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The Analysis of Scenario Simulations of Smart Pharmaceutical Distribution Model in the Pharmaceutical Supply Chain Industry

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ABSTRACT

This study aimed to analyze the effects of governance, network, technology, member, data, service, and demand-related factors on the performance of smart pharmaceutical distribution systems using agent-based simulation. The research employed a mixed-method design combining library studies, expert interviews, and Delphi analysis to identify key factors affecting pharmaceutical supply chain performance. Data were gathered from Tofigh Daru Company through semi-structured interviews and Delphi surveys involving ten experts, and analyzed using content analysis and Delphi consensus. Subsequently, agent-based simulation was conducted using NetLogo to assess the effects of identified factors and their scenarios on system performance metrics including cost reduction, delivery efficiency, and resilience. Results showed that governance-related factors had the highest overall initial impact on distribution performance, followed by member-related and demand-related factors, although their effects plateaued over time. Data-related factors demonstrated the most sustained and linear positive impact on performance. Network, technology, and service-related factors showed significant but gradually stabilizing effects. Simulation of scenario increases in each factor category revealed that governance, data, and member factors led to the largest performance gains, underscoring the need for multi-factorial integration in system design. Smart pharmaceutical distribution performance is driven by the synergistic interaction of governance structures, technological readiness, robust data systems, skilled members, and adaptive demand strategies. Building resilient, transparent, and efficient pharmaceutical supply chains requires balancing these dimensions, supported by continuous innovation, effective policy frameworks, and workforce development.

Keywords: *Smart pharmaceutical distribution; agent-based simulation; pharmaceutical supply chain; governance; blockchain; data sharing; digital transformation.*

1. Introduction

In the contemporary landscape of pharmaceutical supply chain management, the integration of smart technologies, data-driven innovation, and advanced governance mechanisms has become a critical requirement for achieving efficient, transparent, and resilient distribution systems. The pharmaceutical industry is uniquely characterized by its high regulatory burden, complex multi-stakeholder networks, and the necessity of ensuring the quality, safety, and timely delivery of life-saving drugs (Nagpal et al., 2025). With rising demand, the proliferation of counterfeit drugs, and global disruptions such as pandemics, building robust and smart distribution systems in the pharmaceutical sector has evolved from a strategic advantage into an operational imperative (Sarkar, 2023).

In recent years, blockchain technology has been extensively explored as a means to improve traceability, transparency, and security across pharmaceutical supply chains (Bapatla et al., 2022; Lingayat et al., 2021). Studies highlight that blockchain-enabled networks not only mitigate counterfeiting risks but also enhance cold chain monitoring and real-time data sharing, thus fostering trust among stakeholders (Gaynor et al., 2024; Nagpal et al., 2025; Sarkar, 2023). For instance, hybrid blockchain solutions proposed for secure drug traceability offer considerable potential in integrating real-time visibility, which is particularly crucial in environments where tampering and theft have been persistent challenges (Jaleel, 2024). Further, research on token-based and non-fungible token (NFT) approaches in pharmaceutical supply chains suggests new paradigms for ensuring data integrity and provenance (Chıacchıo et al., 2022).

Parallel to technological advances, governance structures and knowledge management practices have emerged as pivotal in sustaining effective distribution processes. In many contexts, leveraging smart governance mechanisms, such as adaptive policies, industry-wide collaboration protocols, and digital integration frameworks, has improved overall supply chain agility and reduced systemic vulnerabilities (Mahmoud et al., 2025). Moreover, leadership capacity and knowledge-sharing behaviors among pharmaceutical managers significantly influence the efficacy of technological adoption and distribution innovation (Alfaiza et al., 2021; Hassan, 2025). These human-centric elements are integral, particularly in regions where rapid regulatory shifts, competitive pressures, and cultural complexities impact the supply chain landscape (Ngah et al., 2019).

Another crucial aspect lies in the deployment of smart tools and technological enablers, such as Internet of Things (IoT) devices and nanocarrier platforms, which facilitate granular monitoring and efficient resource allocation in pharmaceutical logistics (Hwang et al., 2021). Research into advanced last-mile delivery models further demonstrates that technological readiness and innovation in delivery infrastructures, including smart parcel lockers and autonomous routing algorithms, are essential for addressing customer-centric challenges and ensuring timely, safe distribution of sensitive pharmaceutical products (Aghdam et al., 2024). Additionally, the emergence of data originality safeguards, implemented via blockchain-based mechanisms, has revolutionized pharmaceutical manufacturing by reducing the risks of data tampering and enabling more streamlined, transparent auditing processes (Durà-Hernández et al., 2023).

The significance of robust data management frameworks cannot be overstated. Contemporary studies show that ensuring the authenticity, security, and interoperability of pharmaceutical data is foundational for operational success (Wedha et al., 2023; Yadav, 2024). Data-driven innovations, when combined with advanced analytical tools and predictive algorithms, offer pharmaceutical firms the ability to proactively address supply fluctuations, optimize inventory levels, and enhance patient service delivery (Bapatla et al., 2022; Gaynor et al., 2024). Moreover, the strategic use of digital twin technologies and secure data-sharing architectures, especially those leveraging distributed ledger technologies, has underscored the shift towards building intelligent, learning-oriented supply chains that can adapt dynamically to external shocks (Durà-Hernández et al., 2023).

However, integrating these advanced technologies and governance frameworks in the pharmaceutical supply chain is not devoid of challenges. Organizational inertia, limitations in digital literacy among supply chain actors, and concerns over data privacy often hinder large-scale digital transformation efforts (Alfaiza et al., 2021; Lingayat et al., 2021). Research emphasizes that comprehensive staff training, capacity-building programs, and the cultivation of technological culture are necessary preconditions for successful implementation of smart distribution systems (Hassan, 2025; Mahmoud et al., 2025). Furthermore, the interplay between regulatory constraints and technological innovation remains a delicate balance. While stringent regulatory regimes are crucial for ensuring product safety and patient welfare, they can also slow down the deployment of new digital infrastructures, particularly in developing regions (Ngah et al., 2019).

Against this backdrop, the design and simulation of smart pharmaceutical distribution models represent an emergent research focus aimed at bridging theory and practice. Agent-based simulation, in particular, has proven effective in modeling the intricate dynamics of supply chain components, enabling researchers and practitioners to test scenarios, identify potential bottlenecks, and forecast the outcomes of technological and governance interventions before large-scale implementation (Aghdam et al., 2024). Such simulations help illustrate how multi-level factors—including governance, network structure, technological maturity, member competencies, data systems, service quality, and demand fluctuations—interact over time to influence supply chain performance. This systemic, bottom-up approach provides deeper insights into causal mechanisms and offers a platform for building adaptive policy tools and decision support systems (Nagpal et al., 2025; Wedha et al., 2023).

Moreover, research suggests that hybrid strategies, combining blockchain-based traceability systems with machine learning algorithms for demand forecasting and risk analysis, are likely to be the cornerstone of next-generation pharmaceutical supply chains (Jaleel, 2024; Yadav, 2024). These approaches promise not only operational efficiencies but also substantial improvements in patient outcomes, as distribution networks become more responsive, resilient, and transparent. As pharmaceutical markets continue to globalize and face pressures from public health emergencies, the need for such intelligent distribution models becomes even more urgent (Gaynor et al., 2024; Sarkar, 2023).

In this study, we aim to analyze and simulate the impact of various factors on the smart pharmaceutical distribution chain using an agent-based modeling approach.

2. Methods and Materials

In this study, a mixed-method design was adopted combining library research, expert consultation, and agent-based simulation to examine the smart pharmaceutical distribution model within the pharmaceutical supply chain industry. Initially, extensive library studies were conducted to extract existing research gaps and innovations related to smart distribution systems. This foundational step involved reviewing published articles, industry reports, and prior empirical studies that address pharmaceutical supply chain structures, distribution inefficiencies, and the application of smart technologies within these systems. Following the library research, field studies were carried out involving the pharmaceutical company Tofigh Daru as the main context for empirical data gathering. The study domain encompassed the smart pharmaceutical supply chain, and the temporal scope focused on the year 2023 (1402 in the Persian calendar).

Data collection tools included two primary instruments: a semi-structured interview and a Delphi questionnaire. For the first phase, semi-structured interviews were conducted with experts and employees within Tofigh Daru to identify the key components comprising the pharmaceutical supply chain and distribution network. The central interview question focused on eliciting views regarding the factors that constitute the smart pharmaceutical distribution chain. Responses from these interviews were transcribed and subjected to content analysis to extract themes and variables relevant to the research objective. Subsequently, a Delphi questionnaire was constructed including fifteen variables hypothesized to represent critical factors in smart pharmaceutical distribution. Ten experts, selected based on purposive sampling from among staff and practitioners of Tofigh Daru, rated each variable in the Delphi process. Content validity of the questionnaire was evaluated through expert judgment (content validity approach), while reliability was confirmed using Cronbach's alpha coefficient to ensure internal consistency of responses.

Data analysis in this study involved a combination of qualitative and quantitative techniques. Initially, content analysis was applied to interview transcripts and expert feedback to identify the core components and their thematic relations. The Delphi method was then employed to refine and screen the identified factors, ensuring only the most relevant variables were included in the final model. Subsequently, agent-based simulation was performed using the NetLogo software platform. This phase included modeling key agents involved in the pharmaceutical supply chain, such as producers, distributors, warehouses, pharmacies, hospitals, and patients. The behavior of each agent was defined according to specific attributes and decision-making rules, capturing dynamics such as production capacity, delivery times, demand fluctuations, and storage constraints. Interaction protocols between agents were modeled through system rules that represent real-world supply and demand processes, logistical bottlenecks, and distribution delays.

Simulation runs involved testing various scenarios, including disruptions such as supply shortages, shifts in demand, and delays in transportation. This allowed for identification of structural gaps in the current supply chain system and evaluation of alternative scenarios designed to improve resilience and performance. Analytical outputs from NetLogo were examined to identify system bottlenecks, critical points of failure, and opportunities for optimization. Where appropriate, artificial intelligence and machine learning algorithms were proposed as potential enhancements to forecast demand, optimize delivery routes, and automate decision-making within the supply chain network.

3. Findings and Results

The data collected through expert interviews and refined via the Delphi technique revealed a comprehensive structure of 7 main factor categories and 32 sub-factors that collectively shape the smart pharmaceutical distribution model in the pharmaceutical supply chain. Governance-related factors emerged as critical macro-level determinants, highlighting the role of government policy, industrial competition, and strategic investment in smart assets as foundational enablers of transformation. Simultaneously, the network-related dimension encompassed the internal structure and fluidity of the supply chain itself, emphasizing distribution efficiency, partner collaboration, and supply chain integration as essential components for smart logistics. Technology-related factors underscored the role of advanced digital tools, IoT adoption, and system robustness in sustaining a fault-tolerant smart distribution system.

Table 1

Extracted Main and Sub-Factors Influencing the Smart Pharmaceutical Distribution Model

Row	Main Factors	Sub-Factors
1	Governance-Related Factors	Government-issued industrial policies, Inimitability, Industry competition, Investment in smart assets, Regional and cross-border connectivity
2	Network-Related Factors	Network distribution efficiency, Supply chain partner communication, Supply chain scalability, Chain responsiveness, Member credibility validation, Pharmaceutical supply chain structures, Free flow of knowledge and information, Supply chain integration
3	Technology-Related Factors	Technological readiness, Defect-free performance, High level of specialized knowledge, IoT adoption level, Innovation in smart tools
4	Member-Related Factors	Staff and end-user training, Interoperability within the chain, IT literacy level of pharmacists, Accessibility to suppliers
5	Data-Related Factors	Innovation in IT, Information sharing in the supply chain, Logistic data sharing, Data privacy, Information sharing at the chain level
6	Service-Related Factors	Service capacity, Service differentiation
7	Demand-Related Factors	Customer demand focus, Demand fluctuations, Diverse customer needs

In addition, member-related factors reflected the human and organizational capacities necessary for implementation, such as training, interoperability, and pharmacist IT proficiency. Data-related considerations were another major cluster, where information sharing, data security, and IT-driven innovation were identified as central pillars. The analysis also showed that service-related factors—like service differentiation and delivery capacity—are pivotal in ensuring responsiveness and patient-centered care. Finally, demand-related factors such as demand variability, customer-centric approaches, and need diversity were highlighted as influential forces shaping adaptive and dynamic supply strategies. The aggregation of these multi-dimensional elements reveals the complex, interconnected nature of a smart pharmaceutical distribution system and provides a solid foundation for simulation modeling and scenario planning in subsequent stages of the research.

Figure 1

Effect of Governance-Related Factors

In examining the effect of governance-related factors, simulation results revealed a substantial initial impact on the smart pharmaceutical distribution chain. As demonstrated in Figure 1, the influence of these factors is considerable at the outset but gradually declines and stabilizes over time. This pattern suggests that while governance elements such as industrial policies and strategic investments play a critical role in establishing foundational conditions, their marginal effects diminish once regulatory frameworks and policies mature within the system. Overall, the simulation results classify governance-related factors as having a significant effect on the smart pharmaceutical distribution network.

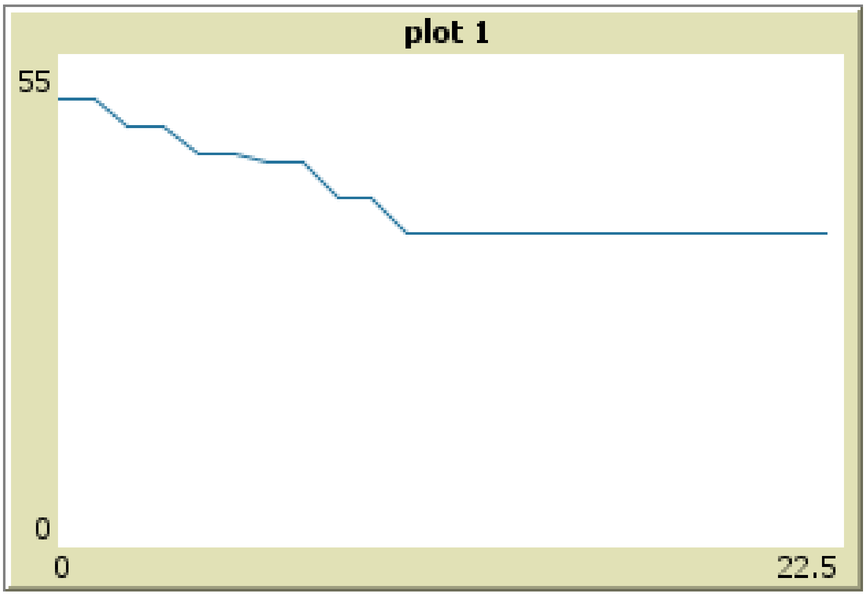
Figure 2

Effect of Network-Related Factors

Analysis of network-related factors, illustrated in Figure 2, showed that these variables also exert notable influence on the smart pharmaceutical distribution chain. However, the scope and duration of this impact are relatively shorter compared to governance-related factors. The graph stabilizes more quickly, indicating that improvements or changes in network efficiency, partner relationships, and integration have substantial short-term effects but tend to reach equilibrium faster. This suggests that while network-related factors are critical for initial system optimization, their long-term influence plateaus.

Figure 3

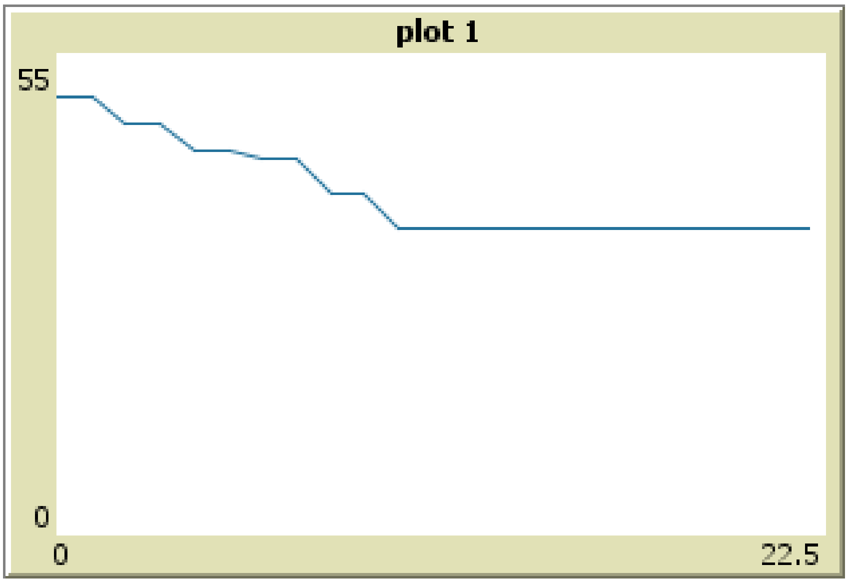
Effect of Technology-Related Factors



For technology-related factors, as depicted in Figure 3, the simulations indicate a similar pattern to network-related factors: an initial pronounced effect that quickly stabilizes. The range of influence, while significant, is limited in duration, suggesting that improvements in technological readiness, IoT adoption, and innovation in smart tools offer immediate performance gains but gradually integrate into the system's baseline operation over time.

Figure 4

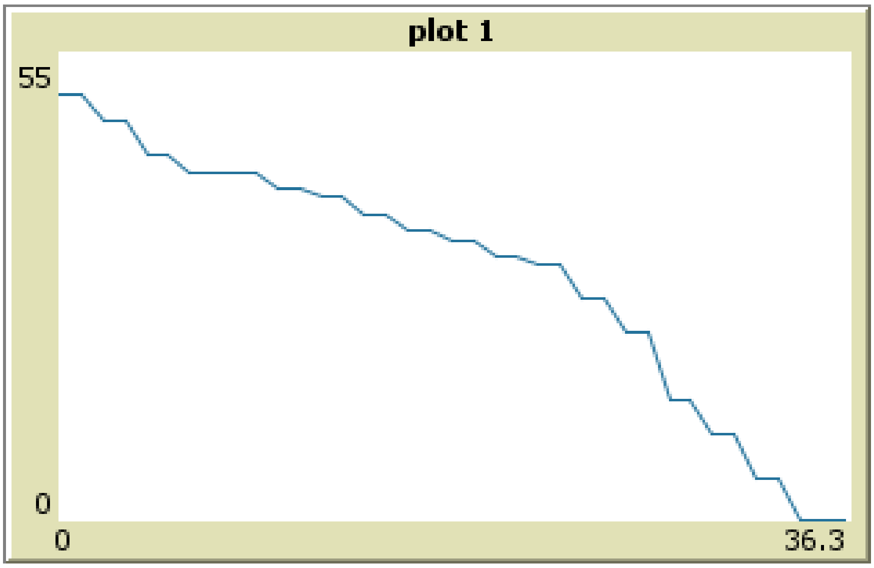
Effect of Member-Related Factors



Regarding member-related factors, the analysis reflected in Figure 4 also reveals a pattern similar to network and technological factors. The impact of member-related elements—such as staff training, interoperability, and pharmacists' IT proficiency—is substantial in the early stages of system implementation. However, the effect stabilizes over time, indicating that once capacity-building and training interventions are absorbed into operational routines, their incremental impact diminishes.

Figure 5

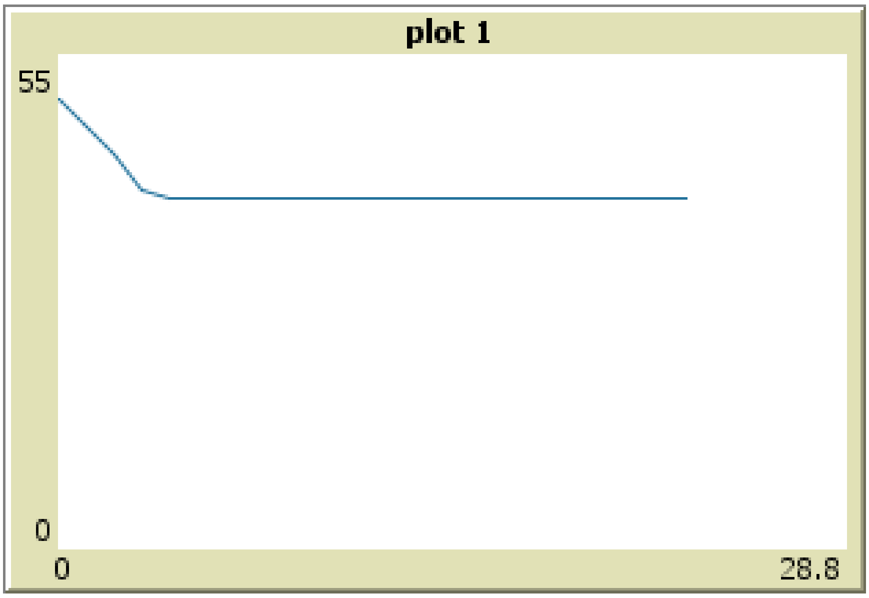
Effect of Data-Related Factors



In contrast, data-related factors demonstrated the highest and most sustained effect among all examined categories. Figure 5 shows a continuously downward trajectory in cost reduction, implying that innovations in IT, data sharing, and privacy mechanisms significantly optimize distribution efficiency and maintain ongoing influence on the system. Thus, data-related factors stand out as the most impactful dimension in reducing costs and enhancing performance in the smart pharmaceutical distribution chain.

Figure 6

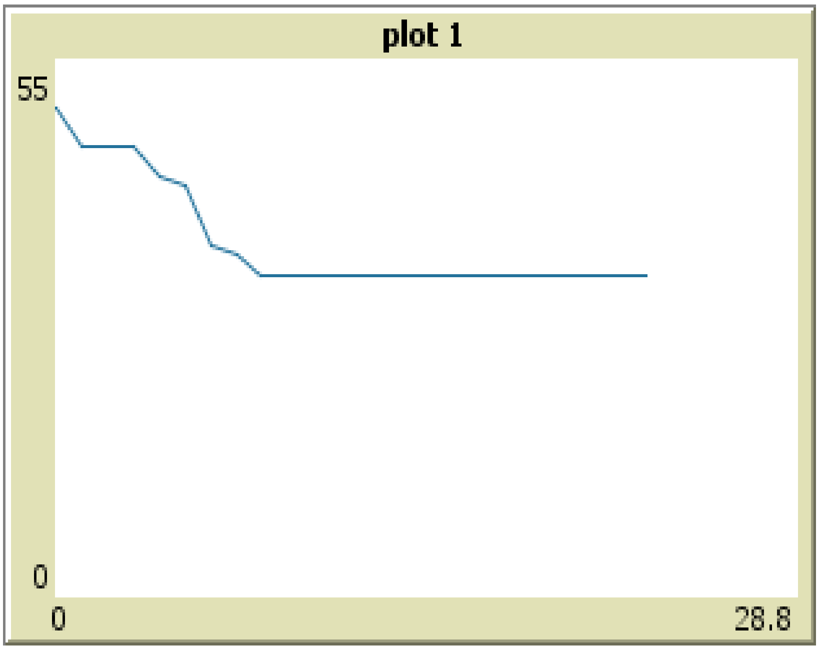
Effect of Service-Related Factors



Examining service-related factors, depicted in Figure 6, shows a relatively minimal and stable effect on the distribution chain. The graph suggests almost immediate stabilization with little fluctuation, indicating that while service capacity and differentiation are necessary components, their overall impact is comparatively modest in transforming the system.

Figure 7

Effect of Demand-Related Factors



Finally, simulation of demand-related factors, shown in Figure 7, demonstrates a substantial and consistent effect on the distribution chain. Variables such as demand fluctuations, customer-centric focus, and need diversity significantly influence supply dynamics and system responsiveness. The sustained impact indicates that managing demand variability and anticipating customer needs are critical to maintaining an efficient and adaptive smart pharmaceutical distribution system.

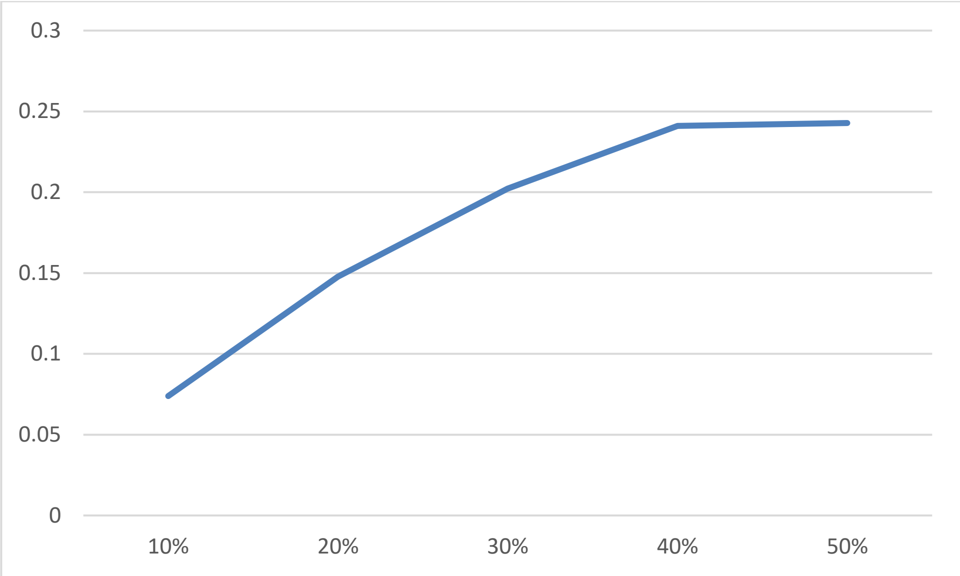
Table 2

Scenario Analysis of Governance-Related Factors

Governance-Related Factors Increase	Smart Pharmaceutical Distribution Performance	Percentage Change
0%	907	-
10%	974	0.07387
20%	1118	0.147844
30%	1344	0.202147
40%	1668	0.241071
50%	2073	0.242806

Figure 8

Scenario Analysis of Governance-Related Factors



The simulation shows an initially sharp positive effect of governance-related factors on smart pharmaceutical distribution performance. Over time, this effect plateaus, stabilizing at an improvement level of just under 25 percent, suggesting that governance improvements have a strong but diminishing marginal return.

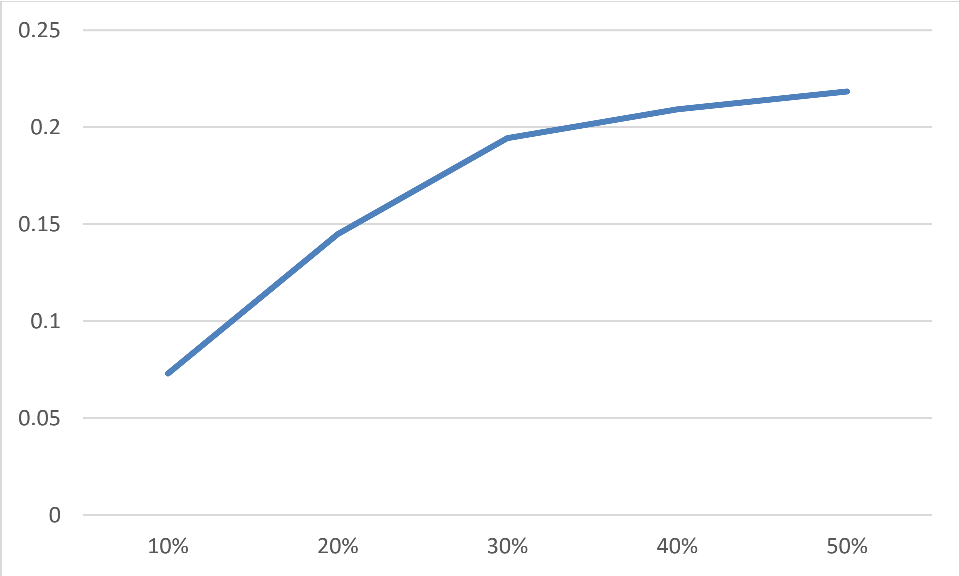
Table 3

Scenario Analysis of Network-Related Factors

Network-Related Factors Increase	Smart Pharmaceutical Distribution Performance	Percentage Change
0%	1068	-
10%	1146	0.073034
20%	1312	0.144852
30%	1567	0.19436
40%	1895	0.209317
50%	2309	0.21847

Figure 9

Scenario Analysis of Network-Related Factors



Network-related factors show a nonlinear rise in effectiveness, with the effect tapering off over time. Unlike governance factors, their influence declines slightly rather than fully stabilizing.

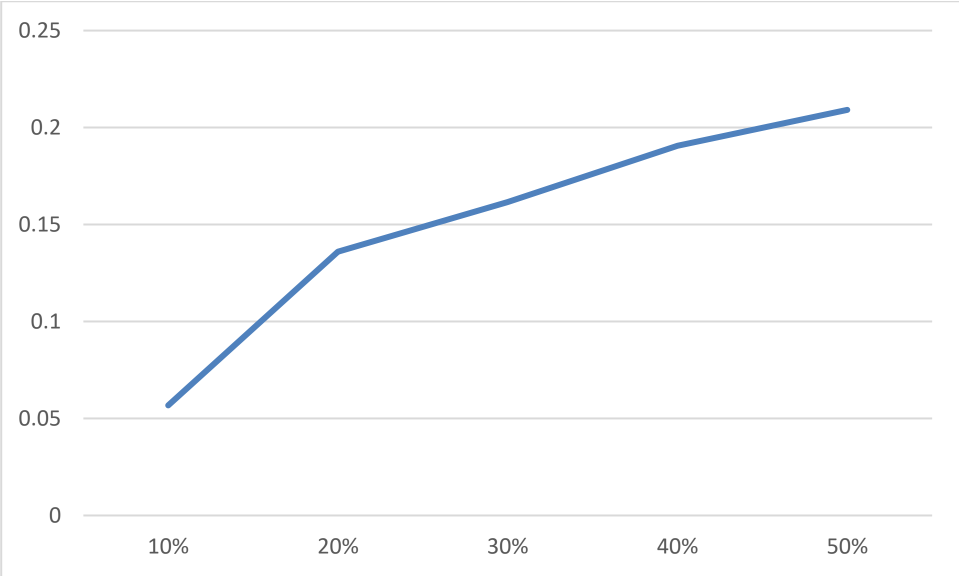
Table 4

Scenario Analysis of Technology-Related Factors

Technology-Related Factors Increase	Smart Pharmaceutical Distribution Performance	Percentage Change
0%	1057	-
10%	1117	0.056764
20%	1269	0.136079
30%	1474	0.161545
40%	1755	0.190638
50%	2122	0.209117

Figure 10

Scenario Analysis of Technology-Related Factors



Technology-related factors show a steady nonlinear increase in effect with less decline than governance and network factors, indicating a more sustained influence.

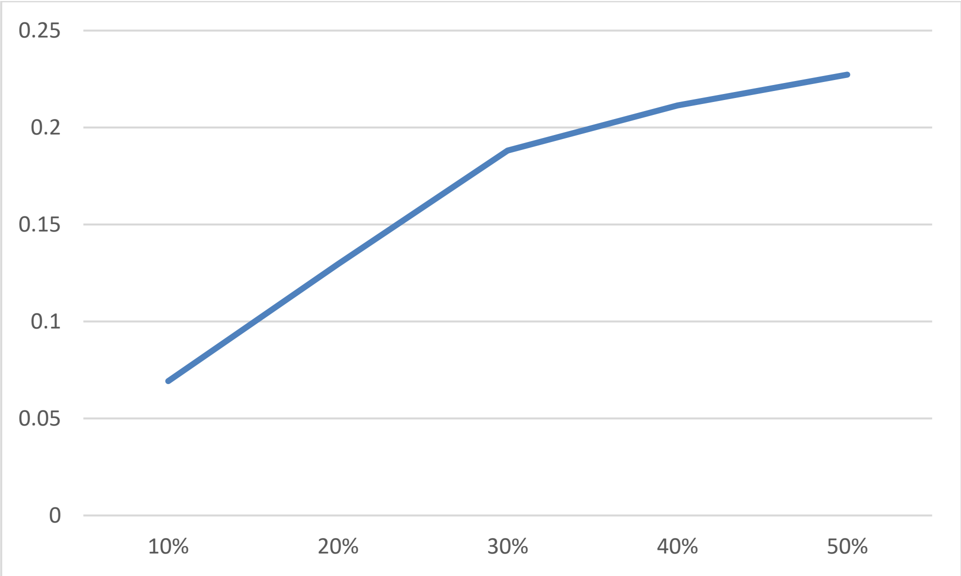
Table 5

Scenario Analysis of Member-Related Factors

Member-Related Factors Increase	Smart Pharmaceutical Distribution Performance	Percentage Change
0%	1025	-
10%	1096	0.069268
20%	1238	0.129562
30%	1471	0.188207
40%	1782	0.211421
50%	2187	0.227273

Figure 11

Scenario Analysis of Member-Related Factors



Member-related factors display sustained positive effects over time, similar to technology-related factors, with no sharp plateauing or decline.

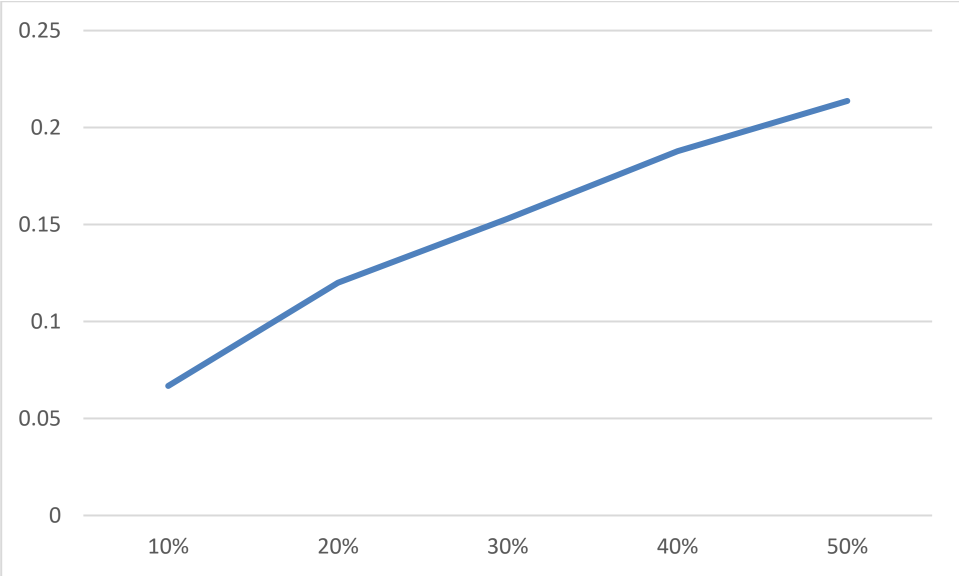
Table 6

Scenario Analysis of Data-Related Factors

Data-Related Factors Increase	Smart Pharmaceutical Distribution Performance	Percentage Change
0%	1078	-
10%	1150	0.06679
20%	1288	0.12
30%	1485	0.15295
40%	1764	0.187879
50%	2141	0.213719

Figure 12

Scenario Analysis of Data-Related Factors



Data-related factors exhibit a nearly linear and stable positive impact, continuing to improve system performance up to over 20 percent with no visible decline.

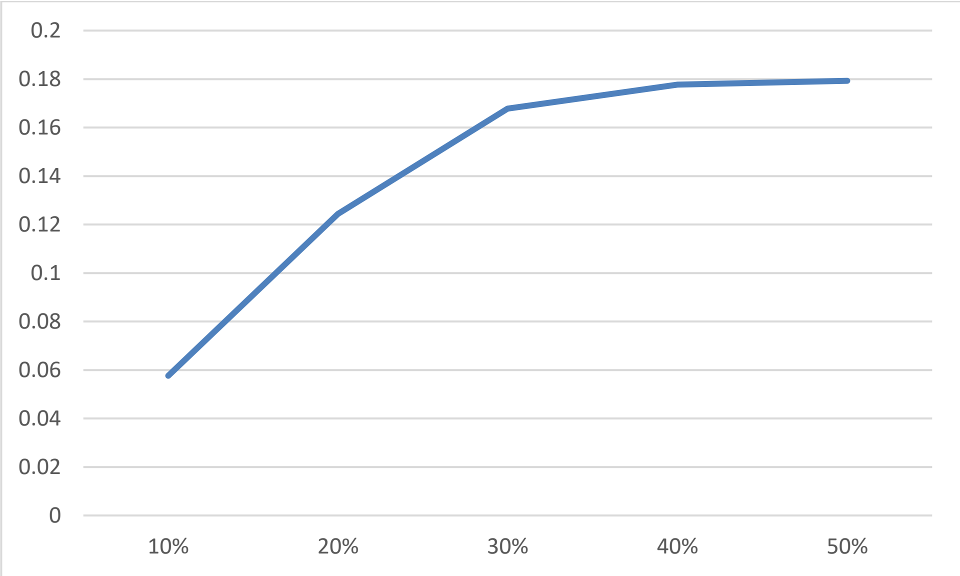
Table 7

Scenario Analysis of Service-Related Factors

Service-Related Factors Increase	Smart Pharmaceutical Distribution Performance	Percentage Change
0%	1163	-
10%	1230	0.05761
20%	1383	0.12439
30%	1615	0.167751
40%	1902	0.177709
50%	2243	0.179285

Figure 13

Scenario Analysis of Service-Related Factors



Service-related factors show early gains that quickly flatten out, resembling the patterns of governance and network factors with diminishing returns.

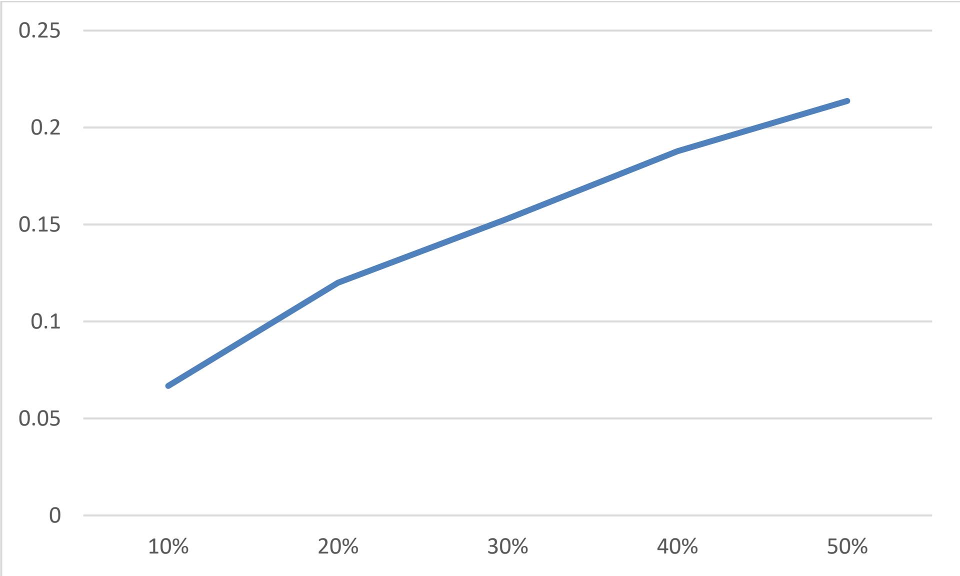
Table 8

Scenario Analysis of Demand-Related Factors

Demand-Related Factors Increase	Smart Pharmaceutical Distribution Performance	Percentage Change
0%	986	-
10%	1060	0.075051
20%	1202	0.133962
30%	1404	0.168053
40%	1702	0.212251
50%	2068	0.215041

Figure 14

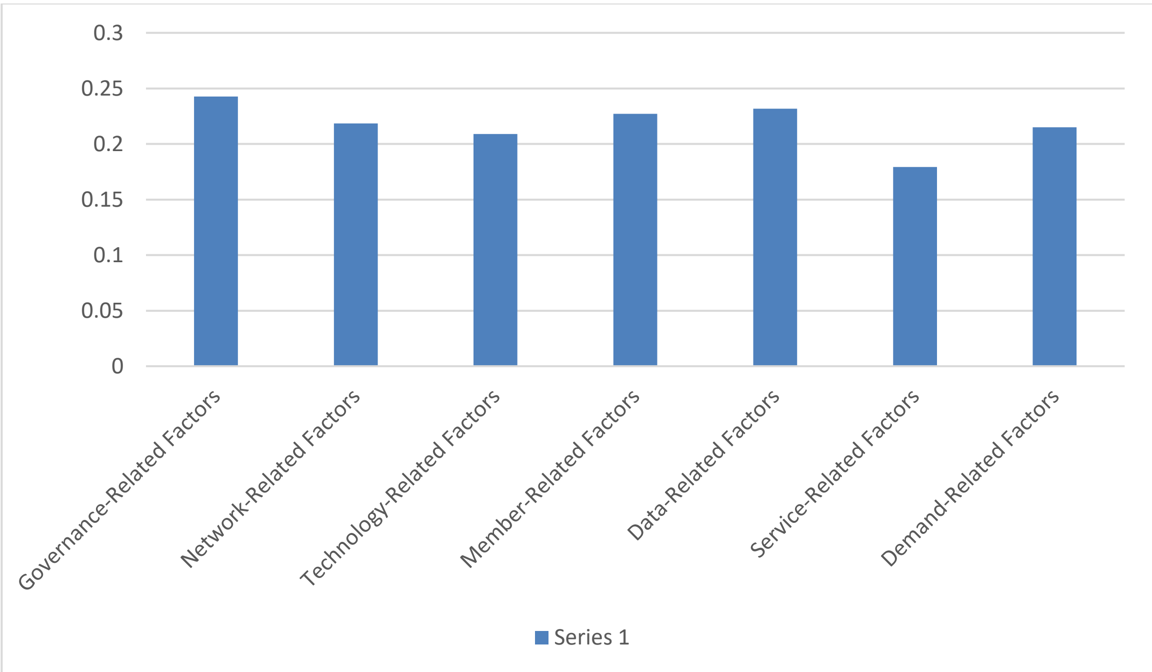
Scenario Analysis of Demand-Related Factors



Demand-related factors reveal a growth trend that stabilizes at just above 21 percent, suggesting their influence also follows a diminishing return pattern over time.

Figure 15

Comparison of Different Scenarios



The final comparison illustrates that governance-related factors had the highest overall effect on smart pharmaceutical distribution performance. Member-related and demand-related factors follow closely behind, while service-related factors exerted the least effect. However, differences among factors were not extremely large, indicating that all categories contributed meaningfully to system performance improvement.

4. Discussion and Conclusion

The results of this study underscore the significant and differentiated impact of governance, network, technology, member, data, service, and demand-related factors on the performance of smart pharmaceutical distribution systems. Simulation outcomes revealed that governance-related factors had the highest overall impact on distribution performance, particularly in the early stages of system improvement, before plateauing near a 25 percent increase in performance metrics. This finding aligns with prior research emphasizing the crucial role of regulatory policy frameworks and government-issued standards in shaping pharmaceutical supply chain transparency, efficiency, and security (Nagpal et al., 2025). Studies have shown that strategic policy interventions, particularly those supporting digital transformation initiatives and enforcing data authenticity, significantly improve traceability and system resilience across pharmaceutical distribution networks (Chıacchıo et al., 2022; Durà-Hernández et al., 2023).

Similarly, the notable, though slightly diminishing, effect of network-related factors corroborates findings in the literature regarding the role of partner relationships, integration, and distribution network design in reducing inefficiencies and bottlenecks (Wedha et al., 2023). Scholars have argued that strong inter-organizational ties, supported by clear communication protocols and flexible network structures, contribute to system adaptability during market shifts or crisis periods (Mahmoud et al., 2025). However, the plateauing effect observed suggests that network optimizations alone are insufficient for sustaining long-term performance improvements unless integrated with broader governance and technological strategies.

The study also found that technology-related factors—particularly the adoption of IoT solutions, smart delivery infrastructures, and digital security mechanisms—produced significant and sustained positive effects on system performance. This outcome mirrors evidence that technological readiness and innovation in delivery mechanisms, such as smart parcel lockers and digital twin solutions, are critical enablers for resilient, customer-focused pharmaceutical distribution (Aghdam et al., 2024; Gaynor et al., 2024). Furthermore, integrating blockchain with machine learning algorithms for predicting demand and streamlining logistics has been highlighted in multiple studies as a pathway to greater transparency, reduced fraud, and cost reduction in pharmaceutical supply chains (Bapatla et al., 2022; Jaleel, 2024; Yadav, 2024).

Member-related factors, including staff training, interoperability skills, and pharmacists' digital literacy, were also shown to have substantial and relatively stable impacts on distribution performance over time. These results are consistent with previous research indicating that human capital development, organizational learning, and the cultivation of knowledge-sharing behaviors are indispensable for sustaining digital transformation and leveraging the full benefits of technological investments (Alfaiza et al., 2021; Hassan, 2025). In contexts where workforce skills and technological culture are lacking, even advanced technical infrastructures fail to achieve their promised operational efficiencies (Mahmoud et al., 2025).

Data-related factors exhibited the most linear and continuous positive effect on smart pharmaceutical distribution performance in the simulations, suggesting that innovations in IT infrastructure, data privacy, and secure information-sharing protocols deliver ongoing, incremental benefits over time. These findings reflect extensive research that highlights the transformative role of data originality safeguards, blockchain-enabled auditability, and real-time data interoperability in reducing counterfeiting, improving demand forecasting, and enhancing patient outcomes (Durà-Hernández et al., 2023; Sarkar, 2023). As prior studies suggest, the shift towards intelligent, learning-oriented supply chains depends on secure, real-time data flows between stakeholders to coordinate delivery, monitor conditions, and anticipate bottlenecks (Gaynor et al., 2024; Lingayat et al., 2021).

In contrast, service-related factors showed the lowest and most quickly stabilizing impact on distribution performance. This outcome may reflect the mature and relatively standardized nature of service delivery processes in the pharmaceutical industry, where improvements in service differentiation and capacity may have less systemic leverage compared to technology or data-driven transformations. This interpretation resonates with research suggesting that while customer service parameters matter, they do not substitute for the structural and technological shifts needed to achieve sustained performance gains (Ngah et al., 2019).

Demand-related factors showed significant early influence on distribution performance that gradually plateaued. These results confirm earlier research showing that demand fluctuations, customer-centric focus, and adaptive capacity are key variables in distribution design, particularly in volatile markets (Wedha et al., 2023; Yadav, 2024). However, without corresponding advances in governance, technology, and data management, demand-side adaptations alone cannot sustain performance gains in the long term (Gaynor et al., 2024).

Overall, the simulation findings highlight the need for an integrated, multi-factorial approach to developing smart pharmaceutical distribution systems. The results show that while certain categories—such as governance, data, and technology factors—offer large immediate gains, sustained system-wide improvements depend on balancing these dimensions with continuous investment in human capital, network optimization, and service quality. This systemic perspective is echoed in prior research arguing that hybrid models combining blockchain traceability, AI-driven forecasting, and strong governance structures provide the most resilient and efficient pharmaceutical supply chains (Bapatla et al., 2022; Nagpal et al., 2025; Sarkar, 2023).

This study is not without limitations. First, while agent-based simulation offers valuable insights into system dynamics, it inherently simplifies certain real-world complexities, such as human behavioral variability, unanticipated regulatory changes, and sudden geopolitical disruptions. The model parameters, while grounded in expert opinion and prior research, may not fully capture the range of organizational and market contingencies faced by pharmaceutical supply chains globally. Additionally, the sample size for expert interviews and Delphi analysis, though aligned with accepted methodological norms, was relatively small, potentially limiting the generalizability of factor weightings and thresholds used in the simulation. Finally, while the model incorporated technological, organizational, and data-related variables, it did not directly integrate externalities such as supplier network disruptions due to climate change or cyber-physical security threats, which are increasingly relevant in modern supply chains.

Future research should expand the scope of simulation models to include additional layers of complexity, such as multi-country regulatory environments, diverse socio-political scenarios, and the impact of external shocks like global health crises. Longitudinal empirical studies are also needed to validate the predictive accuracy of agent-based simulation models with real-world performance data over time. Furthermore, comparative studies examining the effectiveness of different digital governance frameworks, AI-powered decision-support systems, and blockchain architectures across varied pharmaceutical markets would enrich the literature and provide more targeted, context-specific policy recommendations. Finally, integrating environmental sustainability metrics into smart pharmaceutical distribution models could help address the growing industry imperative to balance efficiency with ecological stewardship.

For practitioners, building an effective smart pharmaceutical distribution system requires a coordinated strategy that combines robust governance mechanisms, continuous technological upgrades, and sustained investment in workforce development. Organizations should prioritize secure, interoperable data infrastructures to maximize transparency and traceability while simultaneously fostering a culture of knowledge-sharing and digital literacy among staff. Policymakers should consider adaptive regulatory frameworks that incentivize innovation while maintaining rigorous safety and quality standards. Lastly, stakeholders must engage in collaborative partnerships across the supply chain, leveraging blockchain-based tools and AI-driven analytics to optimize processes, anticipate demand fluctuations, and ensure the timely delivery of safe, high-quality pharmaceutical products to patients.

Authors' Contributions

Authors contributed equally to this article.

Declaration

In order to correct and improve the academic writing of our paper, we have used the language model ChatGPT.

Transparency Statement

Data are available for research purposes upon reasonable request to the corresponding author.

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Declaration of Interest

The authors report no conflict of interest.

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Ethics Considerations

In this research, ethical standards including obtaining informed consent, ensuring privacy and confidentiality were considered.

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