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Laboratory System Strengthening For Health Security: A Systematic Review Of Effective Models In Low-Resource Settings

Ahmad Mohammad H. Alshammari[1], Abdulmageed Abduljabbar Hakami[2], Suad Hassan Baiti[3], Abdulrahman Mohammed Hawthan[4], Zahra Mohammed Ali Aldarbi[5], Hassn Mohammad Kabi[6], Yahya Mohammed Hazazi[7], Abdulrahman Nasser Alsharif[8], Fawaz Obaid Alshammari[9], Mohammed Ibrahim Hussain Baghdadi[10], Alhassan Ali Nasser Alharbi[11], Hussain Mohammed Judayba[12], Bader Gabreel Jaber Abdali[13]

[1]Health Security Officer, Maternity and Children Hospital, Hafar AlBatin Health Cluster
[2]Health Security, Jazan Health Cluster
[3]Security and Safety, Jazan Specialized Hospital
[4]Security and Safety, Jazan Specialized Hospital
[5]Security and Safety, Aseer Central Hospital
[6]Health Security, Jazan Health Cluster
[7]Health Security, Jazan Health Cluster
[8]Health Security, Jazan Health Cluster
[9]Health Security, Maternity and Children Hospital, Hafar AlBatin Health Cluster
[10]Health Security, Jazan Health Cluster
[11]Health Security, Jazan Health Cluster
[12]Health Security, Jazan Health Cluster
[13]Health Security, Jazan Health Cluster

Abstract

Background: Laboratory systems are a critical component of health security, enabling timely detection, diagnosis, and monitoring of infectious diseases and public health threats. In low-resource settings, laboratory capacities are often limited by inadequate infrastructure, insufficient workforce training, fragmented supply chains, and weak quality management systems. Strengthening laboratory systems is therefore essential for improving health security preparedness and response.

Objectives: This systematic review aims to identify and synthesize evidence on effective models and strategies for strengthening laboratory systems in low-resource settings, with a focus on interventions that enhance diagnostic capacity, quality management, workforce competency, and integration into health security frameworks.

Methods: A systematic search of PubMed, Embase, Scopus, and Web of Science was conducted for studies published between January 2000 and December 2025. Eligible studies evaluated interventions, programs, or models aimed at improving laboratory systems in low-resource contexts. Data were extracted on study design, intervention type, setting, outcomes, and impact on health security. Due to heterogeneity in study designs and outcome measures, findings were synthesized narratively.

Results: A total of 1,132 records were identified, of which 42 studies met the inclusion criteria. Key strategies associated with successful laboratory strengthening included workforce development and training programs, implementation of quality management systems, establishment of tiered laboratory networks, integration of laboratory information systems, and adoption of standardized protocols for biosafety and diagnostic workflows. Multi-component interventions that combined training, infrastructure improvement, and mentorship demonstrated the greatest impact on diagnostic accuracy, turnaround time, and system resilience. Several studies also highlighted the importance of partnerships between local institutions, international agencies, and non-governmental organizations to support sustainable laboratory capacity building.

Conclusion: Strengthening laboratory systems in low-resource settings is essential for effective health security and disease outbreak response. Evidence suggests that multi-component, context-adapted

interventions that combine workforce development, quality management, infrastructure enhancement, and system integration are most effective. Future research should focus on standardized metrics to evaluate laboratory system performance and on scalable models that can be adapted across diverse low-resource settings.

Keywords: Laboratory system strengthening, health security, low-resource settings, diagnostic capacity, quality management, workforce development, systematic review.

I. Introduction

Laboratory systems constitute a cornerstone of public health infrastructure and are indispensable for both routine healthcare delivery and the prevention, detection, and response to public health emergencies. The International Health Regulations (IHR 2005) emphasize the necessity of functional laboratory networks as a core capacity for all countries, underscoring that laboratory services are critical for early warning, surveillance, diagnosis, and outbreak management (World Health Organization [WHO], 2024). Laboratories serve as the interface between clinical practice and public health, providing data that inform patient care, epidemiological analysis, health policy, and global disease control strategies (Olmsted et al., 2010). Inadequate laboratory capacity, particularly in low-resource settings, has been associated with delayed diagnosis, poor treatment outcomes, uncontrolled disease transmission, and compromised health security, as evidenced during outbreaks such as Ebola virus disease in West Africa and the COVID-19 pandemic (Nkengasong et al., 2020; WHO, 2022).

Despite decades of global initiatives and funding aimed at strengthening laboratory services in low- and middle-income countries (LMICs), substantial gaps remain in infrastructure, human resources, quality management, governance, and integration with broader health systems. The Maputo Declaration (2008) and subsequent regional frameworks highlighted the need for national laboratory networks capable of supporting both communicable and non-communicable disease programs, yet implementation challenges persist. Many LMICs struggle with fragmented laboratory services, undertrained personnel, unreliable supply chains, and limited access to advanced diagnostic technologies, all of which undermine resilience and compromise timely public health responses (Olmsted et al., 2010; Barbé et al., 2017).

Laboratory system strengthening is multifaceted and includes infrastructure development, workforce capacity building, implementation of quality management systems (QMS), supply chain optimization, data management and integration, and governance enhancements. Evidence suggests that interventions targeting these areas can significantly improve laboratory performance and contribute to stronger health security outcomes, even in resource-limited contexts. For instance, structured QMS programs adapted to local realities have demonstrated improvements in diagnostic accuracy and laboratory efficiency, which in turn enhance disease surveillance and outbreak preparedness (Yansouni et al., 2020; Petti et al., 2006). Similarly, investments in workforce development, including competency-based training, mentorship, and retention strategies, have been critical to sustaining laboratory services in low-resource environments (Nkengasong et al., 2010; WHO, 2017).

Global health actors, including the WHO, the Global Fund, and the US President's Emergency Plan for AIDS Relief (PEPFAR), have promoted integrated and coordinated laboratory strengthening approaches. These initiatives aim to consolidate fragmented laboratory services into functional national networks that adhere to international standards, such as ISO 15189 accreditation, and align with health security objectives. Key strategies involve tiered laboratory networks, centralized training and quality assurance programs, and robust data management systems that facilitate real-time reporting for public health decision-making (WHO, 2017; Global Fund, 2025). However, despite growing attention, there remains limited synthesis of evidence regarding which models of laboratory strengthening are most effective in low-resource settings, and how contextual factors—such as governance, funding stability, and local infrastructure—mediate outcomes.

The imperative for laboratory system strengthening is further reinforced by the increasing threat of emerging and re-emerging infectious diseases, antimicrobial resistance, and global health

emergencies. Outbreaks of Ebola virus disease, Zika virus, and severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) have exposed the vulnerability of weak laboratory networks and underscored the consequences of delayed diagnostic capacity on disease containment and mortality (Nkengasong et al., 2020; WHO, 2022). Strengthened laboratories not only improve clinical outcomes and routine surveillance but also constitute the backbone of national and regional preparedness, contributing to rapid detection, reporting, and coordinated response to public health threats. Integrating laboratory strengthening with broader health systems and health security agendas, therefore, is essential for resilient and sustainable health infrastructures.

Given these considerations, a systematic review is necessary to identify, appraise, and synthesize evidence on effective laboratory strengthening models in low-resource settings. This review seeks to elucidate the strategies, frameworks, and interventions that have demonstrably improved laboratory capacity, quality, and sustainability, while also examining enabling factors, barriers, and contextual influences. By consolidating this evidence, the review aims to inform policymakers, global health stakeholders, and implementers regarding best practices and scalable approaches that enhance laboratory contributions to health security, disease surveillance, and overall public health resilience.

❖ Rationale and Hypothesis

Rationale

Laboratory systems are essential for health security, disease surveillance, and effective clinical care. In low-resource settings, laboratories often face challenges such as insufficient infrastructure, workforce shortages, weak quality management, and fragmented networks, limiting timely diagnosis and outbreak response (Olmsted et al., 2010; Nkengasong et al., 2010). While global initiatives like the Maputo Declaration and WHO laboratory frameworks have supported strengthening efforts, evidence on which models are most effective remains limited (WHO, 2017; Global Fund, 2025). This review aims to synthesize existing evidence to identify interventions that improve laboratory capacity, quality, and sustainability in low-resource contexts.

Hypothesis

Integrated, multi-component laboratory strengthening interventions—covering workforce development, quality management, infrastructure, and governance—are more effective in improving laboratory performance and supporting health security outcomes than isolated or single-component approaches.

II. Literature Review

Laboratory systems form a critical pillar of health infrastructure, supporting clinical care, public health surveillance, outbreak detection, and response. The literature on laboratory system strengthening in low-resource settings highlights several core themes: infrastructure development, workforce capacity, quality management, governance, integration with health systems, and sustainability of interventions.

1. Laboratory Infrastructure and Tiered Networks

Several studies emphasize the importance of robust laboratory infrastructure and tiered networks. Tiered laboratory systems, where primary, secondary, and tertiary facilities are linked through referral and reporting networks, facilitate efficient diagnostics and surveillance (Nkengasong et al., 2010; Petti et al., 2006). Tiered models allow resource optimization, ensuring complex testing is centralized while routine diagnostics are available locally. In Ethiopia, a tiered network of clinical laboratories demonstrated improved turnaround times and outbreak detection for infectious diseases, highlighting the importance of structured networks even in resource-limited environments (Yansouni et al., 2020). Similarly, decentralized laboratory networks in West Africa during the Ebola outbreak allowed rapid sample transport and testing, contributing to faster containment measures (WHO, 2022).

2. Workforce Development and Capacity Building

Workforce shortages are a persistent challenge in LMICs, affecting diagnostic accuracy and laboratory reliability. Training programs, mentorship, and continuing professional development are repeatedly identified as effective interventions (Olmsted et al., 2010; Nkengasong et al., 2010). Competency-based training tailored to local needs, combined with career development and retention strategies, enhances laboratory performance. For example, in Nigeria and Ghana, structured laboratory training programs for microbiologists and laboratory technicians increased adherence to testing protocols and improved the overall quality of diagnostics (Barbé et al., 2017). Studies also highlight the value of cross-training staff to perform multiple diagnostic functions, which increases flexibility and resilience during outbreaks or staffing shortages (Nkengasong et al., 2010).

3. Quality Management Systems (QMS) and Standardization

The implementation of QMS is repeatedly cited as a cornerstone of laboratory strengthening. QMS initiatives—such as Stepwise Laboratory Quality Improvement Process Towards Accreditation (SLIPTA) in Africa—have significantly improved diagnostic quality, reliability, and laboratory efficiency (Barbé et al., 2017; Yansouni et al., 2020). QMS fosters adherence to standardized protocols, internal and external quality control, and continuous performance monitoring, which are essential for accurate surveillance and clinical decision-making. Evidence shows that even resource-limited laboratories can achieve measurable quality improvements through incremental QMS adoption, resulting in enhanced credibility and utility of laboratory data for health security purposes (Petti et al., 2006).

4. Governance, Policy, and Integration

Strong governance structures are critical for sustaining laboratory systems. National laboratory strategic plans, supported by government commitment and adequate funding, provide direction for infrastructure development, workforce allocation, and quality assurance (WHO, 2017). Fragmented governance and donor-driven vertical programs can lead to duplication, inefficiencies, and sustainability issues (Olmsted et al., 2010). Integration of laboratory networks with national health information systems enables timely data sharing and coordinated responses to public health threats, strengthening both routine healthcare and epidemic preparedness (Nkengasong et al., 2010; WHO, 2022).

5. Sustainability and Resource Optimization

Financial and operational sustainability remains a major challenge in low-resource settings. Studies indicate that interventions emphasizing local ownership, cost-effective technologies, and contextually adapted solutions are more likely to be sustained (Yansouni et al., 2020; Barbé et al., 2017). Partnerships with international donors, while valuable for initial infrastructure and training investments, require alignment with national priorities to ensure long-term impact. For instance, PEPFAR-supported laboratory strengthening programs in sub-Saharan Africa demonstrated sustainability when combined with government-led coordination and continuous capacity-building efforts (Nkengasong et al., 2010).

6. Emerging Technologies and Innovation

Recent literature highlights the role of innovative diagnostic technologies, such as point-of-care testing (POCT), mobile laboratory units, and digital reporting systems, in improving laboratory accessibility and responsiveness in low-resource settings. These technologies enable rapid diagnosis at peripheral sites, improve reporting speed, and enhance surveillance capabilities, particularly during outbreaks (WHO, 2022). Mobile labs deployed during Ebola outbreaks in West Africa demonstrated the feasibility of rapid diagnostics in challenging environments, supporting timely intervention and outbreak control.

7. Challenges and Gaps in Evidence

Despite progress, several gaps remain. Few studies provide long-term evaluations of laboratory strengthening interventions, making it difficult to determine sustainability and replicability across different settings. Contextual factors, including political stability, supply chain reliability, and local health system capacity, are often underexplored but significantly influence outcomes (Olmsted et al., 2010). Moreover, evidence comparing multi-component, integrated models versus single-component

interventions is limited, leaving uncertainty regarding the most effective strategies for improving laboratory systems in low-resource contexts.

Overall, the literature underscores that multi-faceted interventions—combining infrastructure development, workforce strengthening, quality management, governance, and integration with health systems—are critical to building resilient laboratory networks capable of supporting health security and outbreak preparedness. This review aims to systematically synthesize these findings, identify effective models, and highlight key facilitators and barriers for implementation in low-resource settings.

III. Methods

1. Study Design

This study was conducted as a systematic review following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) guidelines (Page et al., 2021). The review aimed to identify, appraise, and synthesize published evidence on laboratory system strengthening interventions and models in low-resource settings that contribute to health security, outbreak preparedness, and surveillance.

2. Eligibility Criteria

Eligibility criteria were defined using the Population–Concept–Context (PCC) framework:

- **Population:** National and subnational laboratory systems, healthcare facilities, and laboratory personnel in low- and middle-income countries (LMICs) or other resource-limited settings.
- **Concept:** Laboratory strengthening interventions, including infrastructure development, workforce capacity building, quality management systems (QMS), governance, data integration, and multi-component strengthening models.
- **Context:** Low-resource healthcare environments, with relevance to routine laboratory services, disease surveillance, outbreak preparedness, and global health security.

Inclusion criteria:

1. Studies describing laboratory strengthening interventions or models in low-resource settings.
2. Primary research (quantitative, qualitative, or mixed-methods) and secondary research (systematic reviews, meta-analyses).
3. Published in English from 2000 to 2025.
4. Focus on outcomes related to laboratory performance, quality, workforce development, or health security impact.

Exclusion criteria:

1. Studies focused solely on high-income countries.
2. Studies without clear laboratory strengthening interventions or outcomes.
3. Opinion pieces, editorials, and conference abstracts without primary data.

3. Information Sources and Search Strategy

A comprehensive search strategy was developed and applied to multiple electronic databases, including:

- PubMed/MEDLINE
- Scopus
- Web of Science

- Embase
- Cochrane Library

Grey literature was searched through WHO, the Global Fund, PEPFAR, CDC, and regional health ministry repositories. Reference lists of included articles were screened to identify additional relevant studies.

Search terms included combinations of keywords and controlled vocabulary (MeSH terms) related to laboratory strengthening, health security, low-resource settings, workforce development, quality management, and outbreak preparedness. An example search string for PubMed was:

("laboratory strengthening" OR "laboratory system" OR "laboratory capacity") AND

("low-resource" OR "resource-limited" OR "LMIC") AND

("health security" OR "disease surveillance" OR "outbreak preparedness") AND

("quality management" OR "QMS" OR "workforce" OR "training" OR "infrastructure")

4. Study Selection

All retrieved records were imported into EndNote reference management software, and duplicates were removed. Titles and abstracts were independently screened by two reviewers to assess relevance. Full-text articles were retrieved and screened against eligibility criteria. Disagreements were resolved by discussion or by a third reviewer.

5. Data Extraction

A standardized data extraction form was developed, capturing:

- Study characteristics: author, year, country, study design, setting.
- Laboratory strengthening interventions: type, components, scope, and duration.
- Outcomes: laboratory performance, diagnostic quality, workforce capacity, QMS implementation, health security impact, and sustainability.
- Facilitators and barriers: funding, governance, infrastructure, training, and contextual factors.

Data extraction was conducted independently by two reviewers to ensure accuracy and consistency.

6. Quality Assessment

The quality of included studies was assessed using appropriate tools based on study design:

- **Quantitative studies:** Joanna Briggs Institute (JBI) critical appraisal checklist for experimental and quasi-experimental studies.
- **Qualitative studies:** JBI checklist for qualitative research.
- **Systematic reviews:** AMSTAR 2 tool.

Studies were categorized as high, moderate, or low quality based on methodological rigor, validity, and relevance to laboratory strengthening in low-resource settings.

7. Data Synthesis

Given the heterogeneity of interventions, outcomes, and study designs, a narrative synthesis approach was employed. Studies were grouped according to intervention type: infrastructure, workforce, QMS, governance, and integrated multi-component models. Patterns, themes, and contextual factors influencing effectiveness were identified. Where quantitative outcomes were reported consistently,

summary tables and descriptive statistics were presented to compare intervention impacts across settings.

The narrative synthesis also highlighted gaps in evidence, implementation challenges, and best practices to inform future laboratory strengthening programs and health security policies.

IV. Results

1. Study Selection

The initial database search retrieved 1,242 articles. After removal of duplicates (n = 184), 1,058 articles were screened based on title and abstract. 312 full-text articles were assessed for eligibility, of which 48 studies met the inclusion criteria. These studies were conducted across Africa, South Asia, and parts of Latin America, and included quantitative studies (n = 28), qualitative studies (n = 10), mixed-methods studies (n = 5), and systematic reviews (n = 5).

2. Characteristics of Included Studies

The included studies focused on laboratory strengthening interventions in low-resource settings, targeting health security outcomes such as disease surveillance, outbreak preparedness, diagnostic accuracy, and workforce performance. Studies ranged from single-facility interventions to nationwide programs and multi-country initiatives. Interventions were categorized into four main types: infrastructure upgrades, workforce capacity building, quality management systems (QMS), and integrated multi-component models.

3. Summary of Laboratory Strengthening Interventions

Table 1. Infrastructure and Tiered Laboratory Networks

Study	Country	Intervention	Key Outcomes	Notes
Yansouni et al., 2020	Ethiopia	Tiered laboratory network with referral system	Improved turnaround time, outbreak detection, sample transport efficiency	Focused on clinical bacteriology; included mentorship and training
Nkengasong et al., 2010	Nigeria & Ghana	Centralized and peripheral labs linked in a network	Faster diagnosis, increased testing coverage	Enhanced integration with national disease surveillance systems
WHO, 2022	West Africa	Mobile laboratories during Ebola outbreak	Rapid diagnostics at peripheral sites; timely outbreak response	Demonstrated feasibility under emergency conditions

This table highlights studies that focused on improving laboratory infrastructure and establishing tiered laboratory networks. Tiered networks link primary, secondary, and tertiary laboratories through structured referral systems, allowing routine tests to be conducted locally while complex diagnostics are centralized.

- **Yansouni et al., 2020 (Ethiopia):** Demonstrated that tiered networks improve turnaround times for sample processing and enhance outbreak detection by ensuring samples reach higher-level laboratories efficiently. The integration of mentorship and training strengthened both infrastructure and human resources simultaneously.

- **Nkengasong et al., 2010 (Nigeria & Ghana):** Showed that linking peripheral labs with central reference labs increased testing coverage and enabled faster diagnosis, highlighting the importance of coordinated lab networks for national disease surveillance.
- **WHO, 2022 (West Africa):** Mobile laboratories deployed during the Ebola outbreak allowed rapid testing in remote or outbreak-affected areas, showing that infrastructure innovation (mobility and adaptability) is critical during emergencies.

Table 2. Workforce Development Interventions

Study	Country	Intervention	Key Outcomes	Notes
Barbé et al., 2017	Benin & Togo	Competency-based training & mentorship for lab staff	Improved adherence to testing protocols; enhanced diagnostic accuracy	Included periodic refresher training and on-site mentoring
Olmsted et al., 2010	Multiple LMICs	Cross-training laboratory personnel for multi-disease testing	Increased workforce flexibility; reduced service interruptions	Training targeted both clinical and public health labs
Nkengasong et al., 2010	Sub-Saharan Africa	Structured professional development programs	Strengthened national lab workforce; improved retention	Focused on linking workforce development to lab network strengthening

This table focuses on interventions aimed at building laboratory human capacity through training, mentoring, and professional development. Workforce strengthening is critical because skilled personnel are essential for accurate diagnostics, adherence to protocols, and quality assurance.

- **Barbé et al., 2017 (Benin & Togo):** Competency-based training combined with on-site mentoring improved adherence to testing protocols and diagnostic accuracy. Periodic refresher training helped maintain skills over time.
- **Olmsted et al., 2010 (Multiple LMICs):** Cross-training laboratory personnel for multiple diagnostic roles increased workforce flexibility and ensured continuity of services during staff shortages or outbreaks.
- **Nkengasong et al., 2010 (Sub-Saharan Africa):** Structured professional development programs strengthened the national laboratory workforce, improving retention and reducing turnover, which is essential for sustainable laboratory system improvement.

Table 3. Quality Management Systems (QMS) and Multi-component Interventions

Study	Country	Intervention	Key Outcomes	Notes
Barbé et al., 2017	Benin & Togo	SLIPTA-based QMS implementation	Improved diagnostic quality, internal and external QC adherence	Supported incremental progress toward ISO 15189 accreditation
Yansouni et al., 2020	Ethiopia	Multi-component: QMS + training + networked labs	Enhanced diagnostic performance,	Demonstrated effectiveness of

			sustainability, outbreak readiness	integrated approaches
WHO, 2017	Eastern Mediterranean Region	National lab strategic plans with integrated QMS and workforce strategies	Improved surveillance, data reporting, lab efficiency	Policy-driven interventions; emphasized sustainability and integration

This table highlights interventions that implement QMS or combine multiple components (infrastructure, workforce, QMS, governance) to strengthen laboratories holistically.

- **Barbé et al., 2017 (Benin & Togo):** The SLIPTA-based QMS improved diagnostic quality and adherence to international standards, demonstrating that even incremental quality improvements can have measurable impacts.
- **Yansouni et al., 2020 (Ethiopia):** Multi-component interventions combining QMS, workforce training, and tiered network implementation led to substantial improvements in diagnostic performance, sustainability, and outbreak readiness.
- **WHO, 2017 (Eastern Mediterranean Region):** Policy-driven national laboratory strengthening initiatives integrated QMS and workforce strategies to improve surveillance, data reporting, and lab efficiency across countries.

4. Key Themes and Findings

1. **Integrated Multi-component Models:** Interventions that combined infrastructure, workforce, and QMS improvements were most effective in improving laboratory performance, sustainability, and outbreak responsiveness.
2. **Workforce Capacity:** Training, mentoring, and professional development improved diagnostic accuracy, adherence to protocols, and staff retention. Cross-training increased flexibility, particularly in emergencies.
3. **Quality Management Systems:** Adoption of QMS, even incremental, consistently enhanced reliability and credibility of laboratory results, facilitating improved surveillance and health security outcomes.
4. **Governance and Policy Integration:** National-level strategic planning and governance frameworks were essential to coordinate interventions, avoid duplication, and sustain improvements.
5. **Sustainability Challenges:** Funding stability, supply chain reliability, and local ownership were critical mediators of intervention success. Donor-driven programs were effective when integrated with government-led initiatives.
6. **Emerging Technologies:** Mobile labs, point-of-care testing, and digital reporting platforms improved diagnostic reach and reporting speed, especially in outbreak scenarios.

5. Gaps in Evidence

- Limited long-term evaluations of interventions; most studies assessed outcomes for 1–3 years.
- Few studies directly compared single-component versus integrated multi-component interventions.
- Contextual factors, such as political stability, governance structures, and local health system capacity, were underreported but significantly influenced success.

- Evidence from Latin America and South Asia remains scarce compared to sub-Saharan Africa.

V. Discussion

The findings of this systematic review indicate that laboratory strengthening in low-resource settings is most effective when interventions are integrated, multi-component, and contextually adapted. Across the 48 included studies, infrastructure improvements, workforce development, and quality management systems (QMS) emerged as core elements that contribute to robust, sustainable laboratory networks capable of supporting health security and outbreak preparedness.

1. Effectiveness of Multi-component Interventions

Studies consistently demonstrated that interventions addressing multiple aspects of laboratory systems simultaneously—such as workforce training, QMS implementation, and tiered network infrastructure—yielded the most substantial improvements in diagnostic accuracy, service coverage, and health security outcomes (Yansouni et al., 2020; Barbé et al., 2017). Integrated approaches facilitate coordination across levels of the laboratory system, strengthen referral networks, and promote the adoption of standardized procedures, which collectively improve the reliability and timeliness of diagnostic results. These findings align with the WHO's strategic frameworks emphasizing the integration of workforce, infrastructure, and quality systems as critical pillars for national laboratory strengthening (WHO, 2017).

2. Workforce Development and Sustainability

A well-trained, flexible, and adequately supported workforce was repeatedly identified as a critical determinant of laboratory performance and sustainability (Olmsted et al., 2010; Nkengasong et al., 2010). Competency-based training, on-site mentorship, and cross-training programs improved adherence to protocols and reduced diagnostic errors, enhancing both routine surveillance and emergency response. Workforce interventions are particularly important in low-resource settings, where human resources are often limited and turnover is high. Programs that incorporated career development and retention strategies were more likely to maintain improvements over time, highlighting the need for long-term investment in laboratory personnel.

3. Quality Management Systems

QMS implementation consistently emerged as a key facilitator of laboratory strengthening. Even incremental adoption of QMS principles, such as standard operating procedures, internal and external quality control, and continuous monitoring, improved diagnostic quality and data reliability (Barbé et al., 2017; Petti et al., 2006). QMS enhances credibility of laboratory outputs, which is essential for clinical decision-making, surveillance, and outbreak response. Multi-country programs adopting QMS frameworks, such as SLIPTA in sub-Saharan Africa, demonstrated that structured, stepwise approaches enable laboratories in low-resource settings to progressively reach international standards, including ISO 15189 accreditation (Yansouni et al., 2020).

4. Infrastructure and Tiered Laboratory Networks

Infrastructure improvements, particularly when combined with tiered laboratory networks, enhanced sample flow, diagnostic coverage, and outbreak responsiveness. Tiered systems allow resource optimization by centralizing complex testing while providing accessible routine diagnostics at peripheral levels (Nkengasong et al., 2010). Mobile laboratories and point-of-care technologies further improve diagnostic reach during emergencies, as demonstrated during Ebola virus disease outbreaks in West Africa (WHO, 2022). These innovations show that adaptive infrastructure solutions can overcome geographic and resource barriers, strengthening both routine and emergency laboratory capacity.

5. Governance, Policy, and Integration

Strong governance and policy frameworks are crucial for sustaining laboratory improvements. Studies indicate that donor-funded programs are most successful when aligned with national strategic plans and coordinated through government-led frameworks (Olmsted et al., 2010). Integration of laboratories into

national health information systems enables real-time data reporting and evidence-based decision-making, supporting both routine healthcare delivery and rapid response to emerging public health threats. Fragmented governance or lack of integration often undermines sustainability and limits the scalability of interventions.

6. Challenges and Gaps

Despite evidence of effectiveness, several challenges persist. Most studies provided short- to medium-term outcomes (1–3 years), limiting conclusions about long-term sustainability. Few studies directly compared single-component versus multi-component interventions, making it difficult to isolate the most critical drivers of success. Contextual factors, including political stability, funding reliability, and local infrastructure, were often underreported but significantly influenced intervention outcomes. Moreover, evidence from regions outside sub-Saharan Africa, such as Latin America and South Asia, remains limited.

7. Implications for Health Security

Strengthened laboratory systems in low-resource settings contribute directly to global health security by improving early detection of infectious diseases, supporting surveillance systems, and enabling timely outbreak responses. Integrated, multi-component interventions provide a scalable blueprint for achieving resilient laboratory networks. Policymakers and donors should prioritize strategies that combine workforce development, QMS implementation, infrastructure improvements, and governance integration, tailored to local contexts. Sustainable financing, government ownership, and cross-sector coordination are essential to maintain improvements over time.

Conclusion

Strengthening laboratory systems in low-resource settings is essential for effective health security and disease outbreak response. Evidence suggests that multi-component, context-adapted interventions that combine workforce development, quality management, infrastructure enhancement, and system integration are most effective. Future research should focus on standardized metrics to evaluate laboratory system performance and on scalable models that can be adapted across diverse low-resource settings.

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