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OPTIMIZING DRUG SUPPLY CHAINS TO PREVENT SHORTAGES IN RURAL U.S. HOSPITALS

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ABSTRACT
This study addresses the drug shortage crisis, which disproportionately affects rural U.S. hospitals, where supply chain vulnerabilities threaten patient safety and institutional viability as pharmaceutical shortages increased from 61 cases in 2005 to 178 annually by 2010. The research develops comprehensive supply chain optimization strategies specifically designed for rural healthcare facilities to enhance medication accessibility, improve supply chain resilience and ensure reliable pharmaceutical distribution across geographically isolated communities. The study employs a systematic literature review of 46 pharmaceutical supply chain studies. The findings reveal that rural hospitals experience medication price increases of 300-500% during shortages, which creates unsafe conditions of 60% however, forcing costly treatment modifications and patient transfers that strain already limited resources. The research demonstrates that artificial intelligence-driven demand forecasting, automated inventory management systems, blockchain-enabled transparency and the USDA Rural Development Program's which integrates infrastructure investments, offer transformative potential for supply chain optimization. The study concludes that successful pharmaceutical supply chain resilience requires coordinated implementation of predictive analytics, value-based procurement strategies and collaborative resource sharing mechanisms that address systemic distribution network weaknesses, however, ensuring equitable medication access across rural America's healthcare safety net.

KEYWORDS: *Drug Supply Chain, Rural Hospitals, Pharmaceutical Shortages, Healthcare Logistics, Supply Chain Optimization, Healthcare Access*

INTRODUCTION
The ongoing drug shortage crisis in the United States is a complex issue that has overburdened rural hospitals disproportionately compared to the rest of the healthcare system (Fox et al., 2014). The problem has developed over decades, beginning with sporadic shortages of certain specialized and low-volume drugs, and now includes high-demand pharmaceuticals essential for daily hospital operations. Due to their limited resources and modest purchasing power, these institutions face severe challenges whenever supply interruptions occur in critical therapeutic areas such as antibiotics, chemotherapy drugs and anesthetics (Ventola, 2011).

The issues of geographic isolation and relatively low patient volumes provide the rural hospital with different supply-chain challenges that exacerbate the effects of national drug shortages (Adak, 2024). Compared to those of metropolitan facilities, the negotiating power of many rural institutions is not sufficient to guarantee them preferential access in times of shortage, so in such cases, they often have to resort to costly workarounds, such as finding alternative medications at luxury prices, which changes the course of treatment, or in worst-case scenarios, transferring the patient to a better-stocked location. These recurrent disruptions have been revealing structural weaknesses in the supply chain of pharmaceutical distribution networks, especially their failure to ensure fair access to vital medication across varying healthcare facilities (Fox, Sweet, & Jensen, 2014).

The current-day epidemic of the so-called drug shortage crisis perpetuating rural U.S. hospitals lies in the deep systemic weaknesses that permeate the entire aspects of the system, namely the pharmaceutical manufacturing, regulation and logistics. Healthcare facilities that serve very small markets and have minimal market power and therefore are disproportionately subject to these structural weaknesses due to the geographic isolation of their communities. Ventola (2011) has identified some of the circumstances that exacerbate this weakness to include delays in the manufacturing process, quality-control oversights, breakdowns in the supply of raw materials and economic drivers that deter manufacturers from producing the generic low-margin formulations that rural hospitals rely on to meet cost-effective patient care.

Conceptually, within the pharmaceutical supply ecosystem, information asymmetries and communication gaps exist over long periods, thus subjecting the rural hospitals to specific risks. With tight budgets and limited storage facilities, these institutions generally carry very narrow inventory buffers and thus prove to be very sensitive to prediction errors or rearrangements higher in the supply chain. The implication is clear: even a comparative

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lapse in production or distribution hubs can easily cascade into extreme shortages, which threaten the care of patients in remote locales. Even though these concerns have been extensively documented, the currently available literature provides little and actionable advice on how to strengthen the resilience of the supply chain in the rural healthcare environment. A justifiable research gap still exists, as a result of which the concept of integrated research based on the combination of technological innovation, selective policy and industry collaboration is needed to strengthen the accessibility and availability of drugs and supply chain resilience of rural hospitals and hospitals in the United States. This will ensure that the essential medicines are reliably supplied to these important providers has been developed.

This study focuses on the imminent drug-shortage problem currently plaguing American rural health facilities, in which the escalation between 61 reported supply lapses in 2005 and 178 per year by the year 2010 represents a form of nearly triple increase that most severely impacts poorly equipped hospitals (Ventola, 2011). Rural hospitals and clinics will have to address the avalanche of effects that operate once the shortages lower the access to essential pharmacotherapies, which forces them to divert their limited human and financial resources to revise the treatment regimes, order alternative therapies and increase the level of communication with their clinical staff and patients (Gu et al, 2011).

These are the most vulnerable settings to face the consequences of substitutions, as they often lead to medication errors, delayed treatment, or suboptimal outcomes that threaten patient safety and treatment effectiveness. Populations most at risk include pediatrics, oncology and intensive-care units, where special formulations or dosage quantities are often unavailable (Gu et al., 2011; Fox et al, 2014). The economic consequences are equally severe, as rural hospitals are compelled to rely on secondary suppliers due to supply shortages. In these cases, goods can cost up to 50 times their usual market price during emergencies, placing significant strain on already tight budgets and adversely impacting the long-term viability of life-sustaining care in communities with limited access to affordable pharmaceuticals (Ventola, 2011). Therefore, this study aims to develop a delivery-chain optimization plan specifically for rural hospitals, thereby increasing access to life-saving medications, improving supply chain resilience and enhancing the overall availability of essential drugs in rural America.

LITERATURE REVIEW

Drug shortages are more frequent in rural U.S. hospitals than in urban healthcare facilities, which creates a public health crisis that directly impacts patient care and clinical outcomes in underserved communities. Geographic isolation, the resultant fragmentation of demand makes aggregation challenging due to limited purchasing power and storage capacity. As well, their reliance on massive, centralized distribution networks that are concentrated in high-volume urban markets all play a role. This review integrates existing literature on supply chain optimization techniques, new technologies and policies targeting drug shortages prevention, which focuses on the rural U.S. healthcare landscape expressed in terms of geographic access disparity to identify a knowledge deficit/gap as well as highlight systematic policy demands for betterment.

Drug Shortage Epidemiology and Impact on Rural U.S. Healthcare Systems

A study conducted by Kaakeh et al. (2011) provided seminal insights into the national scope of drug shortages through their comprehensive survey of 353 pharmacy directors across U.S. health systems. Their research revealed that drug shortages impose an estimated $216 million in annual labor costs nationwide, with pharmacists and pharmacy technicians bearing the primary burden of shortage management activities. Their study demonstrated significant associations between time spent managing shortages and institutional characteristics, including facility size and automation levels, which suggests that smaller rural hospitals face disproportionately greater challenges due to limited staffing resources and technological infrastructure. 70% of respondents indicated that available information resources for managing drug shortages were inadequate, which highlights vulnerabilities for rural hospitals that typically lack dedicated shortage management specialists and rely on regional distribution networks with limited alternative sourcing capabilities.

Similarly, another research conducted by Caulder et al (2015) examined regional variations in drug shortage impacts through an extensive survey of 549 pharmacy directors across the Southeastern United States, which achieved a 40% response rate from institutions in North Carolina, South Carolina, Georgia and Florida. Their findings revealed alarming safety implications, with drug shortages creating unsafe conditions for patients and staff 60% of the time while causing hospital error rates of 1% to 5%. Their study documented severe financial strain, with many respondents reporting medication price markups of 300% to 500% during the shortage period burden which disproportionately affects rural hospitals operating on thin profit margins. Additionally, 76% of institutions implemented auto-substitution protocols, which required significant pharmacy and therapeutics committee resources and created operational complexity that rural facilities with limited administrative capacity struggle to manage effectively.

Equally, research conducted by Nuako et al. (2022) examined the intersection of drug shortages with rural healthcare delivery patterns through their analysis of 1,423,166 outpatient visits from 474,674 patients in a large Midwestern healthcare system. Their study revealed that patients in rural clinics demonstrated significantly worse health status compared to urban clinic patients yet paradoxically exhibited lower healthcare utilization (2.49 vs. 3.18 visits, RR = 0.61, 95% CI = 0.55-0.68, $p<0.0001$). This utilization disparity persisted across both primary care and specialty services even after adjusting for multiple demographic and health factors, which suggests that rural patients who already face access barriers and demonstrate higher disease burden are

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served by healthcare systems with inherently limited resources. This creates compounding vulnerabilities when drug shortages disrupt standard treatment protocols.

Furthermore, a study conducted by Vail et al. (2017) demonstrated the life-threatening clinical consequences of critical drug shortages through their examination of the 2011 norepinephrine shortage's impact on septic shock patients across 26 U.S. hospitals and analyzed 27,835 patients admitted between 2008 and 2013. Their research revealed that norepinephrine use declined dramatically from 77.0% to 55.7% during shortage peak periods, with phenylephrine becoming the primary alternative vasopressor. Most significantly, patients admitted during shortage periods experienced significantly higher in-hospital mortality rates (39.6% vs. 35.9%, adjusted OR = 1.15, 95% CI = 1.01-1.30, p = 0.03), which represents an absolute risk increase of 3.7%. This mortality impact disproportionately affects rural hospitals, which typically maintain smaller intensive care units with limited alternative medication inventories and fewer opportunities to transfer critically ill patients to tertiary care facilities during shortage crises.

Additionally, research conducted by Hedlund et al. (2018) emphasized the clinical impact paradigm through their retrospective cohort study examining how the 2011 cytarabine shortage affected acute myeloid leukemia (AML) treatment delivery using SEER-Medicare data spanning 2008-2013. Their analysis revealed that patients diagnosed during major shortage periods were 47% less likely to receive timely inpatient chemotherapy within the critical 14-day window following diagnosis. This treatment delay has profound implications for cancer outcomes, particularly devastating for rural patients who already face longer diagnostic delays and limited access to oncology specialists. Their findings underscore how drug shortages create cascading effects that compound existing rural healthcare disparities, where patients must often travel significant distances for specialized care and have fewer alternative treatment facilities available when primary therapeutic options become unavailable due to supply chain disruptions.

U.S. Healthcare Supply Chain Management Frameworks and Pharmaceutical Distribution Models.

A study conducted by Franco and Alfonso-Lizarazo (2017) provided a comprehensive structured review of quantitative models in pharmaceutical supply chains through their analysis of 46 studies published between 1984 and November 2016. Their systematic classification revealed three primary categories of pharmaceutical supply chain optimization: network design, inventory models and supply chain optimization, with demand uncertainty being the most common source of variability addressed in 56% of the cases. Their research identified a key gap in the literature, finding that while most studies focused on supply chain optimization and inventory models, network design remained understudied notwithstanding its fundamental importance to U.S. pharmaceutical distribution systems. Their finding is particularly relevant for understanding how rural U.S. hospitals integrate into broader pharmaceutical distribution networks, as the limited research on network design suggests insufficient attention to the geographic and structural challenges that characterize rural healthcare supply chains.

Similarly, another research conducted by Oluwole et al (2024) emphasized the transformative potential of predictive analytics and value-based healthcare economics frameworks in optimizing pharmaceutical supply chains within the evolving U.S. healthcare ecosystem (Narteh-Kofi et al, 2025). Their analysis demonstrated how machine learning and artificial intelligence technologies can enable stakeholders to forecast demand patterns, anticipate drug shortages and optimize inventory levels by integrating real-time data from hospitals, pharmacies, manufacturers and external market trends. Their study advocated for incorporating value-based healthcare economics that prioritize high-impact therapies based on quality-adjusted life years (QALYs) and cost-utility analyses. This constituted a fundamental shift from volume-based to value-based distribution strategies. This framework holds promise for rural U.S. hospitals, which must maximize therapeutic impact within severe resource constraints and could benefit significantly from predictive tools that optimize limited inventory investments (Narteh-Kofi et al, 2025).

Equally, research conducted by Dada et al (2025) exposed vulnerabilities in U.S. healthcare supply chains, which were revealed during the COVID-19 pandemic, particularly concerning essential medicine availability and the urgent need for data-driven resilience strategies. Their analysis identified fundamental weaknesses in predictive systems, real-time inventory management and supply chain transparency that contributed to widespread stockouts, increased costs and compromised patient care across U.S. healthcare systems. Their study emphasized how artificial intelligence can revolutionize demand forecasting while blockchain technology ensures transparency and traceability to prevent counterfeit medicines. They underscored that these technologies could particularly benefit rural hospitals with limited pharmacy oversight capabilities. Their research emphasised that technological solutions require supportive policy frameworks, including clear regulatory guidelines for technology integration, public-private partnerships for pilot programs, funding for legacy system modernization and workforce development initiatives to address skills gaps that disproportionately affect rural healthcare facilities.

Furthermore, a study conducted by Yanamandra (2018) developed an integrated healthcare supply chain model through a literature review and addressed the nascent implementation of supply chain management practices within the global healthcare sector, including U.S. systems. Their research identified that hospitals, as the primary entities within healthcare supply chains, have struggled to achieve cost reduction and quality service objectives due to a limited understanding of supply chain management principles and their practical applications. Their integrated model emphasized the importance of coordination

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between multiple supply chain echelons from manufacturers through distributors to end-user healthcare facilities, which highlights how fragmented approaches have historically undermined supply chain efficiency. This integrated framework is particularly relevant for rural U.S. hospitals, which often operate as isolated endpoints in complex distribution networks and require sophisticated coordination mechanisms to ensure reliable access to essential medications despite their geographic and operational constraints.

Additionally, research conducted across these foundational studies reveals that U.S. pharmaceutical distribution models have evolved from traditional volume-based approaches toward more sophisticated, technology-enabled frameworks that emphasize predictive capabilities, value-based outcomes and integrated network coordination. The collective findings demonstrate that successful pharmaceutical supply chain optimization requires simultaneous advancement across multiple dimensions: quantitative modeling sophistication, predictive analytics integration, policy framework development and comprehensive stakeholder coordination.

Rural U.S. Hospital Operational Challenges and Healthcare Delivery Constraints

A comprehensive study conducted by Maganty et al (2023) on barriers to rural healthcare from the provider perspective utilized semi-structured interviews with primary care physicians practicing in western Pennsylvania, the nation's third-largest rural population, to examine healthcare delivery challenges through purposive sampling and thematic analysis. Their investigation revealed three fundamental barriers constraining rural healthcare delivery: cost and insurance limitations, geographic dispersion challenges and provider shortage compounded by professional burnout. These findings demonstrate the multidimensional nature of rural healthcare constraints, where financial barriers prevent patient access to necessary care, vast geographic distances create logistical impediments for both patients and providers and workforce shortages perpetuate a cycle of provider overextension and subsequent burnout.

Pai (2025) conducted a systematic review on Health information technology in rural health care: A systematic review of its impact on critical access hospitals. They employed PRISMA guidelines to analyze 45 peer-reviewed articles published between 2000-2024, with the majority (n=31) published post-HITECH Act. They used diverse methodological approaches, including statistical analyses, surveys, case studies and interviews. The analysis identified persistent, recurring challenges that have remained largely intractable despite significant federal policy initiatives, such as crippling financial constraints preventing adequate technology investment, persistent staffing shortages limiting technical expertise and operational support and frustrating interoperability failures preventing effective information system integration and data sharing (Asamoah et al, 2025). They noted that these barriers create compounding effects wherein rural hospitals struggle to maintain technological parity with urban counterparts, which potentially exacerbates quality disparities between rural and urban healthcare delivery systems.

A qualitative study conducted by Pati et al (2016) on rural healthcare delivery within evolving health models examined the influence of physical healthcare facility infrastructure on care experiences and quality perceptions through semi-structured interviews with upper and mid-level administrators across four rural hospitals in West Texas. Their investigation addressed a significant empirical knowledge gap regarding rural healthcare delivery from a facility perspective, which recognizes the evolution of rural hospitals from traditional acute care providers to comprehensive operations. This offers diversified services, disaster management capabilities and integrated provider network coordination. Their analysis identified two primary factor classes influencing hospital experience and care quality, that is, care configuration challenges and outdated building infrastructure. They emphasized that physical infrastructure may have profound implications for population health performance in rural America, which suggested that facility modernization and strategic redesign should be considered essential components of comprehensive rural healthcare improvement strategies rather than ancillary considerations.

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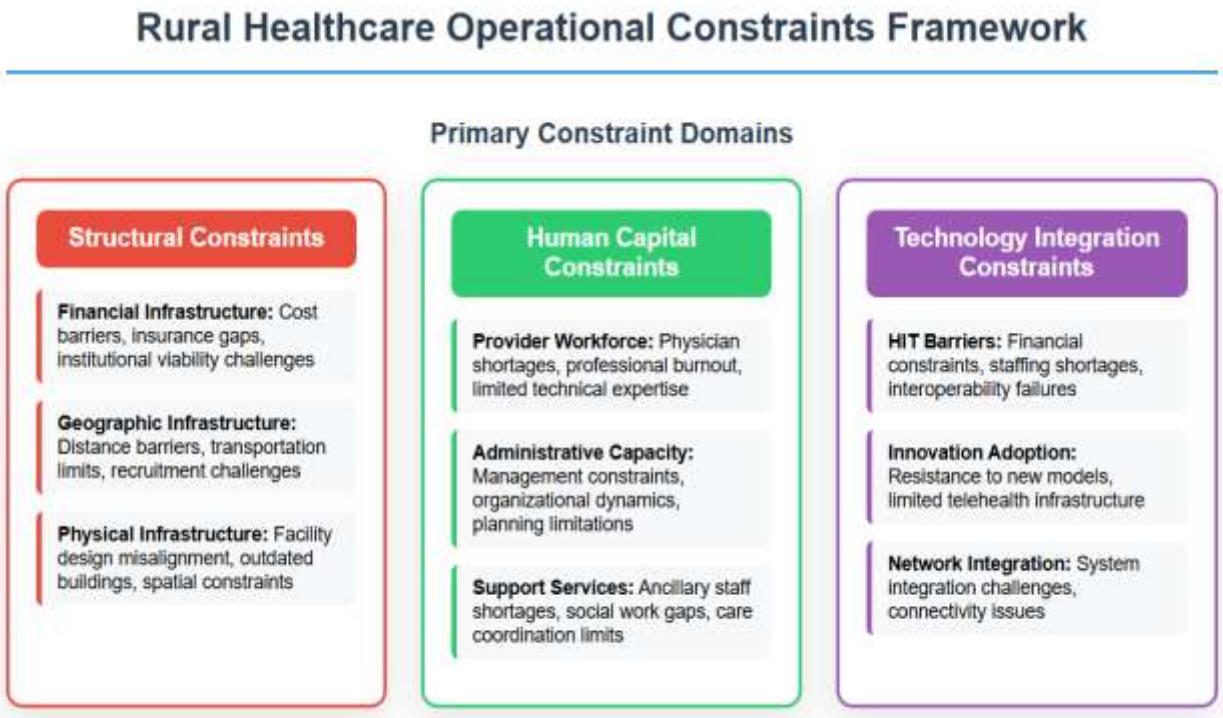
Figure 1: Rural Healthcare Operational Constraints Framework



The chart above shows the Rural Healthcare Operational Constraints Framework that identifies three interconnected domains of barriers that systematically impede healthcare delivery in rural American communities. Structural constraints include financial limitations such as cost barriers and insurance gaps, geographic challenges like distance barriers and transportation issues and physical infrastructure problems including outdated facilities and spatial limitations. Human capital constraints encompass workforce shortages, provider burnout, administrative capacity limitations and gaps in support services like social work and care coordination. Technology integration constraints involve financial barriers to health information technology adoption, staffing shortages that limit technical expertise, interoperability failures and resistance to innovative care delivery models such as telehealth. These three constraint domains operate synergistically to create compounding challenges that require comprehensive, multi-dimensional interventions in addressing structural, workforce and technological barriers simultaneously to improve rural healthcare access and quality.

Technology-Enabled Solutions for U.S. Rural Healthcare Supply Chain Optimization.

According to Ugwu et al (2024), artificial intelligence is emerging as a transformative force in healthcare supply chain optimization. However, digital transformation adoption leads to increased automation and efficiency across the sector. The integration of AI-driven technologies addresses relevant rural healthcare supply chain challenges through intelligent demand forecasting, automated inventory management and predictive analytics that can anticipate supply shortages before they occur (Long et al. 2023). Healthcare supply chain management has gained heightened attention following pandemic-related vulnerabilities, which necessitate AI-powered solutions that enhance resilience and responsiveness in resource allocation. Advanced machine learning algorithms can analyze historical consumption patterns, seasonal variations and demographic health trends to optimize pharmaceutical and medical device distribution to rural facilities, whereas automated procurement systems reduce the administrative burden on resource-constrained rural healthcare organizations (Brintrup, 2020). These technological interventions are especially relevant for rural settings where supply chain disruptions can have disproportionate impacts on patient care quality and access.

According to Carroll & Eliason (2023), the rural clinical and healthcare logistics market is experiencing significant growth driven by technological advancements in medical transportation, telemedicine integration, cold chain logistics adoption and innovation in mobile health units and clinics as the market size is projected to grow by $2.26 billion from 2024-2028. Mobile health technologies and satellite clinics equipped with IoT sensors and real-time monitoring capabilities enable dynamic supply chain management that can adapt to fluctuating demand patterns across geographically dispersed rural communities (Akhtar et al, 2023). Recent systematic reviews demonstrate that AI-driven diagnostic tools and telemedicine platforms are transforming healthcare delivery in rural and underserved communities, with artificial intelligence enhancing access to primary healthcare in areas with underserved rural populations (Lamem et al, 2025). Blockchain technology integration ensures supply chain transparency and pharmaceutical authenticity, however, drone delivery systems and

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autonomous vehicles can overcome geographic barriers that traditionally impede timely medical supply distribution. These technological solutions create interconnected networks that enable rural healthcare facilities to maintain optimal inventory levels while minimizing waste and reducing costs through shared resource pooling and coordinated procurement strategies.

According to Ahmed et al (2023), the convergence of artificial intelligence, Internet of Things sensors and cloud-based platforms creates intelligent supply chain ecosystems that can automatically adjust distribution patterns based on real-time health data, emergency preparedness requirements and population health analytics. Digital transformation and intelligent transformation of public healthcare supply chains demonstrate measurable impacts on sustainable development performance, which indicates that AI integration yields both operational efficiency gains and long-term strategic advantages. Conceptually, rural healthcare organizations can leverage these technology-enabled solutions to establish resilient, cost-effective supply chains that not only address immediate logistical challenges but also position rural communities for improved health outcomes through enhanced resource accessibility, reduced stockouts and optimized distribution networks. These can adapt dynamically to changing healthcare demands and emergency response requirements.

Figure 2: USDA Rural Development Program Investment Framework for Healthcare Supply Chain Optimization

USDA Rural Development Program	Investment Focus	Supply Chain Impact	Technology Integration
Rural Hospital Infrastructure	Building and expanding rural health facilities	Increased delivery destinations and storage capacity	Modern facilities support advanced logistics systems
Health IT Infrastructure	Servers, routers, networking equipment	Enables digital supply chain management	Foundation for IoT and automated systems
Interoperability Projects	Equipment and software for system integration	Coordinated supply chain across networks	Blockchain and AI integration capabilities
Biden-Harris Investing in America	Expanded funding for rural healthcare	Increased investment in supply chain optimization	Advanced technology adoption acceleration

The chart above shows the USDA Rural Development Program's four key investment areas that support drug supply chain optimization for rural U.S. hospitals. Rural Hospital Infrastructure investments build and expand facilities with modern logistics systems that increase delivery destinations and storage capacity for pharmaceuticals. Health IT Infrastructure provides servers, routers and networking equipment that enable digital supply chain management and automated inventory systems to prevent drug shortages. Interoperability Projects focus on equipment and software integration that coordinates supply chains across hospital networks using blockchain and AI technologies. The US government's Investing in America initiative expands funding for rural healthcare with increased investment in supply chain optimization and advanced technology adoption to help rural hospitals maintain adequate drug inventories.

CONCLUSION

This study reveals key findings that demonstrate the need for systematic interventions to address the disproportionate impact of pharmaceutical shortages on rural healthcare delivery. The research findings indicate that rural hospitals face a triple burden

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of geographic isolation, limited purchasing power and inadequate technological infrastructure, which creates cascading vulnerabilities when national drug shortages occur, as evidenced by the dramatic increase from 61 reported supply lapses in 2005 to 178 per year by 2010. The study demonstrates that these shortages impose severe financial strain on rural facilities, with medication price markups reaching 300-500% during shortage periods and creating unsafe conditions for patients and staff 60% of the time. These are forcing costly treatment modifications and patient transfers that threaten the long-term viability of rural healthcare systems. The analysis reveals that technology-enabled solutions, particularly artificial intelligence-driven demand forecasting, automated inventory management systems and blockchain-enabled supply chain transparency, offer transformative potential for rural healthcare supply chain optimization. The study noted that the USDA Rural Development Program's integrated approach provides important infrastructure investments in hospital facilities, health IT systems and interoperability projects. The implications of these findings extend beyond operational efficiency to encompass fundamental questions of healthcare equity and access, as the study establishes that optimized drug supply chains are essential for maintaining patient safety, reducing treatment disparities and ensuring the survival of rural hospitals that serve as critical safety nets for geographically isolated communities.

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