**Lessons from Crisis: Building Resilient Pharmaceutical Supply Chains in a Disrupted World**

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ABSTRACT

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| The constraint of global pharmaceutical supply chains has been laid bare by a series of adverse events—from the COVID-19 pandemic to war, political conflicts, and climate-induced natural disasters. These critical events have exposed the severe vulnerabilities, including overdependencies on China for API (active pharmaceutical ingredients), limited manufacturing facilities, insufficient buffer stocks of critical life-saving medicines, uncontrolled regulations and compliances, and a lack of global harmonized procedures. In this manuscript, we will assess the global disruptions and discuss a strategic solution for building a stringent, harmonized, and equitable pharmaceutical supply chain. We will discuss the recent case studies and interdependent solutions, identify the root causes that contributed to shortages of essential life-saving medicines and protective equipment. We further explore how governments and regulatory agencies can establish a strategic pharmaceutical supply chain that will help to establish regional manufacturing hubs through systematic investments and public-private partnerships. Strengthening and simplifying pharmaceutical supply chain processes are not merely a logistical challenge; it is also a policy imperative to ensure equal access to critical life-saving medicine for the most vulnerable people in this uncertain world. As global uncertainty intensifies due to geographical conflict, war, and emerging infectious diseases in third-world countries, a stringent and accessible pharmaceutical supply chain is a necessity for the most vulnerable populations. |

*Keywords: Medicine Supply Chain, Global Pandemic, Supply Chain Disruption, Covid-19, Medicine Shortage, Pharmaceuticals supply chain Challenges, Supply Chain Strategies, Active Pharmaceutical Ingredients.*

1. INTRODUCTION

The accessibility of essential medicines is a foundation of a strong healthcare system. Recent adverse events have exposed vulnerabilities of pharmaceutical supply chains that were once considered strong, efficient, and self-sufficient. Recently, the COVID-19 pandemic has caused severe disruptions and challenges that have affected the global pharmaceutical supply chain (Moosavi, 2022). Subsequently, some other factors, such as geopolitical conflicts, natural disasters, inaccessibility of life-science technologies, and monopolistic practices of pharmaceutical companies, rapidly increased the crisis. Pharmaceutical supply chains are considerably complex, involving multiple stakeholders at different stages, including the sourcing of raw materials, manufacturing, temperature-controlled logistics such as cold chain, and distribution (Devi, 2023). Technological advancement and globalization have made pharmaceutical supply chains highly efficient—but also highly dependent on a limited number of vendors for sourcing, manufacturers, and logistical services. During the COVID-19 pandemic, the world realized its dependency on China for API (active pharmaceutical ingredients). Developing and underdeveloped countries, especially those in Africa and Southeast Asia, were severely affected due to limited financial resources, inadequate infrastructure, restrictive government policies, and a lack of local manufacturing capacity.

The world witnessed a severe shortage of critical medicine during the COVID-19 crisis, as most of the countries-imposed restrictions on the export of life-saving medicine supplies. This disrupted the pharmaceutical supply chain and triggered panic even in countries with strong sourcing networks, while severely impacting the availability of antibiotics, antivirals, vaccines, and PPE (Personal Protective Equipment) kits in more vulnerable health systems. These critical medicine shortages severely affected the treatment of chronic life-threatening diseases, surgical procedures, and emergency care—making essential medical services inaccessible to vulnerable and poor populations and contributing to excess morbidity and mortality (Choo, 2020). These crises also exposed the weakness and critical vulnerabilities in key areas of the pharmaceutical supply chain, providing learning opportunities to implement more effective strategies for ensuring continuity of critical medicine supply. Countries are utilizing innovative technologies to monitor real-time supply chain activities, investing in manufacturing facilities, and harmonizing policies to mitigate the risk of medicine shortages.

In this manuscript, we primarily focus on vulnerabilities of pharmaceutical supply chains exposed by the COVID-19 pandemic and discuss the compelling reasons for implementing stringent supply chain processes. The manuscript proposes a framework outlining strategic processes for building resilient supply chain systems by adopting harmonized global policies and regulatory recommendations for governments and industry stakeholders.

1. Literature Review

This section provides a comprehensive review of the literature on pharmaceutical supply chain resilience in the context of the COVID-19 pandemic, with a critical focus on emerging strategies and frameworks aimed at optimizing supply chain robustness and adaptability during global health disruption.

Medicines are an essential component of human well-being, and access to healthcare services is a fundamental necessity. Disruptions in the pharmaceutical supply chain can have far-reaching consequences, severely impacting public health and societal stability. Even before the COVID-19 pandemic, the pharmaceutical supply chain faced numerous challenges—including geopolitical tensions, civil unrest, inadequate government funding, extreme climate, poor infrastructure, and limited access to advanced technologies. These factors collectively undermined the resilience and efficiency of global healthcare systems, ultimately leading to widespread medicine shortages.

The COVID-19 pandemic exposed the pharmaceutical industry's heavy reliance on centralized suppliers of Active Pharmaceutical Ingredients (APIs). Most manufacturers had not adequately explored alternative sources or invested in developing regional API production capabilities. This overdependence highlighted a significant vulnerability in the global pharmaceutical supply chain, underscoring the urgent need for diversification and local capacity building.

Developing a resilient pharmaceutical supply chain should be a joint effort involving all stakeholders, from manufacturers to government bodies (Wosińska, 2023). Government and regulatory authorities must take proactive measures by investing in pharmaceutical technologies, offering incentives to manufacturers and healthcare providers, and maintaining buffer stocks of critical medicines to mitigate potential disruptions.

This literature primarily focuses on the key causes of pharmaceutical supply chain disruptions and outlines strategies to mitigate associated risks. The pharmaceutical supply chain will continue to remain vulnerable unless it adopts critical strategies such as supplier diversification, enhanced transparency and visibility through advanced technologies for real-time data tracking, regulatory agility, investment in buffer stock of essential medicines, and collaborative efforts across the industry (Peter, 2025).

The growing volume of research on pharmaceutical supply chains underscores their increasing significance within the healthcare sector. However, greater attention and coordinated efforts are still required to effectively address ongoing supply chain challenges and unlock their full potential. Governments and other key stakeholders can play a crucial role by prioritizing these issues, thereby contributing to improved health outcomes and more efficient, resilient supply chain systems.

1. Related work and methodological approaches

Bibliographic databases and scientific search engines, such as Google Scholar, were systematically searched for studies related to pharmaceutical supply chain risk management, focusing on English-language publications. The search was conducted using a variety of keywords, including "pharmaceutical supply chain disruption," "medicine shortage," "global pandemic," and "pharmaceutical supply chain strategies." Search strategies were tailored to the specific features of each database. All results, including studies abstracts, were initially screened. Titles were reviewed, and non-relevant articles were excluded based on relevance to the research objectives and defined study boundaries. Subsequently, abstracts of the remaining articles were evaluated, and further exclusions were made based on alignment with the study scope. In the final stage, full texts of the selected articles were thoroughly reviewed, and additional exclusions were applied based on the outcomes of interest.

1. the anatomy of a pharmaceutical supply chain

The pharmaceutical supply chain is a complex, integrated process that relies on every stakeholder in the network. Each stakeholder, from sourcing vendors to the final dispenser, must ensure medicines are available and accessible to society. The pharmaceutical supply chain can be broadly divided into three main phases: sourcing from suppliers, manufacturing, and distribution in the market. Based on the composition of the medicine, active pharmaceutical ingredients (APIs) are often procured from specific countries or geographic regions. For example, China and India serve as major manufacturing hubs for generic medicines due to the easy availability of APIs and low labor costs. Additionally, both countries act as Contract Manufacturing Organizations (CMOs), supported by favorable local regulations and government incentives for export. Finally, the logistics phase ensures that medicines are distributed using advanced technologies such as temperature-controlled cold chains and traceability systems. The COVID-19 pandemic and other geopolitical conflicts demonstrated that disruptions in any phase of the supply chain can severely impact the entire system—by making Active Pharmaceutical Ingredients (APIs) inaccessible for manufacturing critical life-saving medicines, causing manufacturing shutdowns, reducing the availability of skilled manpower, and interrupting transportation.

1. CASE STUDIES OF SUPPLY CHAIN DISRUPTION DURING COVID-19 PANDEMIC

COVID-19 was one of the most devastating adverse events in recent history, exposing the vulnerabilities of both the global healthcare system and the pharmaceutical supply chain. It not only affected low-income countries but also highlighted the dominance of financially capable and resource-rich developed nations. The following are some key areas impacted by the COVID-19 pandemic.

* 1. **Global Shortages of Personal Protective Equipment and Medicines**

During the COVID-19 pandemic, the world witnessed a severe shortage of disinfectants, sanitizers, PPE kits, and essential medicines such as hydroxychloroquine, antibiotics, dexamethasone, and paracetamol (Gereffi, 2020). The World Health Organization estimated that approximately 95 countries-imposed restrictions on the export of critical medicines. India, the largest exporter of generic medicines, temporarily prohibited the export of 26 essential drugs. These government policies significantly affected the global pharmaceutical supply chain and disrupted the availability of essential medicines. Similarly, China also reduced the production of certain critical Active Pharmaceutical Ingredients (APIs) required for life-saving treatments. These policies slowed medicine manufacturing due to the non-availability of APIs, as well as shortages of sedatives and anesthetics used for patients on ventilators.

* 1. **Fragmented Global Procurement and Competition imbalances**

Most API and pharmaceutical component sourcing was unorganized, leading to significant inefficiencies in the pharmaceutical supply chain during the COVID-19 pandemic. Even reputed companies competed against each other for the same limited supplies. Some companies inflated the prices of branded medicines and made unverified claims about their efficacy against the COVID-19 virus. As a result, access to essential medicines became inequitable, particularly for African nations and other low-income countries. These countries were the most vulnerable in terms of vaccine access, as many Western developed nations adopted a "country-first" approach due to their greater purchasing power and geopolitical influence. The COVAX facility, designed to promote equity in vaccine distribution, struggled to secure timely deliveries for its member states due to manufacturing delays and hoarding by wealthier countries (Storeng, 2023). This same challenge extended to therapeutics and diagnostics, resulting in critical delays across many regions.

* 1. **implications for managing chronic diseases**

COVID-19 severely affected the world’s most health-vulnerable populations, worsening their conditions due to existing chronic diseases. The supply of essential medications for diabetes, hypertension, blood pressure regulation, and chronic inflammation was disrupted. According to the World Health Organization (WHO), 53% of countries reported partial disruptions in the supply of noncommunicable disease (NCD) medications in 2020 (Luciani, 2020). At the same time, several African countries reported shortages of life-saving medications for communicable diseases such as tuberculosis and HIV/AIDS.

* 1. **disruptions in Transport and Logistics**

The distribution of critical medicines heavily relied on the aviation industry, which handles approximately 70% of global generic medicine shipments. However, logistical services were significantly affected due to border closures, export embargoes, and government decisions and policies. Logistics companies were forced to reduce their container capacities during the COVID-19 pandemic, leading to massive shortages of life-saving critical medicines. Some landlocked countries in Africa experienced inaccessibility to COVID-19 vaccines as lockdowns disrupted routine vaccine supply chains, resulting in stockouts of DTP (diphtheria, tetanus, pertussis) and measles vaccines in several districts (Ajari, 2020). Similarly, in Peru, inland transport restrictions delayed the delivery of COVID-19 test kits and oxygen supplies to rural hospitals, contributing to increased mortality.

* 1. **Manufacturing Disruptions and Workforce Shortages**

During the COVID-19 pandemic, many countries imposed complete lockdowns, which significantly affected the pharmaceutical supply chain. This included factory closures, labor shortages, and limited availability of active pharmaceutical ingredients (APIs). Many companies were forced to shut down their manufacturing units due to reduced workforce availability and an inability to sustain production lines (Bardhan, 2022). India, one of the largest producers of generic medicines in the world, imposed a strict nationwide lockdown for several months due to the COVID-19 pandemic. At the same time, the country faced difficulties accessing the active pharmaceutical ingredients (APIs) required for manufacturing critical medicines due to import embargoes and global supply chain disruptions in key shipping routes.

1. Key Lessons from Crisis

Recently, the world has witnessed multiple crises, including the COVID-19 pandemic, geopolitical instability caused by war, natural disasters, mass migrations from developing countries, and economic downturns. These crises have exposed the vulnerabilities of the pharmaceutical supply chain and highlighted the urgent need for a more robust and decentralized system.

* 1. **overreliance on centralized supply sources threatens sustainability**

Overdependence on centralized sources for API procurement remains a key challenge and poses a significant risk to the pharmaceutical supply chain. A large portion of the world’s Active Pharmaceutical Ingredients (APIs) is produced in China, while India leads in the production of affordable generic medicines. When manufacturing or export operations in these regions were disrupted by COVID-19 restrictions, many downstream countries faced immediate and widespread shortages (Z. Yu, 2021). This situation created an urgent need to diversify and explore alternative sources for API and generic medicine manufacturing. Governments should also invest in strengthening healthcare systems to mitigate such risks and reduce supply chain bottlenecks.

* 1. **insufficient stockpiling for emergency events**

Many low-income and developing countries did not have sufficient stockpiles of critical life-saving medicines and PPE kits during the COVID-19 pandemic. They were heavily reliant on wealthier nations and pharmaceutical giants for grants and charitable donations. These countries lacked replenishment planning and dedicated government budget allocations for stockpiling essential medicines, which contributed to severe fatalities among their most vulnerable populations. The crisis reinforced the necessity of establishing dynamic, risk-adjusted, and scalable national and regional stockpile systems capable of absorbing short-term shocks without compromising healthcare delivery (Handfield, 2020).

* 1. **Limited Visibility Impaired Decision-Making**

A recurring challenge across countries was the absence of real-time data on medicine availability, demand surges, and supply chain disruptions. This lack of visibility made it difficult to coordinate procurement, anticipate shortages, or deploy targeted interventions (Rajan, 2020). The lesson here is the value of investing in digital health supply chain platforms that enable end-to-end monitoring, predictive analytics, and transparent decision-making.

* 1. **Fragmented Global Procurement drives Inequity and Competition**

In the absence of internationally harmonized sourcing policies, major suppliers often compete against one another for market access and increased profit margins. During times of disruption, some suppliers have been known to artificially create scarcity in order to inflate the prices of medicines or APIs (Blanco, 2020). However, while wealthy and developed countries are often able to replenish medicine shortages, such disruptions can lead to the collapse of healthcare systems in low-income nations. While global initiatives such as COVAX were designed to ensure equitable access to vaccines and essential medicines, they faced significant challenges due to funding shortfalls and supply limitations. Moving forward, it is crucial to adopt fair procurement models, implement transparent distribution systems, and foster stronger international cooperation during global health emergencies.

* 1. **limited local manufacturing increas exposure to external risks**

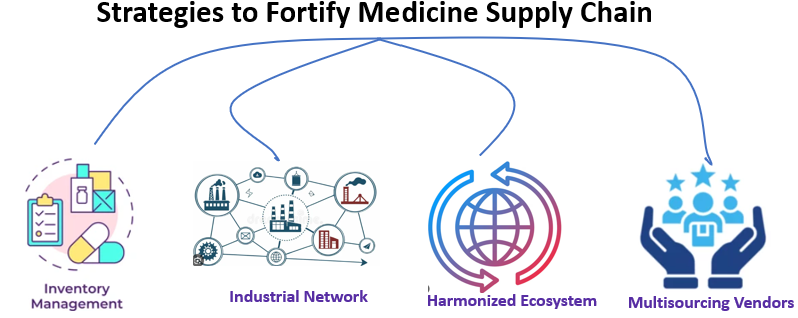
Many countries in Africa and Asia do not have fully developed pharmaceutical manufacturing hubs due to underdeveloped infrastructure, low government spending, unclear policies, and geopolitical instability (Kersan, 2022). The COVID-19 pandemic exposed their vulnerabilities and underscored the fact that strategic healthcare policies, strengthened pharmaceutical manufacturing, and increased government investment in the healthcare sector are not optional—they are strategic necessities.

* 1. **Human Resource and Logistical Gaps undermined Last-Mile Delivery**

The COVID-19 pandemic and other geopolitical instabilities prevented the healthcare industry from operating at its full potential. Some countries were forced to halt pharmaceutical production, while others remained non-functional due to a lack of skilled resources. Similarly, the logistics industry was affected by limited access to ports and weak cold chain management, which disrupted last-mile delivery (Puram, 2022). This underscored the importance of investing in health logistics capacity, training supply chain professionals, and modernizing infrastructure to ensure reliable access to essential healthcare where it is needed most.

1. Strategies to Strengthen Medicine Supply in Uncertain Times

Adverse events such as the COVID-19 pandemic have triggered multiple crises and exposed the world’s vulnerabilities. However, they also created an opportunity for the global pharmaceutical supply chain to develop a strategic, long-term plan to mitigate such challenges in the future (figure 1). To transition from crisis to opportunity, governments and stakeholders must adopt significant reforms and a multipronged strategy that integrates redundancy, equity, innovation, and collaboration.

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**Figure 1. Supply chain strengthening Strategies.**

* 1. **Diversify Supply Sources and Build Regional Manufacturing Capacity**

The COVID-19 pandemic revealed that many countries—particularly those with low and middle incomes—were overly reliant on a small number of international manufacturers and exporters for critical supplies such as medicines, vaccines, diagnostics, and personal protective equipment (PPE). To mitigate issues related to shortages or low production, countries should develop a robust supply chain delivery model, strengthen domestic manufacturing capabilities, and diversify or explore alternative sources for critical APIs and medicines (Gereffi, 2022). A resilient and fair medicine supply system requires more than global supply chains; it must include local production, diversified sourcing, and regional self-sufficiency to withstand disruptions and ensure timely access in emergencies.

* 1. **maintaining strategic medicine reserves**

During the initial phase of the COVID-19 pandemic, many countries faced shortages of critical medicines and PPE kits. Available supplies were often insufficient, outdated, or mismatched with the actual needs of the population (Abedrabboh, 2021). Strategic medicine stockpiles are vital for both emergency response and the continuity of essential health services during prolonged crises. These national or regional reserves include prepositioned medicines, vaccines, diagnostics, and medical devices for rapid deployment during health emergencies, supply disruptions, or humanitarian disasters.

* 1. **Invest in Supply Chain Visibility and Digital Infrastructure**

A truly stringent pharmaceutical supply chain pivots on real-time visibility, data-driven insights, and seamless digital integration across every tier of the health system. The COVID-19 pandemic exposed how outdated, fragmented, and paper-based systems crippled many countries’ ability to accurately track inventories through digital traceability and real-time inventory visibility, anticipate shortages, and pinpoint logistical bottlenecks. This lack of transparency and timely data severely undermined both national responses and global coordination efforts. To overcome these critical gaps, countries must prioritize investment in advanced digital supply chain infrastructures—platforms designed to monitor inventory levels, predict demand, ensure cold chain integrity, and synchronize deliveries across regions in real time (Ivanov, 2021). Digital visibility and transparency are essential for accurate forecasting of inventory needs within the global supply chain.

* 1. **enhance Global and Regional Coordination frameworks**

The COVID-19 pandemic revealed that fragmented national responses and uncoordinated procurement caused inefficiencies and inequities in the global medicine supply chain, with high-income countries securing supplies while many low- and middle-income countries faced delays and shortages. (Javed, 2020). Addressing these disparities requires robust global and regional coordination. By working together, stakeholders can ensure fair access, better distribute resources, eliminate redundancies, and enhance readiness through unified action and mutual accountability.

* 1. **STRENGTHEN REGULATORY Agility and Harmonization**

During the COVID-19 pandemic, many countries—particularly low-income and developing nations—were unable to rapidly produce vaccines, PPE kits, and antibiotics due to export bans, cross-border transit restrictions, and unclear regulations. Policy paralysis further hindered governments from accelerating reforms to expand manufacturing capacity and invest in healthcare infrastructure. In an increasingly interconnected global supply chain, delays in one regulatory system can cause cascading disruptions worldwide. To ensure timely, safe, and equitable access to health products in both routine and emergency contexts, countries must invest in streamlined, flexible, and harmonized regulatory frameworks that can respond quickly without compromising quality or safety (Bolislis, 2021).

* 1. **strengthen and Retain a Skilled Pharmaceutical Logistics Workforce**

To build a robust pharmaceutical supply chain, governments must invest in human capital. However, to date, few comprehensive strategies have been implemented to develop a highly skilled workforce through effective training programs (Ziemann, 2023). Pharmaceutical supply chains demand a highly specialized workforce equipped with expertise in procurement, inventory control, cold chain logistics, data analytics, regulatory compliance, transportation planning, and emergency response. Yet in many contexts, these critical functions remain undervalued and underfunded, and are frequently handled by untrained or overstretched personnel—undermining the efficiency and resilience of the entire system.

* 1. **Emerging digital technologies for enhancing supply chain continuity**

Several studies on the pharmaceutical supply chain have explored the use of groundbreaking technologies such as the Internet of Things (IoT) and blockchain. These technologies, when strategically implemented, have demonstrated significant potential in minimizing supply chain disruptions and enhancing overall system resilience. Industry 4.0 in the pharmaceutical sector is driven by advanced technologies such as artificial intelligence (AI), machine learning (ML), and the Internet of Things (IoT), positioning it as a key enabler of innovation and efficiency within the industry (Saha, 2022). Numerous studies on the application of IoT in the pharmaceutical supply chain have demonstrated that the use of IoT-enabled devices for monitoring temperature-sensitive medications during transportation can significantly reduce medicine wastage caused by temperature deviations (Sharma, 2020).

1. Conclusion

The COVID-19 pandemic served as a wake-up call, revealing deep vulnerabilities in global medicine supply chains. As health threats grow more complex, strengthening these systems is no longer optional—it is essential for protecting lives and maintaining public trust. Building resilient, equitable, and adaptive supply chains requires a shift from crisis response to proactive planning, supported by digital infrastructure, skilled personnel, regulatory agility, and coordinated global action. The future of global health depends on transforming fragile systems into robust networks that can deliver essential care in both emergencies and everyday settings.

**COMPETING INTERESTS DISCLAIMER:**

Authors have declared that they have no known competing financial interests OR non-financial interests OR personal relationships that could have appeared to influence the work reported in this paper.

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Option 1:

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

Option 2:

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