. The results indicated that Digital Infrastructure Readiness significantly positively affected the Pharmaceutical Track-and-Trace Readiness, unstandardized coefficient (B) = 0.334, standardized beta (β) = 0.295, $t = 4.942$ and $p = 0.000$. This suggests that the DIR had a positive relationship with the PTR. Likewise, Data Governance Readiness showed significant positive effect with $B = 0.497$, $\beta = 0.513$, $t = 8.606$ and $p = 0.000$. The standardized beta values showed that Data Governance Readiness ($\beta = 0.513$) had a greater relative contribution to the Pharmaceutical Track-and-Trace Readiness compared to Digital Infrastructure Readiness ($\beta = 0.295$). The significance values were both less than 0.05 indicating that both effects were significant.

Objective 3: To evaluate the impact of Serialization Capability and Technology Adoption Capability on Pharmaceutical Track-and-Trace Readiness among supply-chain stakeholders in India.

H3: Serialization Capability and Technology Adoption Capability have a significant positive impact on Pharmaceutical Track-and-Trace Readiness among supply-chain stakeholders in India.

Table 7: Model Summary

Model Summary				
Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.422 ^a	.178	.170	3.36962
a. Predictors: (Constant), Technology Adoption Capability, Serialization Capability				

Table 7 is the model summary table for the regression analysis that was conducted to determine the effect of Serialization Capability and Technology Adoption Capability on the Pharmaceutical Track-and-Trace Readiness. The model obtained the value of R 0.422 which is positive, and therefore there is a positive relationship between the collective predictor variables and Pharmaceutical Track-and-Trace Readiness. The R Square value of 0.178 showed that Serialization Capability and Technology Adoption Capability accounted for 17.8% of the variance in Pharmaceutical Track-and-Trace Readiness. The value of Adjusted R Square was 0.170, suggesting that 17.0% of the variance in the dependent variable was accounted for by the model, after adjusting for the number of predictors in the model. The standard error of the estimate was 3.36962, which is the average prediction error of the regression model.

Table 8: ANOVA^a

ANOVA ^a						
Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	485.349	2	242.674	21.373	.000 ^b
	Residual	2236.806	197	11.354		
	Total	2722.155	199			
a. Dependent Variable: Track-and-Trace Readiness						
b. Predictors: (Constant), Technology Adoption Capability, Serialization Capability						

The ANOVA analysis for the overall significance of the regression model using Serialization Capability and Technology Adoption Capability as the independent variables to predict Pharmaceutical Track-and-Trace Readiness is presented in Table 8. The results yielded a regression sum of squares of 485.349 and 2 degrees of freedom and a residual sum of squares of 2236.806 and 197 degrees of freedom. The obtained F-value was 21.373 with a significance value of 0.000 ($p < 0.001$). The regression model was statistically significant as the p-value was less than the cut-off value of 0.05, which means that both Serialization Capability and Technology Adoption Capability together significantly predicted Pharmaceutical Track-and-Trace Readiness. Thus, this regression model was a significant explanation of variation of the dependent variable. Thus, H3 was accepted which means that the total effect of both Serialization Capability and Technology Adoption Capability had a significant positive effect on the Pharmaceutical Track-and-Trace Readiness of the stakeholders in supply chain in India.

Table 9: Coefficients

Coefficients ^a						
Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	9.163	1.396		6.564	.000
	Serialization Capability	.163	.062	.176	2.645	.009
	Technology Adoption Capability	.378	.074	.343	5.140	.000
a. Dependent Variable: Track-and-Trace Readiness						

Table 9 shows the regression coefficients for the individual impact of Serialization Capability and Technology Adoption Capability on Pharmaceutical Track-and-Trace Readiness. The results indicated that the unstandardized coefficient (B) of the Serialization Capability was 0.163, the standardized coefficient (β) was 0.176, $t = 2.645$, and $p = 0.009$. This suggests that there was a relationship between the increase in Serialization Capability and the increase in Pharmaceutical Track-and-Trace Readiness. Similarly, Technology Adoption Capability had a significant positive effect, with $B = 0.378$, $\beta = 0.343$, $t = 5.140$, and $p = 0.000$. When the standardized beta value was used to indicate strength of relative contribution in the model, Technology Adoption Capability showed Beta value of 0.343, which was higher than the Beta value obtained for Serialization Capability (0.176). Both predictors were significant with values less than 0.05, meaning they have a statistical impact.

7. DISCUSSION AND IMPLICATIONS

➤ Discussion

The results of the present study showed that there are significant positive correlations between Supply-Chain Transparency and Product Authentication and between Supply-Chain Transparency and Regulatory Compliance. Supply-Chain

Transparency had the highest correlation with Product Authentication ($r = 0.389$, $p < 0.01$) and the second highest correlation with Regulatory Compliance ($r = 0.273$, $p < 0.01$); Product Authentication also had a significant correlation with Regulatory Compliance ($r = 0.247$, $p < 0.01$). The results showed that there was a positive correlation between visibility of pharmaceutical products and supply chain information and authentication and compliance practices. The results were also in line with the study that end-to-end traceability may help verify the product, traceability, and transparency throughout complex pharmaceutical networks (Hossain et al., 2023; Musamih et al., 2021). Pharmaceutical traceability systems also showed that the blockchain technology could enhance accountability by providing secure product histories and provenance systems that can help minimize the chances of counterfeiting products entering legitimate supply chains (Anwar et al., 2023; Tseng et al., 2021). Likewise, recent studies showed that blockchain-based traceability systems combined with IoT could facilitate real-time monitoring and product verification, which would enhance the visibility in the pharmaceutical supply chain (DrugTrace, 2026; Dutta & Priya, 2026). The results then indicated that transparency, authentication and regulatory compliance are not separate operational activities, but rather, they are interrelated in pharmaceutical traceability preparedness.

The regression results also showed that Digital Infrastructure Readiness and Data Governance Readiness together accounted for 51.9% of the variance in Pharmaceutical Track-and-Trace Readiness, and both variables had positive and significant effects. This was compared to the Digital Infrastructure Readiness ($\beta = 0.295$) and in this case, technological infrastructure was better developed with the help of reliable data management and information sharing capabilities (Data Governance Readiness). The second regression model further revealed that both Serialization Capability ($\beta = 0.176$) and Technology Adoption Capability ($\beta = 0.343$) significantly influenced the variance in Pharmaceutical Track-and-Trace Readiness, accounting for 17.8% of the variance. Technology Adoption Capability contributed more to the variance in Pharmaceutical Track-and-Trace Readiness than Serialization Capability. The findings were aligned with existing studies that showed that it was not only technology deployment but also quality and quantity of the data collected and the adoption and interoperability and scalability of the stakeholder that influenced the effectiveness of traceability (Choi et al., 2023; Musamih et al., 2021). In addition, recent mapping studies revealed that governance, access control and reliable on-chain/off-chain data management (Díaz et al., 2026) were significant factors in explaining pharmaceutical traceability outcomes. The studies on blockchain-based pharmaceutical systems also highlighted that interoperability, data provenance, and multi-stakeholder coordination are significant factors to consider for successful traceability (Anwar et al., 2023; Dutta & Priya, 2026). Scalable solutions for drug tracking were also explored and research indicated that digital infrastructure could help boost transparency and traceability, while scalability and operational deployment are still key factors to consider (Rajak et al., 2026). Based on this, the current research results showed that, pharmaceutical track-and-trace readiness was not just the presence of QR codes/barcodes or other identification technologies but was a multi-dimensional capability that consisted of infrastructure, data governance, serialization and technology adoption.

➤ Implications

The study had several implications to the Indian Pharmaceutical Supply Chain. It pointed to the need for Supply-Chain Transparency to ensure greater product visibility. SAP is a possibility to reinforce medicine verification and safety. Enhanced Regulatory Compliance may help to implement the track and trace requirements effectively. The results highlighted the importance of the need to improve the readiness of Digital Infrastructure among stakeholders. Secure and reliable information exchange was another crucial aspect of Data Governance Readiness. Stakeholders required enhancing their product level identification Serialization Capability. Track and trace implementation could be further enhanced by Greater Technology Adoption Capability. So interoperability, digital capability and preparedness of the stakeholders are the areas of focus for regulators and organisations. Overall, the study provided a basis for developing a more transparent, secure and efficient pharmaceutical track-and-trace system in India.

8. CHALLENGES AND LIMITATIONS

There were several limitations and constraints in the study that should be taken into account in interpreting the findings. The study was based on primary data gathered from the stakeholders of the pharmaceutical supply-chain in India, and variations in roles, organizational size and technological competency of the pharmaceutical companies in the supply-chain might have affected the stakeholder's answer. It was also conducted in a quantitative approach with cross sectional design, thus it could not be used to examine the changes in track and trace readiness over time. Moreover, the analysis was limited to only Digital Infrastructure Readiness, Data Governance Readiness and Serialization Capability and Technology Adoption Capability while

other factors like organisational culture, financial constraints, employee training and cybersecurity were not explored. The conclusions as a result were therefore restricted to these variables and respondents analyzed in the current study.

9. CONCLUSION AND FUTURE RESEARCH DIRECTIONS

The study revealed that transparency; product authentication, regulatory compliance, digital infrastructure, data governance, serialization, and technology adoption are key factors in achieving readiness in the pharmaceutical track and trace system in India. The findings showed significant relationships between transparency, authentication and compliance and the ability to be ready for track and trace, while the regression results proved the significant contribution of digital infrastructure, data governance, serialization and technology adoption on the ability to be ready for track and trace. Enlarging the sample size and geographical distribution of the respondents in the study and incorporating the longitudinal and qualitative methods to gain more insight about the stakeholder experiences could be an extension of the study. The research can also be expanded to include cyber-security, employee skills, financial readiness, interoperability and emerging technologies to create a more holistic framework to implement pharmaceutical track-and-trace in India.

REFERENCES

- [1] Alsamani, A., & Beckmann, A. (2026). The role of semantic technologies in addressing systems and data challenges in pharmaceutical supply chains. *Supply Chain Management Research*, 1(2).
- [2] Amin, M. R., Akhtar, N., Hoque, M. E., Nabil, A. R., & Hossain, K. M. S. (2025). Blockchain-enabled traceability in pharmaceutical supply chains: An integrated engineering and IT management framework for regulatory compliance and pandemic resilience. *Journal of Computer Science and Technology Studies*, 7(10), 343-356.
- [3] Anwar, M. M., et al. (2023). PharmaChain: Blockchain-based drug supply chain provenance verification system. *Heliyon*, 9(7), e17957. <https://doi.org/10.1016/j.heliyon.2023.e17957>.
- [4] Aung, M. M., & Chang, Y. S. (2014). Traceability in a food supply chain: Safety and quality perspectives. *Food Control*, 39, 172–184.
- [5] Bapatla, A. K., Mohanty, S. P., & Kougianos, E. (2024). Pharmachain 3.0: efficient tracking and tracing of drugs in pharmaceutical supply chain using blockchain integrated product serialization mechanism. *SN Computer Science*, 5(1), 149.
- [6] Chiacchio, F., D'Urso, D., Oliveri, L. M., Spitaleri, A., Spampinato, C., & Giordano, D. (2022). A non-fungible token solution for the track and trace of pharmaceutical supply chain. *Applied Sciences*, 12(8), 4019.
- [7] Choi, T.-M., et al. (2023). Research on blockchain-enabled pharmaceutical supply-chain traceability and digital information management.
- [8] Díaz, F., Cerna, N., Liza, R., & Motta, B. (2026). Blockchain-enabled traceability in pharmaceutical supply chains: A mapping review of evidence for visibility, anti-counterfeiting, and chain-of-custody control. *Medical Sciences Forum*, 10(4), 85.
- [9] Díaz, F., et al. (2026). Blockchain-enabled traceability in pharmaceutical supply chains: A mapping review of evidence for visibility, anti-counterfeiting, and chain-of-custody control.
- [10] DrugTrace. (2026). DrugTrace: Leveraging blockchain and IoT for anti-counterfeit drug traceability. *SoftwareX*, 34, 102694. <https://doi.org/10.1016/j.softx.2026.102694>.
- [11] Dutta, D., & Priya, G. (2026). Blockchain-based solution for secure and transparent pharmaceutical supply chain management using DrugLedger. *Scientific Reports*. <https://doi.org/10.1038/s41598-026-55187-4>.
- [12] Haji, M., Kerbache, L., Sherif, K. M., & Al-Ansari, T. (2021). Critical success factors and traceability technologies for establishing a safe pharmaceutical supply chain. *Methods and Protocols*, 4(4), 85.
- [13] Hamdi, A. H. A., Hatah, E., & Bakry, M. M. (2024). Operations management of pharmaceutical supply during preparedness and disaster response: A scoping review. *International Journal of Disaster Risk Reduction*.

- [14] Hassan, M. M., et al. (2020). Interoperability challenges in traceability of pharmaceuticals. This source is useful for system interoperability, information exchange and coordination among pharmaceutical supply-chain actors. The study specifically examined interoperability challenges in pharmaceutical traceability.
- [15] Hossain, M. S., et al. (2023). PharmaChain: Blockchain-based drug supply chain provenance verification system. *Heliyon*, 9, e17957.
- [16] Hupman, A. C., Zhang, J., & Li, H. (2024). Predicting pharmaceutical supply chain disruptions before and during the COVID-19 pandemic.
- [17] Ivanov, D. (2021). Supply chain viability and the COVID-19 pandemic: A conceptual and formal generalisation of four major adaptation strategies. *International Journal of Production Research*, 59(12), 3535–3552.
- [18] Kaginalkar, A., Kumar, S., Gargava, P., & Niyogi, D. (2023). Stakeholder analysis for designing an urban air quality data governance ecosystem in smart cities. *Urban Climate*, 48, 101403.
- [19] Kootstra, G., & Kleinhout-Vliek, T. (2021). Implementing pharmaceutical track-and-trace systems: A realist review. *BMJ Global Health*, 6(5), e003755.
- [20] Kshetri, N. (2018). Blockchain's roles in meeting key supply chain management objectives. *International Journal of Information Management*, 39, 80–89. Article DOI
- [21] Ma, J.-Y., Shi, L., & Kang, T.-W. (2023). The effect of digital transformation on the pharmaceutical sustainable supply chain performance: The mediating role of information sharing and traceability using structural equation modeling. *Sustainability*, 15(1), 649.
- [22] 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.
- [23] Maurya, A. P., & Suri, P. K. (2026). Analysing the factors for effective data governance: Indian e-governance context. *IIM Ranchi Journal of Management Studies*, 5(1), 62-82.
- [24] Musamih, A. M., et al. (2021). A blockchain-based approach for drug traceability in healthcare supply chains. *IEEE Access*.
- [25] Nabiyeva, A., & Wu, D. Z. Y. (2018). Implementing serialization in the drug supply chain. *Supply Chain Management Review*.
- [26] Nanda, S. K., Panda, S. K., & Dash, M. (2023). Medical supply chain integrated with blockchain and IoT to track the logistics of medical products. *Multimedia Tools and Applications*, 82(21), 32917-32939.
- [27] O'Mahony, D., Lynch, A., & McDermott, O. (2024). The impact of serialisation on operational efficiency and productivity in Irish pharmaceutical sites. *Therapeutic Innovation & Regulatory Science*, 58, 883–896.
- [28] Pagonidis, T., Sapuric, S., & Lois, P. (2020). Assessing the implementation of serialisation in pharmaceutical industry in Greece: A qualitative approach. *Journal for Global Business Advancement*, 13(1), 4–31.
- [29] Panda, S. K., & Satapathy, S. C. (2024). Drug traceability and transparency in medical supply chain using blockchain for easing the process and creating trust between stakeholders and consumers. *Personal and Ubiquitous Computing*, 28(1), 75-91.
- [30] Pournader, M., Kach, A., & Talluri, S. (2020). A review of the existing and emerging technologies for pharmaceutical supply-chain traceability. *International Journal of Production Research*.
- [31] Queiroz, M. M., Ivanov, D., Dolgui, A., & Wamba, S. F. (2022). Impacts of epidemic outbreaks on supply chains: Mapping a research agenda amid the COVID-19 pandemic through a structured literature review. *Annals of Operations Research*, 319, 1157–1196.
- [32] Rajak, D. K., Khanal, B., & Ansari, M. S. A. (2025). Scalable blockchain-based solution for drug tracking in pharmaceutical supply chain. *Computers & Industrial Engineering*, 111655.

- [33] Rajak, D. K., Khanal, B., & Ansari, M. S. A. (2026). Scalable blockchain-based solution for drug tracking in pharmaceutical supply chain. *Computers & Industrial Engineering*, 111655.
- [34] Rani, J., & Yadav, S. K. (2027). Pharmaceutical Supply Chain Quality Control Towers System Design, Operation Mechanisms, and Compliance. In *Digitally-Enabled Control Towers for Pharmaceutical Supply Chains* (pp. 187-214). IGI Global Scientific Publishing.
- [35] Shekoohi, F., Afkhami, P., Li, B., Khabir, M., & Malekpoor Joneghani, N. (2026). Closed-loop pharmaceutical supply chains: State of the art, emerging trends, and future research needs. *Socio-Economic Planning Sciences*, 106, 102546.
- [36] Sunny, J., Undralla, N., & Pillai, V. M. (2020). Supply chain transparency through blockchain-based traceability: An overview with demonstration. *Computers & industrial engineering*, 150, 106895.
- [37] Tseng, J.-H., Liao, Y.-C., Chong, B., & Liao, S.-W. (2021). Governance on the drug supply chain via gcoin blockchain. *International Journal of Environmental Research and Public Health*, 18(6), 2932.
- [38] Vadia, N., Parmar, R., Kyada, A., & Baldaniya, L. (2026). Regulatory Framework of the Central Drugs Standard Control Organization (CDSCO) in India. In *Pharmaceutical Regulatory Affairs* (pp. 94-110).
- [39] World Health Organization. (2025). Country experiences on implementation of traceability for medical products. Geneva: World Health Organization.
- [40] Yadav, P., Bahmani, K., Pawar, N., & Sharma, A. A. (2021). Review on: Indian Pharma Regulatory System and List of New Drugs Approved by Central Drugs Standard Control Organization in the Year 2021 Till Date. *Int. J. Pharm. Sci. Res*, 12, 5642-5651.