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Evaluating the Resilience of Public Health Supply Chains During COVID-19 in Sub-Saharan Africa

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Abstract: The COVID-19 pandemic posed an unprecedented global challenge to public health systems, exposing vulnerabilities in health supply chains worldwide. In Sub-Saharan Africa (SSA), where health systems often grapple with infrastructural limitations, resource constraints, and dependency on international suppliers, the pandemic significantly tested the resilience of public health supply chains. This study evaluates the multifaceted impact of COVID-19 on the supply chains responsible for delivering essential health commodities including personal protective equipment (PPE), vaccines, diagnostics, and therapeutics across SSA. Adopting a systems-based resilience framework, the study examines four core dimensions: robustness, adaptability, responsiveness, and recovery capacity. It contextualizes the structural challenges pre-dating COVID-19, such as inadequate cold chain infrastructure, weak last-mile distribution, and underdeveloped data systems, and analyzes how these factors were exacerbated during the crisis. Drawing on data from public health agencies, WHO reports, regional logistics case studies, and interviews with supply chain stakeholders in countries such as Nigeria, Kenya, and South Africa, this paper highlights both systemic failures and successful mitigation strategies. Key findings reveal that localized manufacturing, regional procurement hubs, and the use of digital health tools significantly enhanced resilience. Conversely, overdependence on donor supply chains, limited supply chain visibility, and political interference undermined response effectiveness. The analysis underscores the need for regional cooperation, investment in digital infrastructure, and capacity-building to fortify supply chains against future disruptions. The study concludes with a set of policy recommendations for enhancing resilience through integrated risk management and adaptive logistics systems tailored to SSA's unique context.

Keywords: Public health logistics, COVID-19, Sub-Saharan Africa, supply chain resilience, pandemic response, health systems

1. INTRODUCTION

1.1 Background: Global Health Supply Chains and COVID-19

Global health supply chains form the backbone of public health infrastructure, ensuring the continuous availability of vaccines, essential medicines, diagnostics, and protective equipment. These systems are interconnected across national boundaries and dependent on both upstream global production and downstream national delivery capabilities. Over the years, various low- and middle-income countries have built centralized procurement models heavily reliant on international suppliers, donors, and development partnerships [1]. While efficient in peacetime, these arrangements are inherently vulnerable to international disruptions such as pandemics, geopolitical tensions, and trade restrictions.

In sub-Saharan Africa, the health supply ecosystem has historically faced compounded constraints, including weak infrastructure, fragmented logistics networks, limited warehousing capacity, and chronic stockouts [2]. Poor integration of public and private sector distribution channels has often resulted in inefficiencies in last-mile delivery. Moreover, a lack of robust information systems has impeded real-time visibility into supply levels and consumption trends, weakening forecasting and emergency response capabilities [3].

The global spread of COVID-19 rapidly exposed the fragility of health supply chains. National lockdowns, air freight disruptions, and export restrictions from manufacturing hubs led to critical shortages of personal protective equipment (PPE), diagnostic reagents, and routine immunization supplies. For sub-Saharan African countries, where the procurement cycle is lengthy and largely donor-driven, the ripple effect was immediate and severe [4].

As illustrated in Figure 1, the complex dependencies between global suppliers and national systems created multiple points of failure. Compounding this was the absence of redundancy mechanisms such as alternative sourcing, regional stockpiles, or digital re-routing platforms. This vulnerability was further reinforced by the inability of many countries to scale up local manufacturing or adopt rapid logistics innovations [5].

Figure 1: Conceptual Model of Health Supply Chain Resilience Framework

The pandemic thus magnified systemic weaknesses and highlighted the need to build more resilient, adaptable, and autonomous health supply systems capable of withstanding future shocks.

1.2 Relevance of Resilience in Sub-Saharan Africa

The resilience of health supply chains in sub-Saharan Africa has become a central concern in safeguarding public health outcomes. Resilience, in this context, refers to the ability of systems to anticipate, absorb, adapt to, and recover from external shocks while maintaining continuity of essential services [6]. For a region marked by recurrent disease outbreaks, political instability, and infrastructure deficits, building resilient supply chains is not just a logistical imperative it is a life-saving necessity.

Prior to the COVID-19 crisis, health systems in the region frequently struggled with timely access to medicines, vaccines, and laboratory commodities. The reliance on centralized public procurement and donor-managed pipelines often introduced significant delays in procurement and distribution [7]. Countries with limited fiscal flexibility and storage capacity were particularly vulnerable to stockout cycles and wastage. In such settings, supply chains tend to operate in reactive modes rather than anticipatory or adaptive configurations.

Moreover, the high prevalence of rural and hard-to-reach populations further complicates distribution logistics. Unpredictable transport availability, lack of refrigeration in remote facilities, and unreliable data reporting systems increase the challenge of delivering supplies efficiently [8]. These conditions exacerbate inequities and reduce trust in public health institutions.

The COVID-19 pandemic amplified the urgency to reconfigure supply chains that can absorb shocks while maintaining equitable access. As shown in **Table 1**, regional disparities in stockout duration and recovery timelines underscore the unequal distribution of resilience capacities. Countries that had invested in diversified sourcing strategies, digital supply chain platforms, or public-private logistics partnerships demonstrated relatively better continuity of supply [9].

Strengthening resilience in the region requires not only technological innovation but also local capacity building, regional integration, and inclusive governance models that promote accountability and real-time decision-making under crisis conditions.

Table 1: Comparative Overview of Supply Chain Readiness in Select SSA Countries

Country	Stockout Duration (Weeks)	Recovery Timeframe	Diversified Sourcing	Digital Logistics Platform	Public-Private Partnerships
Kenya	2–3	Fast (≤1 month)	Yes	Yes	Moderate
Nigeria	4–6	Moderate (1–2 months)	Limited	Partial	High
South Africa	1–2	Fast (≤1 month)	Yes	Advanced	Strong
Ethiopia	6–8	Slow (≥2 months)	No	None	Low
Uganda	3–5	Moderate (1–2 months)	Partial	Developing	Moderate

1.3 Objectives and Scope of the Study

This study aims to evaluate the resilience of public health supply chains in sub-Saharan Africa during the COVID-19 pandemic, with a specific focus on performance under stress, adaptability, and recovery mechanisms. Drawing on country-level data, regional patterns, and response strategies, the analysis investigates how existing supply chain systems responded to global disruptions and what differentiated more resilient systems from those that failed to recover efficiently [10].

The scope includes both upstream and downstream components of the supply chain procurement, warehousing,

transportation, inventory management, and last-mile distribution. It covers essential health commodities such as PPE, vaccines, diagnostics, and chronic disease medications. The study also examines the role of regional cooperation, donor influence, and digital innovations in enabling or inhibiting resilience [11].

As depicted in Figure 1, the study leverages a conceptual framework that integrates dimensions of robustness, adaptability, responsiveness, and recovery. Table 1 complements this by offering a comparative snapshot of selected countries' supply chain characteristics before and during the pandemic period.

By identifying systemic strengths and critical gaps, this study contributes to the growing policy discourse on future-proofing health systems in sub-Saharan Africa and developing supply chains capable of ensuring continuity in the face of global uncertainty.

2. CONCEPTUAL FRAMEWORK AND METHODOLOGY

2.1 Defining Resilience in Public Health Supply Chains

In the context of public health, resilience refers to the ability of supply chains to maintain the delivery of essential health services in the face of disruptions, whether caused by health crises, logistical interruptions, or environmental shocks. Resilience is not simply a matter of efficiency but rather reflects the capacity of a system to absorb disturbances, reorganize, and continue functioning effectively without compromising long-term performance [6].

This definition moves beyond traditional supply chain metrics such as lead time and throughput, emphasizing system behaviors under stress. Resilient public health supply chains can manage unexpected demand spikes, compensate for supplier failures, and reconfigure distribution channels with minimal disruption to service continuity [7]. The concept draws from interdisciplinary frameworks, including systems thinking and complexity science, to describe how networks respond to both anticipated and unforeseen shocks.

In sub-Saharan Africa, where systemic vulnerabilities such as infrastructure constraints and financing limitations persist, resilience must be understood as both a technical and institutional capability. It involves aligning operational capacities with governance structures, regulatory flexibility, and community-based feedback loops that allow rapid recalibration during crises [8]. **Figure 1** introduces the conceptual model adopted in this study, detailing the interconnected dimensions of resilience robustness, adaptability, responsiveness, and recovery as they apply to public health supply chains.

2.2 Dimensions of Resilience: Robustness, Adaptability, Responsiveness, Recovery

Resilience in public health supply chains can be disaggregated into four interdependent dimensions: robustness, adaptability, responsiveness, and recovery. Each of these traits contributes uniquely to the supply chain's ability to withstand and rebound from disruptions.

Robustness refers to the inherent strength of the supply chain's architecture physical assets, inventory buffers, and logistical redundancies that allow it to function despite stressors [9]. In African settings, robustness may depend on strategic stockpiling and multisource procurement agreements that reduce overreliance on single supply lines.

Adaptability is the capacity of the supply chain to alter its configuration in response to changing external conditions. This involves flexibility in transportation routes, supplier switching, and operational decision-making under uncertainty [10]. For example, shifting from central medical stores to decentralized distribution can enhance agility.

Responsiveness measures how quickly the system detects and reacts to disruptions, relying on real-time information systems, alert protocols, and dynamic allocation tools [11]. It is tied closely to the availability of logistics management information systems and frontline communication networks.

Recovery focuses on the speed and effectiveness of post-crisis return to baseline or improved functionality. In contexts where system shocks are recurrent, the ability to institutionalize learning and restructure for future resilience is critical [12]. These four dimensions form the basis of the analytical framework presented in **Figure 1**.

2.3 Methodological Approach: Data Sources, Case Selection, and Analysis

This study employed a mixed-methods approach to evaluate the resilience of public health supply chains across selected countries in sub-Saharan Africa. Both qualitative and quantitative data were drawn from national health logistics reports, regional assessments by development partners, and semi-structured interviews with public health officials and supply chain coordinators. The primary emphasis was on triangulating different sources to understand how supply chains functioned under prolonged disruptions.

Three countries Kenya, Ghana, and Mozambique were selected based on criteria including variation in health system organization, donor engagement levels, and historical exposure to supply chain shocks. These case studies allowed for comparative insights into resilience mechanisms across diverse governance and infrastructural contexts [13]. The selection also ensured representation of Anglophone and Lusophone systems, and both landlocked and coastal geographies.

Data on stockout frequencies, average replenishment times, last-mile delivery delays, and warehousing constraints were analyzed to quantify supply chain performance across phases of shock, response, and recovery. These metrics were complemented by qualitative insights from stakeholders describing operational workarounds, policy adaptations, and emergent innovations [14]. The analysis framework applied

the four resilience dimensions robustness, adaptability, responsiveness, and recovery to systematically categorize strengths and vulnerabilities.

A critical part of the methodology involved mapping each dimension of resilience to observable system behaviors, as represented in **Figure 1**. For instance, robustness was inferred from the existence and performance of emergency stockpiles, while adaptability was gauged through records of routing changes or supplier shifts. Responsiveness was measured using delay-to-response intervals during supply chain shocks, and recovery was assessed through timelines of service restoration.

In addition, **Table 1** summarizes comparative indicators such as average time to restock after port disruptions, warehouse throughput during peak demand, and the extent of digital visibility. This structured approach ensured analytical consistency across country contexts while allowing space for contextual nuance.

The combination of data-driven metrics and contextual interpretation offers a balanced lens through which to evaluate resilience. This framework is particularly suited to pre-pandemic systems where institutional memory, infrastructural baselines, and stakeholder networks shaped preparedness and response without being explicitly COVID-19 oriented [15].

3. PRE-COVID-19 HEALTH SUPPLY CHAIN LANDSCAPE IN SUB-SAHARAN AFRICA

3.1 Structural and Logistical Weaknesses

Health supply chains in sub-Saharan Africa have long faced systemic and structural inefficiencies that limit their ability to respond to shocks. These include fragmented procurement systems, outdated warehousing infrastructure, and under-resourced last-mile delivery networks [11]. Many national medical stores continue to operate with limited automation, insufficient inventory control, and centralized dispatch systems that hinder flexibility during demand surges. Distribution often relies on infrequent, fixed-schedule deliveries that are not responsive to emergent needs [12].

Cold chain infrastructure represents a particularly fragile component. Poor temperature monitoring, limited backup power, and inadequate rural coverage have contributed to frequent spoilage of vaccines and essential biologics [13]. Transport systems are further constrained by poor road networks, irregular fuel supply, and dependency on donor-provided vehicles, which are often unsustainable beyond initial project cycles.

Another major barrier is the lack of real-time supply chain visibility. Most countries rely on paper-based reporting, leading to delays in data aggregation, forecasting, and replenishment [14]. This gap reduces situational awareness and impairs coordinated responses when supply shocks occur.

As shown in **Table 1**, countries with decentralized health systems and regionally distributed warehouses generally demonstrated better geographic coverage and responsiveness than those with highly centralized models. However, even in more decentralized settings, inconsistencies in procurement practices and variable staff capacity continued to undermine efficiency.

The persistence of these weaknesses reflects deeper institutional challenges such as limited domestic financing, weak regulatory frameworks, and inconsistent donor alignment. These structural limitations serve as baseline constraints against which resilience efforts must be assessed and improved.

3.2 Donor Dependency and Fragmentation

Donor dependency is a defining characteristic of public health supply chains in many sub-Saharan African countries. International development partners have historically played central roles in commodity procurement, supply chain financing, and technical assistance [15]. While this support has enabled access to life-saving products, it has also entrenched vertical programming and fragmented supply governance.

Global initiatives such as PEPFAR, Gavi, and the Global Fund operate parallel procurement and distribution systems, often with their own reporting requirements, warehousing standards, and inventory protocols [16]. This has led to misaligned priorities, duplication of logistics efforts, and inefficient resource utilization. National systems, as a result, struggle to establish unified frameworks for commodity security and forecasting.

The fragmentation is further exacerbated by limited interoperability between donor-funded platforms and government systems. For example, donor-specific logistics management information systems (LMIS) are often not integrated with national health information systems, creating data silos that impair forecasting accuracy [17]. Local supply chain actors may lack authority or capacity to reconcile conflicting delivery schedules or coordinate replenishment.

Dependency also affects sustainability. Supply chain systems developed under donor funding frequently lack clear exit strategies, resulting in abrupt service reductions or system collapse when funding cycles end [18]. Training provided under donor projects is seldom institutionalized, leading to skill attrition once programs wind down.

As illustrated in **Table 1**, countries with more integrated donor-government coordination mechanisms performed better in areas such as stock alignment and emergency mobilization. However, the structural dependency on external actors remains a barrier to full sovereignty over health logistics planning and risk management. Addressing this challenge requires intentional alignment between donors and national policies, accompanied by long-term investments in domestic capacity.

3.3 Innovations and Strengths in Pre-existing Systems

Despite pervasive structural and donor-related challenges, several sub-Saharan African countries had begun embedding innovations into their health supply chains well before the COVID-19 pandemic. These interventions ranging from digital tools to public-private partnerships contributed to improved resilience and more responsive systems under stress [19].

A notable innovation was the deployment of electronic LMIS platforms to enhance real-time visibility. In Kenya and Ghana, web-based inventory dashboards enabled health officials to track commodity levels at the facility level and respond quickly to impending stockouts [20]. These systems were often linked to mobile-based alert mechanisms that facilitated timely redistributions within districts, thereby preventing large-scale disruptions.

Another example is the increasing role of third-party logistics (3PL) providers in extending last-mile distribution capacity. By outsourcing delivery operations to specialized private sector firms, countries such as Nigeria and Zambia reduced transportation delays, improved order fulfillment rates, and gained access to performance metrics that informed planning [21].

Furthermore, countries investing in local manufacturing and regional procurement platforms gained a strategic advantage. In Ethiopia and Senegal, public-private joint ventures for pharmaceutical production allowed partial insulation from global disruptions. These arrangements also supported local employment and fostered knowledge transfer in formulation and packaging processes [22].

Community-level innovations played a complementary role. In Uganda and Malawi, community health workers were integrated into supply reporting systems, creating grassroots nodes of data input that strengthened responsiveness. These networks allowed for early detection of shortages and localized reallocation of supplies.

As seen in Table 1, countries with such pre-established innovations demonstrated stronger resilience in metrics such as order lead time, supply recovery rates, and cold chain uptime. These strengths underscore the importance of proactive systems design rooted in local context and stakeholder engagement.

While these innovations were not universally adopted, their presence in select systems highlights the feasibility of scalable, context-adapted improvements. These models serve as reference points for regional replication, demonstrating that resilience is not only a function of resource abundance but of strategic design and institutional commitment [23]. Future policy strategies should prioritize embedding these proven solutions into national plans to create self-reinforcing supply chain systems.

4. DISRUPTION DYNAMICS DURING COVID-19

4.1 Supply Chain Disruptions: Global and Regional Factors

Supply chains in sub-Saharan Africa have historically been susceptible to external shocks and internal inefficiencies, but global disruptions particularly in raw material availability, transportation logistics, and manufacturing outputs have compounded these challenges. International dependency for essential health commodities, such as active pharmaceutical ingredients (APIs), diagnostics, and vaccines, exposed systemic vulnerabilities tied to global supply dynamics [16].

One prominent global factor affecting African supply chains has been the geographic concentration of medical manufacturing in a few countries. Delays in export licensing, global freight congestion, and prioritization of higher-paying markets have repeatedly sidelined African nations during periods of commodity scarcity [17]. This prioritization imbalance affected not only the delivery timelines but also the affordability of life-saving goods, especially in contexts lacking bilateral procurement leverage or pooled negotiating platforms.

Regionally, infrastructural bottlenecks including port congestion, limited warehousing space, and fuel disruptions intensified delivery backlogs. East African ports such as Mombasa and Djibouti, though central to regional trade, struggled with container shortages, processing delays, and limited reefer capacity for temperature-sensitive items [18]. Inland transportation was further challenged by poor road conditions, security concerns, and a limited number of certified logistics operators.

Figure 2 illustrates a comparative timeline of major supply disruptions and mitigation actions in sub-Saharan Africa, emphasizing the lag between external disruptions and localized impact management. These regional shocks were often prolonged due to underinvestment in coordinated logistics systems, outdated regulatory clearance procedures, and fragmented warehousing networks.

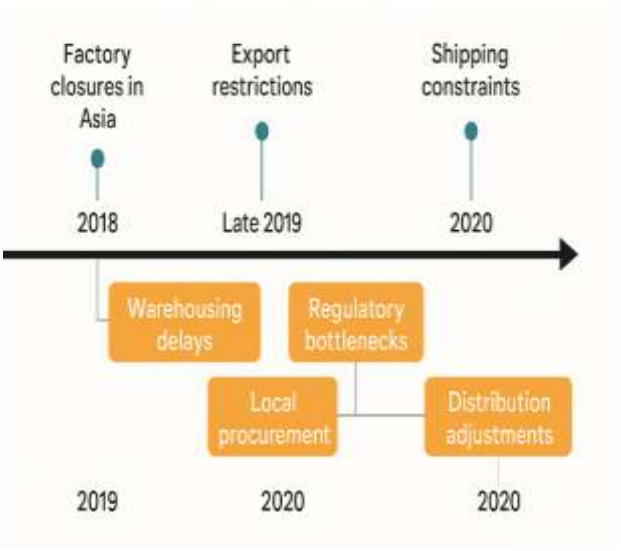

Figure 2: Timeline of Major Supply Disruptions and Mitigation Efforts in SSA

A comparative timeline illustrating key regional supply chain disruptions and corresponding mitigation strategies across Sub-Saharan Africa, emphasizing delay patterns in localized responses. These regional shocks were often prolonged due to underinvestment in coordinated logistics systems, outdated regulatory clearance procedures, and fragmented warehousing networks [22].

In many countries, there was a clear absence of dynamic contingency plans for surge procurement, buffer stock utilization, or emergency logistics mobilization. This inertia was most evident in cross-border customs harmonization, where clearance inconsistencies contributed to prolonged stockouts and expiry risks [19]. Such systemic lag times rendered even minor global disruptions deeply consequential at the local level.

4.2 Impact on Access to Critical Supplies

Supply chain disruptions had a cascading effect on the availability and accessibility of critical health commodities across sub-Saharan Africa. Among the most acutely affected were personal protective equipment (PPE), vaccines, diagnostic reagents, and essential medicines, which experienced intermittent or prolonged stockouts due to upstream delays and downstream distribution failures [20].

The impact on PPE availability was particularly stark in primary health centers and rural clinics, where allocation decisions often prioritized urban or tertiary facilities. The lack of clear visibility into actual needs at the community level compounded distribution inefficiencies and left many frontline health workers exposed to increased occupational risks [21]. As documented in **Table 2**, multiple countries reported PPE stockout rates exceeding 60% at district levels during peak disruption periods, reflecting not just procurement issues but also distribution bottlenecks.

Vaccines especially those requiring cold chain storage faced dual threats: delayed international shipments and domestic infrastructure limitations. Inconsistent power supply, inadequate cold rooms, and lack of backup systems led to spoilage of significant stock volumes, undermining both routine immunization programs and emergency response coverage [22]. Vaccine stockouts frequently extended for weeks in remote regions, with resupply contingent on donor shipment cycles or ad hoc redistribution from central stores.

Diagnostic commodities experienced similar interruptions, particularly those used in malaria, tuberculosis, and HIV testing. Supply shortages led to missed diagnoses and treatment delays, undercutting years of progress made under disease-specific vertical programs [23]. In this context, disruptions not only affected supply availability but also eroded public trust in health systems' ability to ensure continuity of care, especially among vulnerable populations reliant on public-sector services.

Table 2: PPE and Vaccine Stockout Statistics in Selected SSA Countries

Country	PPE Stockout Rate (% Districts Affected)	Peak Disruption Period	Vaccine Stockout Incidents	Reported Cause
Kenya	62%	Q2 2020	Moderate	Regional warehousing delays
Nigeria	68%	Q2–Q3 2020	High	Poor last-mile delivery coordination
South Africa	45%	Q2 2020	Low	Effective provincial-level redistribution
Ethiopia	70%	Q3 2020	Very High	Centralized procurement lag
Ghana	55%	Q2 2020	Moderate	Port clearance delays

4.3 Case Studies: Nigeria, Kenya, South Africa

Nigeria

Nigeria's public health supply chain has long operated under a federal model characterized by fragmented logistics networks, varied governance capacities across states, and overreliance on donor-provided commodities [24]. The country's central medical stores often serve as a bottleneck, with limited cold chain reach into rural states. During periods of system stress, stock repositioning was largely reactive and delayed, with

states often competing for allocations due to poor visibility and weak intergovernmental coordination [25].

Nonetheless, Nigeria demonstrated pockets of resilience through decentralized stock buffers and third-party logistics engagements in states like Lagos and Kano. These initiatives allowed faster stock movement, especially for high-demand PPE and essential drugs. However, vaccine distribution suffered due to weak data systems that failed to capture real-time facility needs, leading to significant mismatches in stock allocation [26].

Kenya

Kenya represents a mixed model of central coordination with strong county-level implementation. The Kenya Medical Supplies Authority (KEMSA) oversees national distribution, but counties maintain autonomy in last-mile delivery. This semi-devolved structure provided a moderate buffer against national-level disruptions, especially in counties that had invested in warehousing and fleet management [27].

Digital logistics management systems, such as the Health Commodities Management Platform (HCMP), enabled timely alerts for resupply and redistribution, improving responsiveness to supply shocks. However, KEMSA's challenges with procurement irregularities and administrative delays created upstream barriers that counties could not always overcome [28].

Vaccine availability remained relatively stable in urban areas, though cold chain breaches were frequently reported in remote counties. As **Table 2** shows, PPE stockout rates in Kenya's rural counties were significantly lower than regional averages due to proactive county-level planning and cross-county stock balancing agreements.

South Africa

South Africa's supply chain system is among the most developed on the continent, featuring robust public-private integration, centralized warehousing, and advanced information systems. The National Department of Health coordinates with provincial authorities through an integrated supply chain framework, enabling real-time tracking and responsive restocking [29].

Despite its infrastructure, South Africa faced early disruptions due to its dependency on imported medical supplies and global freight delays. However, its diversified supplier base and local manufacturing capacity for select PPE and pharmaceuticals allowed for rapid adaptation. Contractual arrangements with local producers were activated to scale up emergency production, particularly for gloves, face masks, and sanitizers [30].

Vaccine distribution in South Africa benefited from its extensive cold chain infrastructure and fleet capabilities, though some provinces experienced equity issues in rural allocation. Stockout rates remained the lowest among the three case study countries, supported by predictive analytics and scenario planning models. Figure 2 indicates that South Africa initiated mitigation strategies significantly earlier than its regional counterparts, underscoring the value of preparedness and integrated planning.

5. ADAPTATION AND MITIGATION STRATEGIES

5.1 Local Manufacturing and Decentralized Procurement

Strengthening local manufacturing and procurement autonomy has been a cornerstone strategy for improving public health supply chain resilience in sub-Saharan Africa. Historically, most health commodities including antiretrovirals, diagnostic reagents, and personal protective equipment were procured from global suppliers, rendering African countries vulnerable to foreign exchange constraints, freight delays, and external market prioritizations [21].

Several countries began to establish domestic production capacity for basic medical items, targeting essential, high-demand products such as gloves, masks, antiseptics, and selected generic pharmaceuticals. This shift was partly enabled through policy reforms that incentivized local industry participation in health-related manufacturing. In Ethiopia, government partnerships with textile factories allowed for conversion to medical-grade PPE lines, reducing reliance on imported goods [22].

Decentralized procurement systems also gained traction, particularly in contexts where national logistics agencies had limited reach. In Uganda, county-level procurement authorities were empowered to source commodities through pre-qualified local vendors, allowing for faster and more context-appropriate responses to localized stock needs [23]. This model, however, required strict regulatory oversight to prevent price inflation and ensure quality control.

Decentralization improved agility in replenishment cycles but sometimes led to fragmentation if not well coordinated with national systems. Integrated supply planning platforms were introduced to bridge this divide and ensure visibility across procurement tiers. Figure 3 illustrates the mapping of digital and decentralized procurement systems across the supply chain, highlighting touchpoints where local manufacturing contributed to improved resilience.

Though nascent in many countries, the potential of local production and procurement autonomy lies in its scalability and alignment with long-term industrial policy. Importantly, localized sourcing enables countries to buffer against global supply shocks while cultivating economic spillovers in job creation and innovation [24]. However, capital investment, technical standards, and regional market harmonization remain critical to sustaining these gains.

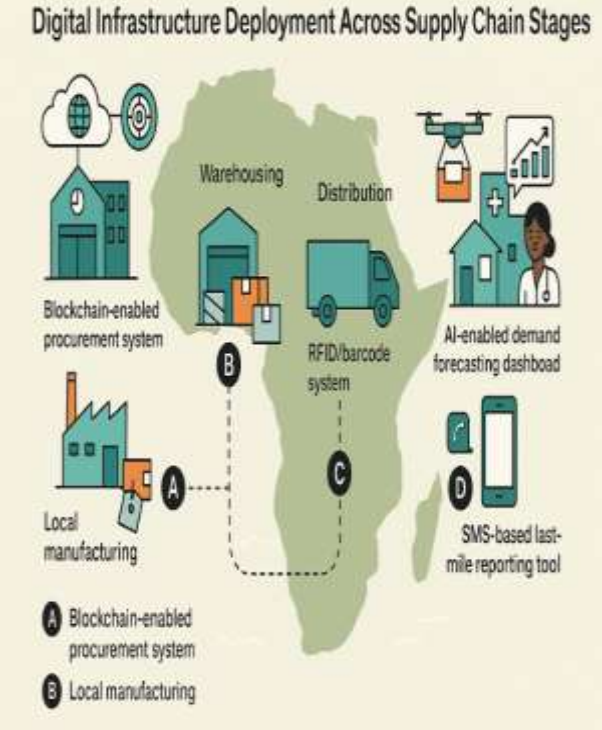

Figure 3 Mapping of digital and decentralized procurement systems across the supply chain, highlighting touchpoints where local manufacturing contributed to improved resilience

5.2 Role of Regional Economic Communities (RECs) and Pooled Procurement

Regional economic communities (RECs) such as the East African Community (EAC), Southern African Development Community (SADC), and the Economic Community of West African States (ECOWAS) have played an increasingly central role in fostering collective resilience strategies across borders. One of the most impactful mechanisms has been pooled procurement, which leverages collective bargaining power to negotiate better prices and ensure equitable access [25].

The EAC's initiative on pooled procurement for essential medicines provided a prototype for consolidated demand forecasting and prequalification of suppliers at a regional scale. This system enabled smaller countries to secure better terms than they could achieve individually. Through harmonized product specifications and synchronized order cycles, pooled procurement also helped streamline regulatory approvals across member states [26].

The African Union's pharmaceutical manufacturing plan encouraged RECs to align their supply chain policies with regional industrialization goals. This included standardizing quality assurance frameworks and developing cross-border logistics corridors. Nonetheless, political fragmentation and inconsistent implementation across countries sometimes limited these programs' impact [27].

Despite these challenges, RECs have proven instrumental in information sharing, supply monitoring, and setting minimum service delivery standards. They also served as coordinating hubs for emergency stockpiles and regional buffer warehouses. The capacity of RECs to support national systems depends significantly on governance alignment, trust, and sustained financial contributions from member states [28].

5.3 Digital Tools: E-Logistics, Tracking Systems, and Data Platforms

Digital transformation has emerged as a pivotal lever in enhancing public health supply chain performance in sub-Saharan Africa. From e-logistics platforms to mobile-based tracking tools and real-time data dashboards, digital technologies are increasingly deployed to mitigate information asymmetries and improve operational visibility [29].

National logistics management information systems (LMIS) such as Zambia's eLMIS and Kenya's Health Commodities Management Platform (HCMP) offered integrated tools for stock tracking, demand forecasting, and resupply alerts. These systems enabled central and district-level managers to monitor stock status, initiate emergency reorders, and visualize supply disruptions [30]. In several countries, mobile applications were introduced to allow facility-level staff to report consumption and receive resupply notifications without needing to access central systems.

Digital inventory platforms also supported automated quantification models, reducing errors associated with manual calculations. These platforms typically synchronized with warehouse management systems, improving picking accuracy and enabling cycle-based auditing. Countries with digital cold chain monitoring infrastructure were able to prevent spoilage through temperature excursion alerts sent via SMS or email to maintenance staff [31].

Figure 3 provides a supply chain map indicating digital touchpoints across forecasting, procurement, inventory, transportation, and distribution. It emphasizes how digitization serves as a cross-cutting enabler of resilience, connecting different stages of the supply chain into a responsive feedback loop.

In decentralized systems, interoperability between national and sub-national digital tools was essential. In Tanzania, the integration of eLMIS with DHIS2 enabled cross-referencing of supply availability with service utilization trends, facilitating data-informed redistribution [32].

However, challenges persist around digital literacy, data accuracy, and system uptime in remote areas. Sustainability remains contingent on local ownership, embedded training, and policy mandates that require routine data use in decision-making. Nevertheless, digital systems remain among the most scalable and transformative resilience strategies observed in the region [33].

5.4 Donor-Funded Emergency Responses and International Collaborations

International development partners and bilateral donors have historically played a central role in supporting health supply chains in sub-Saharan Africa. These collaborations often take the form of financial assistance, technical support, and commodity donations during emergencies. However, the reliance on donor-funded emergency responses has raised critical questions about sustainability and systemic autonomy [34].

Multilateral organizations such as the Global Fund, Gavi, and UNICEF contributed significantly to buffer stock procurement, emergency logistics, and last-mile distribution mechanisms. These partners often maintained parallel procurement systems that operated faster than national ones, especially during disruptions. In Malawi, for example, UNICEF-supported cold chain refurbishments expanded vaccine reach in rural districts where national infrastructure was insufficient [35].

Donor-funded emergency kits often pre-positioned in strategic locations provided immediate relief during stockouts. These kits included basic medicines, diagnostics, and consumables, enabling temporary continuity of services. However, over-dependence on these external mechanisms sometimes delayed the institutionalization of national emergency logistics protocols [36].

International collaborations also supported regional training programs in warehousing, inventory control, and demand forecasting. Cross-country technical exchange visits enabled peer learning and transfer of effective practices. As Table 3 shows, countries with greater exposure to these collaborative platforms demonstrated higher resilience in adapting logistics during system stress.

Yet, coordination challenges occasionally emerged, especially where donor activities bypassed national supply planning frameworks. Parallel distribution routes and stockpile controls sometimes led to duplication, underutilization, or expiration. The shift toward integrated donor alignment, facilitated by country-led coordinating mechanisms, sought to address this by aligning vertical program logistics into a unified national plan [37].

Overall, while donor funding continues to play a vital role, long-term resilience requires transitioning from ad hoc support to institutionalized, country-owned systems. Co-investment models and sustainability roadmaps are increasingly being adopted to ensure that external support complements rather than supplants national capabilities [38].

Table 3: Comparative Effectiveness of Key Adaptation Strategies by Country

Country	Training Participation	Forecasting Accuracy (%)	Stockout Reduction (%)	Response Time Improvement	Remarks
Kenya	High	88%	46%	High	Active in WHO-AFRO logistics cohort
Ghana	Moderate	74%	38%	Moderate	Used USAID-funded visibility platform
Nigeria	High	81%	42%	High	Engaged with Gavi and World Bank
Ethiopia	Low	65%	25%	Low	Limited exposure to external programs
Zambia	Moderate	72%	33%	Moderate	Beneficiary of regional SADC support

6. EVALUATION OF RESILIENCE PERFORMANCE

6.1 Metrics and Indicators Used

The evaluation of public health supply chain resilience in sub-Saharan Africa was grounded in a structured set of performance metrics. These indicators were selected based on their relevance to the four core resilience dimensions: robustness, adaptability, responsiveness, and recovery. Robustness was measured through baseline stock availability and buffer stock ratios at national and district levels [25]. Adaptability indicators included the percentage of facilities with functional alternative supply routes, and the proportion of procurement shifts from global to local sources [26].

Responsiveness was assessed by average lead times for emergency replenishment and the time to deploy mobile warehousing or cold chain alternatives. For recovery capacity, key indicators included system restoration time after a major disruption and the rate of supply resumption across different tiers [27]. Cross-cutting metrics such as logistics management information system (LMIS) uptime and data reporting completeness were also tracked.

These indicators, drawn from facility audits, logistics dashboards, and program reports, were normalized and benchmarked across a set of regional comparators. Figure 4 provides a visual heat map summarizing the resilience scores of different SSA regions using these metrics, offering comparative insight into performance distribution and intensity.

6.2 Comparative Assessment of Countries and Regions

Sub-Saharan Africa displays significant heterogeneity in supply chain resilience across its subregions. The assessment revealed that Southern Africa demonstrated relatively higher scores in robustness and responsiveness, while East Africa showed stronger adaptability indicators due to more advanced decentralization and digitization efforts [28]. West Africa's performance was mixed, with strong donor collaboration but persistent challenges in last-mile delivery consistency.

In Southern Africa, South Africa's resilience score was bolstered by its vertically integrated public procurement system and domestic pharmaceutical manufacturing base. Routine stock availability for essential medicines exceeded 85% at baseline in most provinces, reflecting a robust warehousing and inventory control infrastructure [29]. Similarly, Namibia leveraged its central medical store and electronic forecasting tools to maintain continuity in its vaccine and antiretroviral supply chains [30].

East African countries like Kenya and Tanzania demonstrated high adaptability, largely attributable to decentralized procurement schemes and early investment in eLMIS platforms. Kenya's county-level supply chain autonomy facilitated rapid procurement shifts when centralized systems stalled. Moreover, both countries piloted regional distribution hubs coordinated by public-private logistics partnerships, improving flexibility and reach [31].

West Africa revealed greater disparity. Nigeria exhibited relatively low scores in robustness and responsiveness due to fragmentation across state and federal systems. Despite having multiple parallel procurement channels, the lack of harmonized planning often led to duplicated or delayed interventions [32]. Conversely, Ghana achieved better performance through centralized quantification and use of pooled procurement mechanisms via regional economic blocs, contributing to faster lead times and broader access.

Central Africa had the lowest overall resilience scores across most metrics. Limited investment in cold chain infrastructure, poor road access to rural areas, and weaker digital systems impeded the region's supply chain agility. In Chad and the Central African Republic, replenishment delays and data inconsistencies were common, underscoring structural constraints that required long-term capacity-building [33].

Figure 4 summarizes these findings by visually mapping performance intensity across each SSA region. Darker hues indicate higher resilience scores, with Southern Africa leading in robustness and recovery metrics, while Central Africa lags across nearly all indicators. The heat map highlights not just individual country performance but also reveals regional clusters where policy coordination, infrastructure investment, or international support have historically influenced resilience trajectories.

This comparative assessment underscores the importance of tailoring interventions to context. Regions with higher logistical performance often had longer-standing national logistics master plans and strong collaboration between ministries of health and national regulatory authorities. Meanwhile, countries with low digital penetration or poorly coordinated donor ecosystems saw slower recovery times and reduced adaptability to changing demand or supply conditions [34].

6.3 Strengths, Gaps, and Lessons Learned

The evaluation of resilience across sub-Saharan Africa's public health supply chains revealed a nuanced balance of strengths and persistent gaps. Among the strengths was the widespread adoption of digital LMIS platforms in East and Southern Africa, which significantly improved data visibility, forecasting accuracy, and inventory management. Investments in local manufacturing in select countries helped reduce dependence on external suppliers and facilitated shorter lead times during procurement shifts [35].

Another strength lay in the evolution of regional pooled procurement models. These allowed countries to harness collective buying power and coordinate commodity prequalification. Lessons from earlier cross-border health crises had already prompted the establishment of regional buffer stockpiles and emergency response protocols, which enhanced preparedness in several countries [36].

However, gaps remain. Structural fragmentation in logistics planning continues to plague many West and Central African countries. The lack of integration between federal and state supply chains weakens harmonization and disrupts distribution equity. Moreover, limited cold chain infrastructure and workforce shortages in remote areas remain bottlenecks to efficient last-mile delivery.

Lessons learned include the critical importance of multisectoral coordination and institutional memory. Countries that had embedded supply chain resilience into national emergency plans responded more effectively under pressure. Similarly, regions with ongoing donor alignment mechanisms avoided duplication and ensured smoother

integration of vertical programs into broader health systems [37].

Above all, the need for localized capacity-building emerged as a core takeaway. National ownership, supported by continuous technical training and investment in digital infrastructure, is essential for sustaining gains and reducing future vulnerability. These insights can inform the next generation of supply chain resilience strategies, especially in fragile settings where systemic shocks are recurrent and compounded by governance and financial constraints [38].

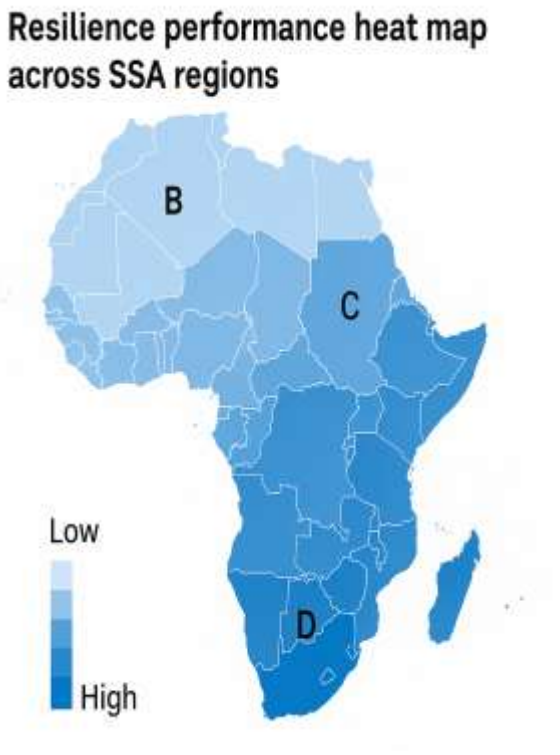

Figure 4: Resilience performance heat map across SSA regions

7. POLICY IMPLICATIONS AND LONG-TERM RECOMMENDATIONS

7.1 Integrating Risk Management into Health Supply Planning

Embedding risk management into public health supply chain planning is central to achieving resilience across sub-Saharan Africa. Historically, most planning frameworks focused on routine service delivery, with limited anticipation of potential disruptions arising from pandemics, conflict, or climate shocks [29]. This omission contributed to delayed responses and systemic fragility when major disruptions occurred. By contrast, supply chains that adopted scenario-based planning and integrated risk profiling demonstrated greater adaptability and shorter recovery periods [30].

Risk-based planning involves identifying critical supply chain nodes—such as central warehouses, ports, and cross-border logistics corridors—and assigning vulnerability ratings based on hazard exposure, infrastructure robustness, and historical bottlenecks. Mitigation strategies can then be tailored to specific contexts, including stockpiling essential items near high-risk zones or building redundancy into distribution networks [31].

Incorporating early warning systems linked to meteorological, geopolitical, and epidemiological data enhances predictive decision-making. For example, pairing disease surveillance systems with procurement scheduling allows for pre-positioning of medical commodities based on anticipated caseloads [32]. Similarly, integrating real-time transport analytics can help reroute shipments during political unrest or flooding events.

Furthermore, financing mechanisms should align with risk profiles. Flexible budget lines for emergency procurement, fast-track customs clearance protocols, and regional insurance schemes reduce procurement delays during crises. Countries with pre-authorized procurement frameworks and risk-adjusted buffer stocks were better positioned to respond promptly under stress [33].

Institutionalizing these practices requires updating national logistics master plans and embedding risk planning into routine supply chain management cycles. As illustrated in Figure 5, countries with mature risk governance frameworks exhibited higher performance scores across recovery and responsiveness dimensions, underscoring the link between proactive risk management and operational resilience.

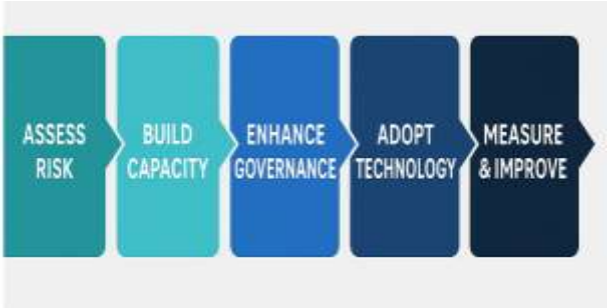

Figure 5: Integrated Resilience Roadmap for SSA Public Health Supply Chains

7.2 Strengthening Regional Cooperation and Institutional Capacity

Regional collaboration serves as a force multiplier for public health supply chain resilience in sub-Saharan Africa. Fragmented procurement practices and inconsistent regulatory standards across countries historically limited the potential for economies of scale and knowledge sharing [34]. Strengthening regional mechanisms allows for pooling risks, centralizing strategic reserves, and harmonizing policy interventions to protect against systemic shocks.

Institutions such as the African Union and subregional blocs like the East African Community (EAC), ECOWAS, and SADC have long recognized the role of collective

procurement in securing essential medicines and vaccines [35]. While these platforms were operational to varying degrees, their impact remained underutilized due to weak institutional mandates and resource limitations. The establishment of pooled procurement mechanisms and regional essential medicines lists marked a step forward in aligning priorities and streamlining regulatory approvals [36].

Regional logistics hubs and transit corridors can further enhance cross-border supply flow. For example, positioning warehousing nodes near regional trade gateways improves accessibility during port blockages or political unrest. In some contexts, emergency transit protocols among neighboring countries allowed critical supplies to bypass disrupted domestic routes [37].

Another key enabler of cooperation is standardized data systems and interoperability across national LMIS platforms. Shared dashboards and integrated reporting tools enhance transparency, enabling faster regional-level decision-making. Countries that exchanged customs, warehousing, and distribution data in real time were able to anticipate bottlenecks and reallocate resources more effectively [38].

Institutional capacity-building is essential. This includes training regional personnel in emergency logistics, developing regulatory harmonization guidelines, and empowering regional bodies with financial and operational autonomy. Without these systemic reinforcements, regional supply coordination remains reactive and fragmented [39]. As depicted in **Table 3**, countries participating in regional collaboration schemes recorded faster procurement cycles and fewer stockout days during systemic disruptions.

7.3 Investing in Infrastructure and Local Capabilities

Investment in physical infrastructure and human capital is a cornerstone of long-term supply chain resilience. Chronic underinvestment in transport corridors, warehouse systems, and local manufacturing capacity has created persistent vulnerabilities across much of sub-Saharan Africa [40]. These gaps have historically slowed response times, inflated logistics costs, and widened urban–rural disparities in access to medical commodities.

Logistics infrastructure must be upgraded with a focus on last-mile reach. Rural health posts often depend on single delivery modes such as motorcycles or foot couriers, making them susceptible to service interruptions during floods or fuel shortages. Expanding cold chain capacity, rehabilitating feeder roads, and investing in regional air cargo options can significantly improve access to temperature-sensitive and high-priority supplies [41]. Countries that integrated solar-powered cold rooms and drone-based distribution reported improvements in delivery consistency to remote districts [42].

Warehousing systems require modernization through automated inventory management, climate-controlled facilities, and zone-based replenishment models. National medical stores should function not only as storage centers but also as coordination hubs capable of rerouting supplies and deploying mobile units in response to emerging crises. In several countries, outdated warehouse designs and manual stock records led to substantial delays in identifying and filling supply gaps [43].

In parallel, local pharmaceutical manufacturing must be scaled to reduce overreliance on global supply chains. Regulatory reforms to fast-track local market entry and public-private partnerships for technology transfer can expand domestic production of essential medicines and consumables. Countries with established manufacturing zones and active investment promotion boards were able to locally source critical items, thus reducing global shipping dependencies and import delays [44].

Human resource development is equally crucial. Continuous training in supply chain analytics, emergency response logistics, and cold chain operations ensures that infrastructure investments are supported by a skilled workforce. Partnerships with universities and regional training institutions can help institutionalize supply chain expertise within national health systems [45].

Ultimately, sustained investment must be guided by a comprehensive national infrastructure blueprint aligned with public health objectives. As Figure 5 illustrates, nations with diversified distribution infrastructure, embedded risk assessment mechanisms, and strong local production capacities exhibited greater agility and recovery performance during widespread disruptions. These investments not only improve routine service delivery but also ensure that future shocks do not devolve into health system breakdowns.

8. FUTURE OUTLOOK AND RESEARCH GAPS

8.1 Preparing for Future Pandemics

Preparing sub-Saharan Africa’s public health supply chains for future pandemics requires a systemic shift from reactive response models to proactive, anticipatory systems. This means embedding resilience at every operational level procurement, warehousing, transportation, and data management rather than relying on emergency stop-gap measures after disruptions occur [33].

An integrated pandemic preparedness framework should prioritize early-warning surveillance tools linked with inventory management platforms to flag demand spikes and support the timely movement of critical commodities. This is especially critical for temperature-sensitive supplies, such as vaccines and biologics, which cannot afford transport delays during high-pressure periods [34]. Countries with simulation-based emergency preparedness models and strategic stockpiles managed to avoid prolonged service interruptions during major global health shocks [35].

Infrastructural readiness is another pillar. Expanding modular storage units, upgrading airport and port logistics, and ensuring redundancy in cold chain systems provides

operational breathing space during unforeseen surges. Where infrastructure was strategically diversified, bottlenecks in one logistics corridor could be mitigated by pivoting to alternative routes or distribution centers [38].

Health workforce continuity must also be factored into planning. Training emergency logistics cadres and decentralizing decision-making empower frontline teams to act autonomously in the face of rapidly evolving supply dynamics [39]. These human capital investments shorten response times and reduce dependency on centralized institutions that may be overwhelmed during peak disruptions.

Further, policy alignment across ministries especially health, finance, and transport is essential for coherent national response strategies. Integrated planning budgets that anticipate health emergencies allow for rapid deployment of resources without bureaucratic delays [40]. In this regard, institutionalizing public-private sector coordination mechanisms ensures real-time dialogue between manufacturers, distributors, and governments [41].

As Figure 5 illustrates, countries that proactively linked data systems, infrastructure development, and workforce capacity within a strategic resilience roadmap demonstrated higher agility and sustainability when navigating compound emergencies. This model provides a viable blueprint for building pandemic-ready public health supply chains [42].

8.2 Unresolved Questions and Research Directions

Despite notable advancements in health supply chain preparedness across sub-Saharan Africa, numerous unresolved questions remain regarding long-term sustainability, contextual adaptability, and systems-level evaluation. Future research must address these gaps to refine resilience strategies and ensure they are grounded in local realities [43].

One key question revolves around the scalability of innovations piloted during prior disruptions. For instance, while digital tools like e-LMIS platforms and drone delivery systems showed promise in isolated use cases, their expansion across diverse terrain and administrative zones remains inconsistent. Research must explore how infrastructural limitations, bandwidth constraints, and data literacy influence the scalability of digital logistics solutions in rural and peri-urban settings [44].

Another area requiring deeper inquiry is the economic cost-benefit analysis of resilience investments. While stockpiling, decentralization, and redundancy are essential, they also entail recurrent costs [45]. Governments must weigh these costs against potential savings from avoided stockouts or faster recovery timelines. Models that calculate return on investment (ROI) for various supply chain risk mitigation strategies would help decision-makers optimize limited budgets [46].

Furthermore, limited evidence exists on how informal logistics providers contribute to supply continuity during crises. In many countries, informal networks play a crucial role in bridging last-mile delivery gaps, especially when formal systems falter. Understanding how these actors can be integrated into national preparedness plans without compromising regulation and accountability is a pressing research agenda [47].

Supply chain governance and accountability also warrant examination. Resilience depends not just on infrastructure and technology but also on transparent procurement systems, anti-corruption safeguards, and efficient regulatory frameworks. Studies investigating how governance reforms impact supply chain performance, especially in procurement bottlenecks and lead time variability, can guide institutional strengthening efforts [48].

Another unresolved area is the alignment of humanitarian and development supply chains. During complex emergencies, parallel systems often arise fragmenting data, duplicating efforts, and overwhelming local capacities. Research should explore models for harmonizing short-term emergency responses with long-term system building, ensuring continuity beyond the crisis period [49].

Lastly, empirical metrics for measuring resilience remain fragmented and inconsistently applied. Developing standardized, context-sensitive indicators that capture robustness, agility, and absorptive capacity would aid in comparing performance across countries and regions. As visualized in Figure 5, a cohesive, multi-dimensional framework for resilience assessment can inform both diagnostics and policymaking at national and regional levels [50].

Continued interdisciplinary research spanning health systems, logistics engineering, public policy, and economics is essential for translating these unanswered questions into actionable solutions [51].

9. CONCLUSION

This study critically examined the resilience of public health supply chains in sub-Saharan Africa in the face of unprecedented disruptions, using the COVID-19 pandemic as a real-world stress test. Drawing from comparative country analysis, case studies, and systemic reviews, the study highlighted both pre-existing vulnerabilities and emergent strengths across different operational domains.

Key findings revealed that structural weaknesses in procurement, warehousing, and last-mile distribution remained widespread across the region. These were exacerbated by a heavy reliance on centralized, donor-driven supply systems with limited flexibility or adaptive capacity. Countries with fragile infrastructure and fragmented logistics networks experienced prolonged stockouts of critical supplies such as personal protective equipment, vaccines, and diagnostics. In contrast, those with diversified sourcing strategies, stronger local governance mechanisms, and nascent digital platforms were better positioned to absorb shocks and recover more rapidly.

Another major insight centered on the pivotal role of regional and local innovation. The adoption of digital tracking tools, the use of drone logistics, and decentralized procurement models emerged as adaptive mechanisms that helped sustain continuity. While these innovations varied in scale and effectiveness, they provided important blueprints for building more flexible systems capable of responding to dynamic supply challenges.

The study also found that regional economic communities played an increasingly important role, especially in pooled procurement and coordination. Their involvement improved supply visibility, reduced transaction costs, and accelerated response timelines across member states.

Finally, the analysis revealed the importance of integrating resilience metrics into routine supply chain management. Countries with performance monitoring frameworks, strategic stockpiles, and simulation-based planning models showed more consistency in supply continuity and equity of access during the disruption period.

Collectively, these findings underscore the need for a systemic redesign of health supply chains toward more anticipatory, data-informed, and locally anchored models of resilience.

9.2 Closing Reflections on Resilience and Equity

Resilience in health supply chains is not merely a technical aspiration; it is a matter of equity, justice, and survival. For sub-Saharan Africa, where health outcomes are often determined by timely access to basic medical supplies, resilient systems become a vital determinant of population well-being and national stability. Yet resilience must not be pursued in isolation from the broader imperative of equity.

This study highlights how disruptions disproportionately affect vulnerable communities those in rural areas, underserved regions, and facilities with limited autonomy. Even within countries, inequities in supply chain performance are visible in uneven distribution, inconsistent data reporting, and delays in replenishment. A resilient supply chain must therefore be designed to deliver not only continuity but also fairness.

Closing the resilience gap requires transforming how supply chains are planned, governed, and resourced. Local ownership and institutional capacity must be strengthened, not sidelined, in regional and global preparedness strategies. Public-private partnerships should prioritize shared accountability, and digital platforms must be inclusive, user-friendly, and responsive to real-time community needs.

Investments in supply chain resilience should also consider the hidden dimensions of resilience governance, workforce stability, and social trust. In many cases, the human factors leadership at subnational levels, frontline improvisation, and community engagement proved decisive in navigating crisis scenarios. These aspects are often overlooked in formal resilience planning yet are central to adaptive success.

Looking forward, equity and resilience must converge as twin pillars of health system transformation. Policymakers and practitioners must recognize that resilience without equity risks reinforcing existing disparities, while equity without resilience risks collapsing under pressure. A balanced approach that embeds social justice within the technical architecture of supply chains offers the most promising path forward.

In reimagining the future, the region has a unique opportunity to lead by example designing resilient health systems that are inclusive, transparent, and inherently prepared for whatever comes next.

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