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AI-Driven Geospatial Analytics for Pharmaceutical Supply Chain Resilience: Integrating Business Intelligence, Compliance, and Healthcare Equity

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Abstract

The COVID-19 pandemic and subsequent global disruptions exposed critical vulnerabilities in pharmaceutical supply chains, particularly in emerging economies where inefficiencies, regulatory lapses, and inequitable distribution amplified systemic risks. This paper proposes an integrated framework that leverages artificial intelligence (AI), data science, and geospatial analytics to strengthen resilience in pharmaceutical supply chains. Building on advances in business intelligence and compliance-driven systems, the study demonstrates how machine learning algorithms and spatial decision models can optimize drug distribution, forecast demand surges, and monitor regulatory adherence in real time. Methodologically, the framework combines predictive analytics (for demand forecasting), optimization models (for inventory and logistics planning), and geospatial AI tools (for route optimization, equity-based allocation, and climate-risk sensitivity). Regulatory compliance is embedded through algorithmic audit trails aligned with GDPR, the EU AI Act, and Nigeria's National Drug Policy to ensure legal accountability. The study further integrates an equity dimension, prioritizing underserved regions in drug allocation and access. The findings illustrate how AI-driven geospatial intelligence not only enhances operational efficiency but also bridges the gap between compliance and equity in healthcare delivery. Case studies from Nigeria and comparative insights from U.S. pharmaceutical distribution highlight the framework's cross-continental applicability. By uniting technical innovation with regulatory and ethical guardrails, this research establishes a model for sustainable, equitable, and resilient pharmaceutical supply chains. This contribution advances interdisciplinary scholarship at the nexus of AI, healthcare supply chain management, and regulatory science, offering novel pathways for global pharmaceutical resilience in the age of digital transformation.

Keywords: AI-driven supply chain resilience, Geospatial analytics, Pharmaceutical distribution equity, Regulatory compliance (GDPR, AI Act), Predictive demand forecasting

Introduction

The COVID-19 pandemic revealed severe vulnerabilities within global pharmaceutical supply chains, exposing their limited capacity to absorb large-scale disruptions. When international logistics networks ground to a halt in early 2020, essential medicines, vaccines, and medical equipment became scarce across many regions, highlighting structural weaknesses in procurement, manufacturing, and distribution (Golan et al., 2020). These weaknesses were amplified in emerging economies such as Nigeria, where approximately 70 % of pharmaceutical products are imported, leaving the country highly dependent on international suppliers and exchange rate fluctuations (Faiva, 2021). The resulting shortages led to drug price inflation, widespread stockouts, and reduced access to life-saving medicines, disproportionately affecting rural and underserved communities (Olutuase et al., 2022). Traditional pharmaceutical supply chain models emphasize operational efficiency through just-in-time systems and cost minimization, but these designs leave little room for flexibility during crises. They rarely integrate mechanisms for real-time risk monitoring, geospatial tracking, or equity-oriented allocation (Smyth et al., 2023). Research on resilience in healthcare logistics increasingly advocates for the integration of digital technologies such as artificial intelligence (AI) and machine learning (ML) to anticipate disruptions, optimize inventory, and improve overall supply chain agility (Katakam et al., 2019). Yet, most studies focus narrowly on predictive analytics or inventory optimization, with limited attention to embedding regulatory compliance frameworks or equitable access principles into AI-enabled systems (Sharma et al., 2024).

In Nigeria, the challenges are especially complex: inadequate storage infrastructure, poor distribution networks, regulatory gaps, and persistent infiltration of counterfeit drugs undermine supply reliability (Nwankwo & Ezenduka, 2022). During COVID-19, border closures and foreign exchange shortages disrupted procurement cycles, further delaying the distribution of essential medicines (Faiva, 2021). These realities underscore the urgency for a holistic framework that can integrate predictive intelligence, compliance monitoring, and geospatial analytics to provide equitable drug access even during crises.

This study therefore proposes an AI-driven geospatial analytics framework designed to strengthen resilience in pharmaceutical supply chains by uniting three key dimensions: predictive analytics for demand forecasting, optimization models for inventory and logistics planning, and compliance-driven audit mechanisms aligned with global and national regulations such as Good Distribution Practice (GDP), Good Manufacturing Practice (GMP), and Nigeria's National Drug Policy. Geospatial intelligence forms a critical layer in this framework, enabling route optimization, hotspot mapping for counterfeit drug detection, and spatial prioritization of underserved populations. The comparative dimension of this research examines both Nigeria and the United States. Nigeria provides a high-risk environment where weak infrastructure and regulatory enforcement magnify supply chain disruptions, making it an ideal setting to test resilience interventions. The United States, on the other hand, offers lessons from its large-scale COVID-19 vaccine rollout, which combined advanced analytics with federal and state-level compliance requirements to achieve nationwide coverage (CDC, 2022). Together, these cases demonstrate how a unified AI-driven approach can be contextually adapted to both emerging and developed economies.

By integrating business intelligence systems, geospatial modelling, and regulatory guardrails, this study contributes a novel pathway for building supply chains that are not only efficient but also legally compliant and socially equitable. The ultimate aim is to transform pharmaceutical supply chains from reactive networks into intelligent, self-correcting systems capable of withstanding future pandemics, geopolitical shocks, and climate-related disruptions.

Literature Review

Pharmaceutical Supply Chains and Disruptions

The pharmaceutical supply chain (PSC) represents a complex network encompassing raw material sourcing, manufacturing, distribution, and last-mile delivery to health facilities. Disruptions at any of these nodes have a cascading effect on medicine availability, with significant implications for public health outcomes (Tukamuhabwa et al., 2015). The COVID-19 pandemic demonstrated how quickly PSCs could be destabilized when global transport systems were constrained and manufacturing hubs shut down (Dolgui & Ivanov, 2021). Studies have documented how lockdowns and border closures amplified drug shortages, increased costs, and compromised equitable acces (Trabucco & De Giovanni, 2021). In Nigeria, supply chain vulnerabilities are magnified by the heavy reliance on imports and the absence of robust domestic pharmaceutical production. Onwujekwe et al. (2023) report that medicine availability in public facilities fell sharply during the pandemic, forcing patients to seek costly alternatives in the private sector. Rural and peri-urban populations were particularly affected due to weak distribution infrastructure and poor storage facilities (Olutuase et al., 2022). Counterfeit drug infiltration, facilitated by inadequate regulatory oversight, further exacerbated health risks (Nwankwo & Ezenduka, 2022). These findings underscore the necessity of resilient supply chains that can dynamically adapt to shocks and ensure continuity of essential drug provision.

Figure 1 presents a schematic representation of global pharmaceutical supply chain disruptions, illustrating key choke points such as manufacturing bottlenecks, customs delays, and last-mile distribution gaps. This visualization reinforces the argument that resilience must be approached as a system-wide objective rather than a localized intervention (Pettit et al., 2010).

Figure 1 Schematic Representation of Global Pharmaceutical Supply Chain Disruption

AI and Business Intelligence in Healthcare

Artificial intelligence (AI) and machine learning (ML) have been increasingly employed to improve forecasting accuracy, optimize inventory, and monitor risks across PSCs (Katakam et al., 2019). AI-driven predictive analytics models, such as Long Short-Term Memory (LSTM) networks, have demonstrated improved accuracy in anticipating demand surges, as seen in vaccine allocation during the pandemic (Guo et al., 2023). Business intelligence (BI) systems complement these approaches by consolidating data into dashboards that support real-time decision-making for managers and policymakers (Chatterjee et al., 2023).

Nevertheless, Al-Hourani and Weraikat (2024) identify significant gaps in empirical deployment, noting that over 59 % of studies fail to address regulatory or ethical dimensions. Moreover, adoption barriers such as data silos, lack of skilled personnel, and integration challenges with legacy systems hinder the full potential of AI in healthcare logistics (Smyth et al., 2023).

Geospatial Analytics in Supply Chain Optimization

Geospatial analytics offers a spatial decision-support layer that can enhance PSC resilience by enabling route optimization, hotspot detection, and real-time tracking of deliveries (WHO, 2023). For example, GIS-based systems have been used to map counterfeit drug hotspots in Nigeria, enabling regulators to target enforcement actions (Nwankwo & Ezenduka, 2022). Route optimization algorithms combined with ML models have also been applied to minimize delivery times and reduce wastage of temperature-sensitive products (Mahdavimanshadi et al., 2021). In contexts such as Nigeria, geospatial tools can address distribution inequities by prioritizing underserved regions where stockouts are frequent (Adebayo et al., 2023). This approach aligns with global health objectives that emphasize equitable access to medicines and universal health coverage (WHO, 2023).

Compliance and Healthcare Equity in AI Systems

Regulatory compliance is central to PSC operations, governed by frameworks such as Good Distribution Practice (GDP), Good Manufacturing Practice (GMP), and, at the global level, the General Data Protection Regulation (GDPR) (Kiani Mavi et al., 2022). Embedding compliance in AI systems requires algorithmic audit trails and traceability features to ensure that all decisions can be reviewed against regulatory standards (Emmanuel et al., 2022). Equity considerations are equally critical. Mhlanga (2023) warns that algorithmic decision-making may unintentionally reproduce inequities if models are trained on biased data or fail to include marginalized populations in their design. Ensuring fairness, transparency, and accountability in AI-driven distribution models is thus not only a technical challenge but also an ethical imperative (Naik et al., 2021). Taken together, the reviewed literature highlights both the promise and the gaps in current PSC resilience research. While AI, BI, and geospatial analytics offer powerful tools for forecasting and optimization, their integration with compliance frameworks and equity-oriented objectives remains underdeveloped. Addressing these gaps forms the rationale for the conceptual framework proposed in this study.

Methodological Approach (Conceptual)

This study employs a conceptual methodology grounded in systems thinking and literature synthesis to construct an integrative framework for pharmaceutical supply chain (PSC) resilience. Systems thinking is particularly suitable for this research because PSCs are characterized by complex interdependencies between manufacturing, regulation, logistics, and healthcare delivery (Pettit et al., 2010). By combining multiple strands of scholarship on AI, geospatial analytics, business intelligence, and compliance, the proposed model captures the dynamic interactions across the supply chain rather than treating them as isolated functions (Dolgui & Ivanov, 2021). The framework development process followed an iterative approach. First, a comprehensive synthesis of recent peer-reviewed studies was conducted, emphasizing literature that addressed resilience strategies, AI/ML applications, and regulatory considerations (Al-Hourani & Weraikat, 2024; Smyth et al., 2023). Insights were classified along five key dimensions: resilience strategy, AI/ML application, functional areas, study type, and regulatory challenge. This classification enabled the identification of gaps, such as the underrepresentation of equity-oriented allocation models and algorithmic compliance systems, which the framework aims to address.

For illustration and validation purposes, two case contexts were selected. The first is **Eli Lilly Nigeria**, representing an emerging-economy setting where workflow optimization, counterfeit drug mitigation, and compliance integration are critical challenges (Onwujekwe et al., 2023). The second case draws on **U.S. vaccine distribution systems**, which exemplify large-scale application of predictive analytics, geospatial tracking, and compliance auditing during the COVID-19 response (CDC, 2022). These contrasting cases support the framework's cross-context relevance and demonstrate how it can be adapted to different infrastructure and regulatory environments. Because the objective is to advance early-stage theory, a conceptual rather than empirical design was adopted. As Gregor (2006) argues, conceptual frameworks play a vital role in clarifying constructs, proposing relationships, and guiding future empirical research, particularly in emerging fields such as AI-enabled PSC resilience.

Proposed Framework

This study proposes a comprehensive conceptual framework that unites AI-driven predictive analytics, geospatial intelligence, business intelligence (BI), and compliance-embedded systems to build pharmaceutical supply chain (PSC) resilience. The framework is organized into three layers: **core** components, integration layer, and equity dimension, ensuring that technical capabilities are systematically aligned with regulatory requirements and public health objectives.

Core Components

The core of the framework is anchored on AI predictive analytics, which provide the foundation for dynamic demand forecasting, disruption prediction, and inventory optimization. Studies have shown that machine learning models such as Random Forest and Gradient Boosting significantly improve forecast accuracy under volatile demand conditions (Mariappan et al., 2023; Mahdavimanshadi et al., 2021). In pharmaceutical contexts, this predictive capability is essential for planning production and distribution in time-sensitive situations such as vaccine rollouts (Guo et al., 2023). Geospatial intelligence forms the second component, enabling spatial decision-making through route optimization, hotspot analysis, and facility location planning. Research highlights the ability of GIS-based systems to improve last-mile drug delivery by identifying underserved regions and minimizing transportation delays (Nwankwo & Ezenduka, 2022; WHO, 2023).

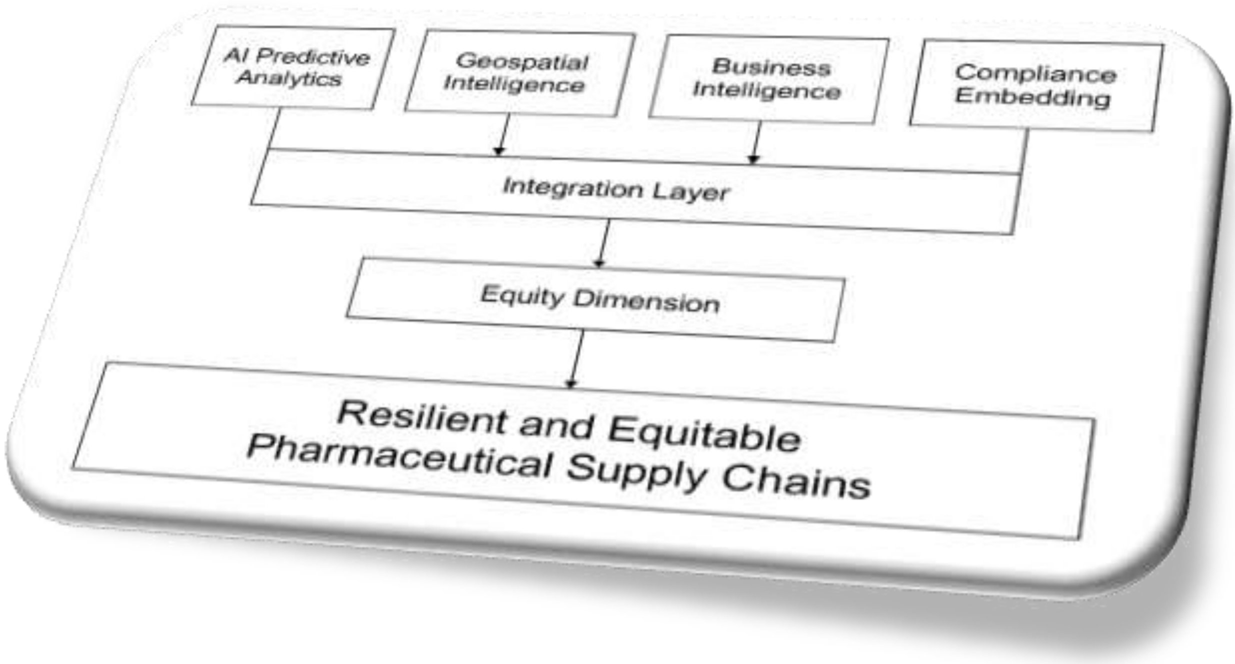
The third component, compliance embedding, ensures that every AI decision process is traceable and auditable against regulatory frameworks such as Good Distribution Practice (GDP) and Good Manufacturing Practice (GMP) (Kiani Mavi et al., 2022). Embedding algorithmic audit trails and explainability features ensures that AI systems can withstand regulatory scrutiny, thus building trust among stakeholders. Finally, **business intelligence systems** act as the visualization and orchestration layer, translating predictive insights and geospatial outputs into actionable dashboards for decision-makers (Chatterjee et al., 2023). This allows stakeholders, including regulators, suppliers, and distribution managers, to collaborate around a shared view of the supply chain's status.

Integration Layer

The integration layer describes how the core components interact to create resilience. Predictive models feed demand and risk forecasts into optimization engines, which then generate inventory allocation and routing recommendations. These recommendations are overlaid on geospatial maps to highlight vulnerable regions and enable rapid intervention (Dolgui & Ivanov, 2021). Compliance engines continuously monitor whether decisions adhere to GDP, GMP, and data privacy regulations, automatically flagging non-compliant actions for review (Emmanuel et al., 2022).

Equity Dimension

A defining feature of this framework is its explicit commitment to equity. Existing research indicates that most AI-enabled PSC studies neglect fairness and inclusivity in resource allocation (Mhlanga, 2023). The proposed model integrates equity-based allocation algorithms that prioritize underserved and rural populations, taking into account health outcome disparities and geographic access barriers (Olutuase et al., 2022). This ensures that distribution efficiency does not come at the expense of vulnerable populations. **Figure 2** below illustrates the proposed framework, showing how AI predictive analytics, geospatial intelligence, compliance mechanisms, and BI dashboards are layered into a cohesive, feedback-driven system that promotes resilience and equitable access.



Case Illustrations

Nigeria Case Study

Nigeria's pharmaceutical supply chain is uniquely vulnerable due to its structural dependence on imports, weak domestic manufacturing base, and limited regulatory oversight. Roughly 70 % of medicines consumed in the country are imported, primarily from India and China, leaving Nigeria highly sensitive to external shocks (Faiva, 2021). During the COVID-19 pandemic, port congestion, foreign exchange shortages, and border closures triggered medicine shortages and price surges, exposing how brittle the existing supply networks were (Olutuase et al., 2022). These shortages were not evenly distributed: rural and peri-urban areas suffered longer delays due to poor last-mile logistics infrastructure and the absence of real-time visibility tools.

The proposed framework applies AI-driven predictive analytics to this setting by forecasting demand fluctuations using time-series models and machine learning approaches. Research shows that Long Short-Term Memory (LSTM) models outperform traditional statistical forecasting methods under high volatility, allowing suppliers to anticipate surges in antimalarial and antibiotic demand (Guo et al., 2023). These forecasts can then be paired with **inventory optimization models**, including reinforcement learning–based approaches, to allocate scarce stock efficiently across regional warehouses (Ramasamy & Pravinkumar, 2023).

A second priority is counterfeit drug mitigation. Nigeria faces one of the highest rates of counterfeit and substandard medicines globally, with the World Health Organization estimating that up to 10 % of medicines in circulation in sub-Saharan Africa are falsified (WHO, 2023). Geospatial analytics can map counterfeit hotspots by integrating inspection data, patient complaints, and market surveillance findings. Such mapping enables regulators like the National Agency for Food and Drug Administration and Control (NAFDAC) to prioritize enforcement in high-risk areas (Nwankwo & Ezenduka, 2022). Machine learning classification models can also detect anomalies in distribution patterns, flagging unusual shipments for further investigation (Emmanuel et al., 2022).

The equity dimension of the framework is critical for Nigeria, where healthcare access disparities are pronounced between urban and rural areas. Equity-based allocation algorithms can prioritize shipments to facilities in underserved northern states or hard-to-reach riverine regions, where maternal and child mortality rates are higher (Onwujekwe et al., 2023). By combining GIS routing with AI-driven optimization, distribution can be tailored to minimize delays to remote communities even when road infrastructure is poor. Furthermore, embedding compliance mechanisms aligned with Nigeria's National Drug Policy (2021 revision) ensures that all distribution decisions follow quality assurance protocols, preventing diversion or contamination during transit. These applications do not merely enhance efficiency—they create a more transparent, accountable, and patient-centered supply chain. Dashboards powered by business intelligence tools would allow health officials, regulators, and donors to monitor stock levels, shipment progress, and compliance status in real time. This transparency can improve stakeholder coordination, reduce corruption, and build public trust in the health system (Chatterjee et al., 2023).

U.S. Case Study

In contrast, the United States presents a relatively mature pharmaceutical supply chain characterized by advanced regulatory oversight, cold-chain infrastructure, and large-scale analytics capacity. The COVID-19 vaccine rollout provides a case study in compliance-driven AI implementation. Operation Warp Speed and subsequent federal initiatives leveraged predictive analytics to model demand at county and state levels, ensuring vaccine shipments matched population profiles (CDC, 2022). Optimization algorithms guided distribution from manufacturing plants to state depots, while geospatial dashboards tracked shipment arrival times and storage conditions. Machine learning models were also used to forecast uptake rates and adjust shipment schedules dynamically. For example, logistic regression and gradient boosting algorithms helped predict which communities would have slower initial uptake, allowing targeted outreach and redistribution of excess doses to avoid wastage (Mahdavimanshadi et al., 2021). Compliance monitoring was deeply embedded: every batch of vaccine was tracked using serialization and barcoding systems that complied with the Drug Supply Chain Security Act (DSCSA), providing full traceability from production to administration (FDA, 2023).

Equity was explicitly built into distribution strategies. Federal guidelines required states to prioritize high-risk populations such as frontline workers and the elderly, and geospatial tools were used to identify vaccine deserts, areas with low access to vaccination sites (Schmidt et al., 2021). This allowed the deployment of mobile clinics and pop-up sites, reducing disparities in vaccine coverage across racial and socioeconomic lines.

Comparative Insights

The Nigeria and U.S. cases provide complementary insights that strengthen the proposed framework. Nigeria highlights the importance of geospatial intelligence and counterfeit detection in settings with weak enforcement and infrastructural challenges, whereas the U.S. case demonstrates the value of embedding compliance and traceability mechanisms at scale. Together, they confirm that AI-driven predictive analytics, when combined with geospatial and BI tools, can enhance responsiveness and efficiency under very different institutional conditions. A key lesson from both contexts is that resilience cannot be pursued in isolation from governance. In Nigeria, algorithmic decision support must be paired with strong institutional capacity building for agencies like NAFDAC. In the U.S., while compliance systems are strong, future work could focus on enhancing agility and decentralization to improve response speed in emergencies. Both cases also show that equity must be a deliberate design choice, as algorithms without fairness constraints risk amplifying disparities (Mhlanga, 2023).

Thus, the case illustrations validate the framework's relevance across diverse geographies, demonstrating that the integration of predictive analytics, geospatial intelligence, compliance, and equity can create a supply chain that is both robust to shocks and socially responsive.

Discussion

The findings of this study demonstrate that AI-driven geospatial intelligence can significantly improve pharmaceutical supply chain (PSC) resilience by enhancing demand forecasting, optimizing logistics, and embedding compliance monitoring. However, translating these technical advances into real-world outcomes requires a multidimensional approach that balances operational efficiency, regulatory obligations, and healthcare equity.

Implications for Industry Practice

From an industry perspective, the integration of predictive analytics with geospatial intelligence offers a powerful lever for improving agility and reducing losses from stockouts or wastage. Predictive models have been shown to outperform traditional statistical forecasting under high-variance demand, enabling manufacturers and distributors to anticipate shortages and re-route supplies before crises escalate (Guo et al., 2023). The case of Nigeria illustrates that inventory optimization combined with GIS-enabled route planning can shorten lead times for remote facilities and minimize transportation losses, which is crucial in countries where cold-chain infrastructure is limited (Olutuase et al., 2022). Business intelligence (BI) systems serve as a critical interface between analytics engines and decision-makers, providing real-time dashboards that consolidate demand forecasts, shipment locations, and regulatory status indicators (Chatterjee et al., 2023). When fully implemented, such systems can improve stakeholder collaboration, ensuring that suppliers, logistics providers, and regulators operate on shared situational awareness. This level of transparency has been linked to improved trust among partners, reduced duplication of efforts, and faster resolution of bottlenecks (Tukamuhabwa et al., 2015).

Importantly, the literature cautions that technological sophistication alone does not guarantee resilience. Many AI deployments fail due to lack of integration with governance structures or absence of workforce capacity to act on the insights generated (Smyth et al., 2023). Industry leaders must therefore invest in training, change management, and cross-functional teams that can interpret model outputs and translate them into actionable decisions. Furthermore, robust data governance policies are necessary to ensure that AI models operate on high-quality, ethically sourced data and remain free from bias (Naik et al., 2021).

Compliance and Regulatory Implications

Regulatory compliance is not a peripheral concern but a central pillar of resilient PSC design. As Badmus and Adebayo (2020) argue, compliance-aware frameworks reduce legal and reputational risk by integrating risk management, model governance, and data controls directly into the development and deployment pipeline. Their DevOps-oriented approach provides a blueprint for continuous compliance, where audit trails and automated testing are embedded into AI systems, ensuring that every decision can be traced and justified. Similarly, Badmus, Adebayo, and Ehigie (2018) highlight the importance of secure and scalable model lifecycle management in healthcare AI, emphasizing that privacy, traceability, and compliance are co-equal goals alongside predictive performance. Their approach aligns with the need for pharmaceutical supply chains to adopt algorithmic audit trails and serialization systems that satisfy regulations such as Good Distribution Practice (GDP), Good Manufacturing Practice (GMP), and, in the U.S., the Drug Supply Chain Security Act (DSCSA). These compliance layers build public trust by assuring that supply chain decisions meet legal and ethical standards.

Adebayo (2024) further underscores the importance of aligning data transfer and storage practices with evolving privacy regulations, particularly in cross-border contexts. For Nigeria, where much of the pharmaceutical data may be stored on servers located abroad, ensuring adherence to data protection laws is critical. Failure to do so can expose organizations to legal sanctions and undermine public confidence in AI-driven interventions. Compliance-by-design approaches mitigate these risks by embedding regulatory logic directly into system architectures, enabling automatic flagging of non-compliant actions before they propagate through the supply chain (Emmanuel et al., 2022).

Equity and Ethical Considerations

A major contribution of this study is the explicit integration of equity as a design parameter within PSC resilience frameworks. As Mhlanga (2023) observes, AI models trained solely for efficiency may inadvertently concentrate resources in already well-served areas, thereby exacerbating disparities. By contrast, equity-aware allocation algorithms can prioritize underserved regions, as demonstrated in the Nigeria case, where stock allocation can be weighted to favor northern states with higher maternal and child mortality rates. This approach aligns with the World Health Organization's objective of universal health coverage and equitable medicine access (WHO, 2023). Equity considerations are also crucial in advanced economies. During the COVID-19 vaccine rollout in the U.S., geospatial dashboards were used to identify vaccination deserts, prompting the deployment of mobile clinics and targeted outreach campaigns (Schmidt et al., 2021). These initiatives illustrate how data-driven insights can actively redress inequities when deliberately designed to do so. Future AI frameworks must incorporate fairness metrics, bias detection modules, and stakeholder consultation processes to ensure that vulnerable populations are not left behind.

Global Relevance and Scalability

The cross-continental design of the proposed framework enhances its generalizability. While Nigeria highlights the need for counterfeit detection and last-mile optimization, the U.S. case showcases how large-scale compliance regimes can be harmonized with AI-driven logistics. This dual perspective suggests that the framework can be scaled across contexts by calibrating its components to local infrastructure, regulatory maturity, and epidemiological profiles.

Scalability, however, depends on addressing key challenges such as data fragmentation, interoperability of health information systems, and availability of skilled personnel. Public–private partnerships may be necessary to pool resources, share data, and co-develop infrastructure, particularly in low-resource settings. Global health donors can play a catalytic role by funding pilot projects that demonstrate the cost-effectiveness of AI-driven geospatial solutions in improving medicine availability and health outcomes (Mahdavimanshadi et al., 2021).

Limitations and Future Directions

While the proposed framework advances the conversation on PSC resilience, it remains conceptual and requires empirical validation. Simulation studies using historical demand and disruption data can test the predictive accuracy and robustness of the model under different crisis scenarios (Dolgui & Ivanov, 2021). Field trials in selected Nigerian states could provide real-world evidence of how geospatial optimization and equity-based allocation affect stockout rates, delivery times, and patient outcomes. Future research should also explore socio-technical challenges, including stakeholder adoption, resistance to algorithmic decision-making, and the costs of integrating AI with legacy systems. Ethical implications related to data privacy, algorithmic bias, and explainability must be continually reassessed as regulations evolve. These areas represent fertile ground for interdisciplinary collaboration among supply chain specialists, data scientists, ethicists, and policymakers.

Conclusion and Future Research

This paper has presented a conceptual framework that integrates AI-driven predictive analytics, geospatial intelligence, business intelligence (BI) systems, and compliance embedding to enhance pharmaceutical supply chain (PSC) resilience. By combining these elements into a unified system, the framework addresses critical weaknesses revealed by recent global disruptions, including COVID-19, and seeks to ensure that medicine distribution is not only efficient but also legally compliant and equitable. The Nigeria and U.S. case illustrations demonstrate the cross-context relevance of this approach: Nigeria underscores the urgency of counterfeit detection, rural distribution optimization, and compliance enforcement, whereas the U.S. case highlights how predictive analytics and regulatory monitoring can be applied at scale to achieve near real-time visibility and traceability (Olutuase et al., 2022; CDC, 2022).

The proposed model contributes to both theory and practice by bridging the gap between technical innovation and governance structures. Its emphasis on algorithmic audit trails, equity-oriented allocation, and geospatial optimization aligns with calls for resilient health systems capable of withstanding future shocks (Badmus & Adebayo, 2020; Adebayo, 2024). For industry practitioners, this framework provides a roadmap for embedding AI systems that are auditable, transparent, and aligned with global and national regulations such as GDP, GMP, and DSCSA (Kiani Mavi et al., 2022).

Future research should focus on empirical validation through simulation studies and pilot deployments in both emerging and developed contexts. Evaluating key performance indicators such as stockout reduction, delivery lead-time improvement, and compliance adherence will provide evidence of the framework's effectiveness. Additionally, socio-technical factors, including user adoption, training requirements, and ethical safeguards, should be examined to ensure that the system delivers equitable outcomes without amplifying existing disparities (Mhlanga, 2023). In doing so, this research opens a pathway toward a new generation of PSC systems that are robust, accountable, and socially responsive.

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