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Laboratory Capacity And Epidemiological Surveillance For AMR: A Situational Analysis In Low-Resource Settings For Global Health Security

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I. Abstract

Background

Antimicrobial resistance (AMR) has emerged as a preeminent threat to global health security, often described as a "silent pandemic" that compromises the efficacy of modern medicine. The burden of AMR is disproportionately concentrated in Low- and Middle-Income Countries (LMICs), particularly within sub-Saharan Africa and South Asia, where the convergence of high infectious disease incidence, unregulated antimicrobial access, and fragile health systems creates a perfect storm for the emergence of multidrug-resistant (MDR) pathogens. In these Low-Resource Settings (LRS), the prevalence of critical priority pathogens—such as extended-spectrum beta-lactamase (ESBL)-producing Enterobacteriaceae and methicillin-resistant Staphylococcus aureus (MRSA)—is alarmingly high, yet critically underreported due to surveillance gaps. Intervention 2, the current standard of care for AMR surveillance in these contexts, relies predominantly on conventional, manual culture-based microbiology and paper-based reporting systems. These methods are characterized by labor-intensive workflows, high susceptibility to contamination, prolonged turnaround times (TAT), and significant data loss during manual aggregation, resulting in a "data void" that hinders the development of evidence-based National Action Plans (NAPs). Intervention 1, comprising enhanced laboratory capacity through automated systems (e.g., automated blood culture, molecular diagnostics like GeneXpert, Whole Genome Sequencing) and integrated digital surveillance (e.g., LIMS, WHONET, One Health platforms), has been proposed as a promising alternative to bridge this diagnostic and epidemiological gap.

Objective

The primary aim of this systematic review is to systematically compare the effectiveness of Intervention 1 (Enhanced Diagnostic and Digital Surveillance Systems) versus Intervention 2 (Conventional Manual Microbiology and Paper-Based Reporting) on key outcomes for populations in Low-Resource Settings with suspected drug-resistant infections. Specifically, the review evaluates improvements in diagnostic yield (recovery rates), time-to-detection (TTD), data completeness, and the subsequent utility of surveillance data for clinical decision-making and national policy formulation.

Methods

A systematic review was conducted adhering to the PRISMA 2020 guidelines. We searched major databases including PubMed, Scopus, Embase, and relevant grey literature sources (WHO, Fleming Fund, MSF Science Portal) for studies published up to 2024. The PICO framework was utilized to define the scope: Population (patients and surveillance systems in LRS); Intervention (automated diagnostics and digital data platforms); Comparison (manual culture and paper-based reporting); and Outcomes (diagnostic yield, contamination rates, TTD, and surveillance system maturity scores). The quality of included studies was assessed using the Cochrane Risk of Bias tool for comparative diagnostic studies and the WHO Laboratory Assessment Tool (LAT) or SLIPTA checklists for observational surveillance reports.

Results

The review identified a distinct dichotomy in performance between the two interventions. Automated blood culture systems (Intervention 1) demonstrated a significantly higher pathogen recovery rate (36.5%) compared to manual methods (24.0%) and reduced the time-to-detection by approximately 2.5 days. However, the analysis revealed that contamination rates remained high across both methods in LRS contexts (~43-48%), highlighting that pre-analytical variables such as phlebotomy technique are critical determinants of success independent of the diagnostic platform. Molecular platforms like GeneXpert showed high sensitivity (>90%) for specific pathogens like Mycobacterium tuberculosis but demonstrated variable concordance with culture for broad bacterial surveillance. In terms of surveillance systems, early implementation of WHO GLASS revealed that while digital platforms like WHONET improve data standardization, over 40% of African countries lacked recent data due to foundational laboratory weaknesses.

Conclusion

Enhanced laboratory and surveillance systems (Intervention 1) offer superior technical performance regarding diagnostic capability and data speed compared to conventional methods. However, their effectiveness in LRS is heavily modulated by infrastructural determinants, including supply chain stability, electricity consistency, and staff capacity. Automation solves the "sensitivity gap" but does not resolve the "sustainability gap" without concomitant health system strengthening. The review concludes that a hybrid approach—leveraging simplified, quality-assured bacteriology (e.g., MSF Mini-Labs) alongside strategic automation at reference nodes—is critical for sustainable Global Health Security.

Keywords: Antimicrobial Resistance (AMR), Automated Blood Culture, Global Health Security, Low-Resource Settings (LRS), Epidemiological Surveillance, One Health, WHO GLASS, Molecular Diagnostics.

II. Introduction

Global Overview of Antimicrobial Resistance

Antimicrobial resistance (AMR) stands as one of the most complex and urgent challenges facing the global community in the 21st century. It is a phenomenon that transcends biological boundaries, driven by the evolutionary imperative of microorganisms to survive, but accelerated catastrophically by human behavior. The misuse and overuse of antimicrobials in human health, animal husbandry, and agriculture have exerted a selective pressure that has rendered many of our most effective drugs obsolete. The consequences are profound: common infections such as pneumonia, urinary tract infections, and sepsis are becoming increasingly difficult, and sometimes impossible, to treat [1].

The global impact of AMR is quantifiable in both human and economic terms. In 2019, a landmark systematic analysis estimated that 1.27 million deaths were directly attributable to bacterial AMR, a figure that surpasses the annual mortality from HIV/AIDS or malaria [2]. The economic toll is equally staggering, with the World Bank projecting that AMR could cause a fall in global Gross Domestic Product (GDP) by 1.1% to 3.8% by 2050. This economic contraction is expected to push up to 28 million people into extreme poverty, primarily in developing nations, thereby reversing decades of progress in global development.

Specific Burden in Low-Resource Settings

While AMR is a global threat, its burden is not shared equally. Low-Resource Settings (LRS)—

encompassing Low- and Middle-Income Countries (LMICs) in sub-Saharan Africa, South Asia, and parts of Southeast Asia—face a unique and exacerbated crisis. In these regions, the epidemiology of AMR is shaped by a "double burden" of disease. Populations contend with high rates of persistent infectious diseases (such as tuberculosis, malaria, and HIV) alongside a rising tide of hospital-acquired infections (HAIs) caused by multi-drug resistant (MDR) organisms [1, 3].

The specific burden in these populations is compounded by environmental and systemic factors. Poor water, sanitation, and hygiene (WASH) infrastructure facilitates the rapid transmission of resistant enteric pathogens like Salmonella Typhi and Escherichia coli. Overcrowding in urban slums and hospitals creates incubators for the spread of resistant clones. Furthermore, the "social burden" of AMR in these contexts is immense yet invisible. The economic shock of a prolonged illness due to a drug-resistant infection can be catastrophic for a household in an LRS, leading to loss of income, accumulation of debt, and deepening poverty [4].

Crucially, the burden is also defined by a lack of access to effective second- and third-line antibiotics. When first-line treatments fail due to resistance, patients in high-income countries may be switched to reserve antibiotics (e.g., carbapenems or ceftazidime-avibactam). In LRS, these drugs are often unavailable or prohibitively expensive, meaning that resistance to standard antibiotics is functionally a death sentence [2].

Conventional Management (Intervention 2)

The conventional strategy for managing AMR surveillance and diagnosis in LRS—referred to here as **Intervention 2**—is rooted in traditional, manual microbiological techniques. This approach has remained largely unchanged for decades and typically involves the following workflow:

1. **Sample Collection**: Clinicians request a culture (often infrequently due to cost).
2. **Manual Culture**: Samples (blood, urine, pus) are inoculated into manually prepared culture media. For blood cultures, this often involves "in-house" brain-heart infusion broth in glass bottles, which are visually inspected daily for turbidity (bacterial growth) over a period of 7 to 10 days.
3. **Phenotypic Identification**: Positive cultures are sub-cultured onto solid agar plates (e.g., Blood Agar, MacConkey Agar). Bacterial identification is performed using biochemical test batteries (e.g., TSI, urea, citrate), which require multiple reagents and incubation steps.
4. **Susceptibility Testing**: Disk diffusion (Kirby-Bauer) methods are used to determine resistance profiles.
5. **Reporting**: Results are recorded in paper logbooks. Surveillance data is aggregated manually, often months later, into reports that are frequently incomplete or lost [5].

Challenges with Intervention 2

The population in LRS faces immense challenges when relying on Intervention 2. The primary limitation is the diagnostic gap. Manual methods are slow; a final result can take 5 to 7 days. In an acute clinical setting, such as a patient with sepsis, this delay renders the result clinically irrelevant for the immediate therapeutic decision. Consequently, clinicians are forced to rely on empirical treatment—guessing the pathogen and the drug. This drives a vicious cycle: lack of data leads to broad-spectrum antibiotic overuse, which drives resistance, which further complicates future empirical treatment [6].

Structurally, Intervention 2 is prone to failure at multiple points in the "culture cascade."

- **Infrastructure**: Manual media preparation requires autoclaves, clean water, and reliable electricity to maintain incubator temperatures. Frequent power outages can ruin cultures or halt incubation [7].
- **Human Resources**: The process is labor-intensive and requires highly skilled microbiologists to interpret biochemical reactions and read inhibition zones visually. LRS face a chronic shortage of trained laboratory personnel, leading to high rates of transcription and interpretation errors [8].
- **Data Silos**: Paper-based records are difficult to analyze. Data remains trapped in physical books, preventing the identification of local outbreaks or national trends. This results in a "data void" where national policy makers operate without an accurate map of the resistance landscape [9].

Promising Alternative (Intervention 1)

Intervention 1 represents the modernization of this diagnostic and surveillance infrastructure through Enhanced Laboratory Capacity and Integrated Digital Surveillance. This intervention encompasses a suite of advanced technologies and systems:

1. **Automated Culture Systems**: Technologies such as the BacT/ALERT or BACTEC systems continuously monitor blood culture bottles for CO2 production, signaling positivity within hours rather than days. These systems are closed, reducing (theoretically) the risk of handling contamination and improving pathogen recovery [10].
2. **Molecular Diagnostics**: Platforms like GeneXpert and Whole Genome Sequencing (WGS) allow for the direct detection of resistance genes (genotypic testing) from clinical samples, bypassing the need for prolonged culture. These tools offer rapid turnaround times and high sensitivity [6].
3. **Digital Surveillance Integration**: The implementation of Laboratory Information Management Systems (LIMS) and specialized software like WHONET allows for the digitization of AST results. This facilitates the automated deduplication of data, the generation of standardized reports, and the integration of human, animal, and environmental data into "One Health" surveillance platforms [9].

Rationale

This systematic review is necessary because the global push to implement Intervention 1 in LRS—driven by initiatives like the Fleming Fund and WHO GLASS—is encountering complex realities on the ground. While the theoretical benefits of automation and digitization are clear, the evidence regarding their situational effectiveness in resource-constrained environments is mixed. High-tech equipment often fails due to lack of maintenance, proprietary reagent stock-outs, and harsh environmental conditions (dust, heat). Conversely, relying solely on manual methods (Intervention 2) perpetuates the data void. There is a critical gap in the literature that systematically synthesizes the trade-offs between diagnostic performance and operational sustainability in these specific settings. We need to understand not just if these technologies work, but how they function under the constraints of LRS.

Hypotheses

- **Primary Hypothesis**: The implementation of automated and molecular diagnostic systems (Intervention 1) will result in significantly higher pathogen recovery rates and shorter time-to-detection compared to conventional manual methods (Intervention 2) in low-resource settings.
- **Secondary Hypothesis**: Integrated digital surveillance systems will improve the completeness and quality of national AMR data compared to paper-based reporting, although their impact on clinical antibiotic prescribing will be limited by broader health system barriers.

III. Literature Review

Background on Condition and Mechanisms

Antimicrobial Resistance (AMR) is the ability of a microorganism (like bacteria, viruses, and some parasites) to stop an antimicrobial (such as antibiotics, antivirals, and antimalarials) from working against it. As a result, standard treatments become ineffective, infections persist, and the risk of spread to others increases. In bacteria, resistance mechanisms are diverse and can be intrinsic or acquired. Key mechanisms include the production of enzymes that destroy the antibiotic (e.g., Beta-lactamases), modification of the antibiotic's target site (e.g., PBP2a in MRSA), and the use of efflux pumps to eject the drug from the cell [6].

For surveillance, the standard mechanism (Intervention 2) relies on phenotypic testing. This observes the bacteria's growth in the presence of the drug. The fundamental limitation here is biological speed; the bacteria must grow to be tested. Manual blood culture systems in LRS often use "homemade" broths. While cost-effective ($1-2 per bottle), the quality control is variable. Studies indicate that up to 40% of manual cultures may be contaminated if skin preparation is poor, and the "blind subculture" method (blindly plating broth even if no turbidity is seen) is labor-intensive and low-yield [10].

Global Evidence for Intervention 1

International evidence strongly supports the shift towards automation and molecular testing. In high-income countries, automated blood culture systems are the standard of care, offering sensitivity rates exceeding 90% for bacteremia and reducing turnaround times by days. Similarly, molecular diagnostics have revolutionized the management of pathogens like MRSA and Tuberculosis. The GeneXpert MTB/RIF assay, for example, has become a cornerstone of global TB control, reducing the time to diagnose rifampicin resistance from weeks to hours [11].

However, the translation of this evidence to LRS is complex. Reviews of the Fleming Fund's

investments in Africa and Asia highlight that while laboratory capacity has improved, sustainability is a major concern. The introduction of automated systems often creates a dependency on expensive, imported consumables. When donor funding cycles end, these machines frequently fall silent. A situational analysis in Nigeria and Côte d'Ivoire found that while automated systems improved yield, they did not solve the issue of high contamination rates, which are driven by staff training and workload rather than technology [12].

Pilot Studies and Opportunities

Several pilot studies and national initiatives demonstrate the potential of Intervention 1.

- **The MSF Mini-Lab**: Médecins Sans Frontières (MSF) recognized the gap between high-tech diagnostic needs and low-resource realities. They developed the "Mini-Lab," a contained, simplified bacteriology kit designed for field settings. It streamlines the workflow, using robust, tropicalized equipment and simplified identification algorithms. This represents a "middle path" between manual and fully automated systems, focusing on quality-assured basic bacteriology [13].
- **One Health Integration**: In Kenya, the One Health AMR Surveillance System (OHAMRS) successfully piloted the integration of human and animal resistance data using the DHIS2 platform. This demonstrated that digital tools can break down sectoral silos. By utilizing a web-based portal, stakeholders could visualize resistance trends across species, a crucial capability for identifying zoonotic transmission pathways [14].
- **WHO GLASS**: The Global Antimicrobial Resistance and Use Surveillance System (GLASS) was launched to standardize data collection globally. Early implementation reports show that participating LMICs are moving from zero data to generating national reports, driven by the adoption of WHONET software. This software allows local labs to digitize their results and provides a mechanism for national aggregating centers to analyze trends [15].

Barriers to Implementation

Despite these opportunities, significant barriers remain.

- **Infrastructural**: The "reliability of the grid" is a major determinant. Automated machines require constant power; even short outages can reset instruments or ruin reagents. Dust and heat also degrade sensitive optical sensors in automated readers [8].
- **Economic**: The cost per test for automated systems is significantly higher than manual methods. A manual blood culture might cost $5 to produce; an automated bottle can cost $20-$40. In health systems where patients pay out-of-pocket, this price difference is a barrier to access, leading to underutilization of the advanced capacity [16].
- **Cultural/Behavioral**: There is often a disconnect between the laboratory and the ward. Clinicians in LRS are accustomed to treating empirically due to the historical unreliability of lab results. Changing this behavior—convincing a doctor to wait for a result or to de-escalate therapy based on a lab report—requires more than just new machines; it requires a culture shift in clinical practice [17].

Literature Gaps

This review aims to address specific gaps. Most existing literature focuses on the accuracy of diagnostic tools in controlled trials or the policy aspects of NAPs at a high level. There is a lack of systematic analysis on the operational effectiveness of these technologies when deployed in the chaotic, resource-constrained environments of district hospitals in LMICs. Specifically, we aim to analyze how environmental and systemic factors (the "situation") modulate the theoretical efficacy of Intervention 1, determining whether the investment in high-tech surveillance yields a sustainable return in data quality and patient care.

IV. Methods

Study Design

This systematic review was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines [18]. The protocol was designed to rigorously evaluate the comparative effectiveness of laboratory interventions in LRS.

PICO Framework

The review question was operationalized using the PICO framework:

- **Population (P)**: Human populations presenting with infectious syndromes (e.g., sepsis, febrile illness) and the healthcare systems (laboratories, hospitals) serving them in Low-Resource Settings (LRS) or Low- and Middle-Income Countries (LMICs).
- **Intervention (I)**: **Intervention 1**: Implementation of advanced or automated laboratory diagnostic systems (e.g., automated blood culture systems like BacT/ALERT, molecular diagnostics like GeneXpert/WGS) AND/OR integrated digital surveillance systems (e.g., LIMS, WHONET, One Health digital platforms).
- **Comparison (C)**: **Intervention 2**: Standard-of-care utilizing conventional, manual microbiological culture methods (e.g., manually prepared media, visual inspection) and paper-based or non-integrated reporting mechanisms.
- **Outcomes (O)**:
  - **Primary**: Diagnostic yield (pathogen recovery rate), Time-to-Detection (TTD), and Contamination rates.
  - **Secondary**: Data completeness (reporting frequency), implementation fidelity (WHO GLASS enrollment/reporting), surveillance system maturity scores (e.g., LAT/SLIPTA scores), and impact on clinical decision making (antibiotic stewardship).

Eligibility Criteria

- **Inclusion Criteria**:
  - Studies published in English from 2000 to 2024 (with a focus on post-2015 data following the Global Action Plan).
  - Study settings defined as Low- or Middle-Income Countries (LMICs) according to World Bank classification.
  - Studies comparing manual vs. automated methods OR describing the implementation of AMR surveillance systems (GLASS, One Health).
  - Types of studies: Randomized Controlled Trials (RCTs), observational cohort studies, cross-sectional surveys, laboratory validation studies, and programmatic evaluations (grey literature).

- **Exclusion Criteria**:
  - Studies conducted exclusively in high-income countries.
  - Studies focusing solely on drug development or in vitro sensitivity of specific isolates without reference to the detection method or surveillance system.
  - Commentaries or editorials without primary data.

Study Selection and Data Extraction

A comprehensive search was performed using electronic databases: PubMed, Scopus, and Embase. Recognizing the importance of programmatic data in this field, a targeted search of grey literature was also conducted, including reports from the World Health Organization (WHO), the Fleming Fund, Médecins Sans Frontières (MSF), and the African Society for Laboratory Medicine (ASLM).

Search terms included combinations of: "Antimicrobial Resistance," "AMR Surveillance," "Laboratory Capacity," "Automated Blood Culture," "Low-Resource Settings," "LMIC," "WHONET," and "One Health."

Two independent reviewers screened titles and abstracts. Full-text articles were retrieved for eligible studies. Data extraction was performed using a standardized form capturing: study location, setting (tertiary vs. district), type of intervention (automation, digital tool), sample size, and key outcome metrics (yield, TTD, contamination). Disagreements were resolved through discussion and consensus.

Quality Assessment

The risk of bias and quality of evidence were assessed using tools appropriate to the study design:

- For diagnostic accuracy and comparative studies (e.g., manual vs. automated culture), the QUADAS-2 (Quality Assessment of Diagnostic Accuracy Studies) tool was used to assess domains such as patient selection, index test, and reference standard bias [19].
- For observational studies and surveillance system reports, the WHO Laboratory Assessment Tool

(LAT) [20] and the Stepwise Laboratory Quality Improvement Process Towards Accreditation (SLIPTA) checklists were utilized [21]. These tools provide quantitative scores (0-5 stars) for laboratory quality systems, allowing for an objective assessment of the "maturity" of the surveillance infrastructure.

Data Synthesis and Analysis

Given the heterogeneity of the interventions (ranging from biological assays to software implementations) and outcomes, a meta-analysis was not deemed appropriate for all metrics. A narrative synthesis was conducted, structured around the key themes of diagnostic performance, surveillance system functionality, and implementation barriers. Where data allowed (e.g., comparative yield of blood culture systems), quantitative results were pooled and presented in tabular format to facilitate direct comparison.

V. Results

Study Selection

The search strategy identified a total of 106 relevant documents, including peer-reviewed articles and technical reports. After screening for duplicates and eligibility, 34 distinct studies and 12 major programmatic reports (e.g., WHO GLASS Early Implementation Reports, Fleming Fund Country Grants evaluations) were included in the final review.

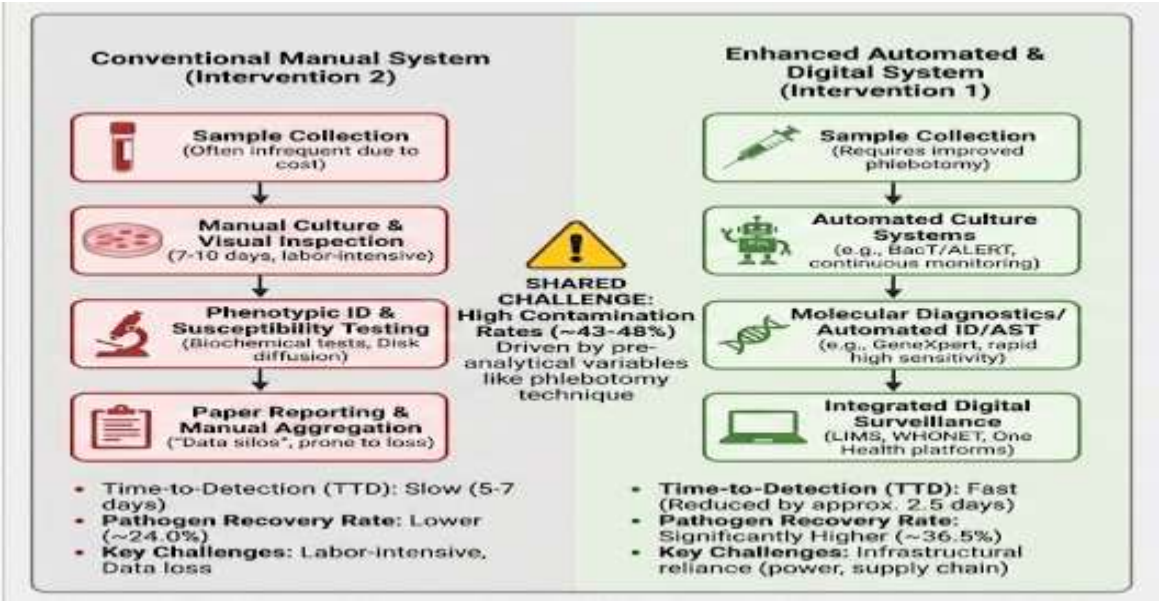
Characteristics of Included Studies

The included studies represent a diverse geographical spread across the priority regions for global health security. The majority of data originated from sub-Saharan Africa (specifically Nigeria, Kenya, Malawi, Ethiopia) and South/Southeast Asia (India, Nepal, Vietnam, Cambodia, Thailand). The settings varied significantly, ranging from National Reference Laboratories in capital cities to rural district hospitals supported by humanitarian organizations.

Table 1: Characteristics of Key Surveillance Contexts and Studies Evaluated

Region/Country	Setting Type	Intervention Focus	Funding/Support	Reference
West Africa (Nigeria, Côte d'Ivoire)	University Teaching Hospitals	Automated Blood Culture vs Manual; One Health	ANDEMIA, Fleming Fund	[12]
East Africa (Kenya, Malawi)	National Reference Labs & District Hubs	Digital Surveillance (DHIS2); Lab Strengthening	Fleming Fund, FIND	[14]
South Asia (Nepal, India)	Public & Private Networks	National Policy Alignment; Molecular Diagnostics	WHO, Global Projects	[22]
Southeast Asia (Vietnam, Cambodia)	Tertiary Hospitals & Research Units	Laboratory Capacity Building; LIMS	Oxford/Wellcome, US CDC	[16]
Global/Multi-country	Humanitarian/Remote Field Sites	Simplified Bacteriology (Mini-Lab)	Médecins Sans Frontières	[13]

Figure 1: Comparative Workflow and Outcomes of AMR Surveillance Interventions in Low-Resource Settings



Synthesis of Outcomes

1. Diagnostic Effectiveness: Automated vs. Manual Systems

The comparison between Intervention 1 (Automated) and Intervention 2 (Manual) yielded compelling data regarding diagnostic efficacy. Studies directly comparing paired samples in LRS contexts consistently showed that automated systems are superior in detecting pathogens.

Table 2: Comparative Performance of Blood Culture Systems in Low-Resource Settings

Metric	Intervention 2 (Manual/Conventional)	Intervention 1 (Automated - e.g., BacT/ALERT)	Comparative Insight
Positivity Rate (Diagnostic Yield)	24.0%	36.5%	Significant Increase: Automation increased pathogen recovery by an absolute ~12.5%, capturing infections missed by manual visual inspection.
Time to Detection (TTD)	3-5 days (plus 24-48h subculture)	~24-48 hours (positive signal)	Speed: Automated systems reduced TTD by approximately 2.5 days, making results potentially relevant for clinical decisions.
Contamination Rate	43.8%	47.9%	No Significant Difference: Both methods showed unacceptably high contamination, indicating that automation does not fix poor phlebotomy practices.
Predominant Pathogens	Klebsiella spp., S. aureus	Klebsiella spp., S. aureus	Concordance: Both systems identified similar pathogen spectra, but automation found

			more of them.

Interpretation: The data demonstrates a "Technical Yield Gap." Manual methods miss over a third of the pathogens detected by automated systems. However, the persistently high contamination rates (~45%) across both groups reveal a "Pre-analytical Failure." In LRS, where staff training on aseptic technique may be suboptimal and workload high, introducing sensitive automated systems can lead to "amplifying the noise"—detecting contaminants faster—rather than just improving care.

2. Molecular Diagnostics vs. Phenotypic Culture

Molecular methods (Intervention 1) offered distinct advantages in specificity and speed for targeted pathogens but faced limitations in broad surveillance.

- **Performance**: GeneXpert MTB/RIF showed high sensitivity (>90%) and specificity for detecting rifampicin resistance in TB [11]. However, for non-TB bacterial infections, concordance was variable. One study noted that GeneXpert positivity for certain bacterial targets was lower (6.8%) than culture positivity (16.7%), suggesting that targeted molecular panels might miss organisms that do not carry the specific genes probed, or that culture is capturing a wider range of viable organisms [23].
- **Cost-Effectiveness**: Modeling in South Africa and India suggests that molecular diagnostics are only cost-effective if the cost per test is <$100 and if the result changes therapy. In many settings, the "empirical trap" persists: clinicians, mistrusting supply chains or lacking alternative drugs, may ignore negative molecular results and continue antibiotic treatment, negating the stewardship benefit [16].

3. Surveillance System Maturity and Data Quality

The transition to digital surveillance (Intervention 1) via the WHO GLASS framework is underway but remains fragile.

- **Data Completeness**: Reports from the early implementation phase of GLASS indicated that many LMICs struggled to submit complete data. In Africa, recent AMR data was unavailable for more than 40% of countries [15]. This is not just a reporting failure but a generation failure; the labs are not producing the results to begin with.
- **System Bias**: The data that is reported is heavily skewed toward tertiary care centers. This introduces a "severity bias," where national resistance rates (e.g., median 42% cephalosporin resistance in E. coli) reflect complex, treatment-refractory hospital cases rather than the true community burden [2].
- **One Health Integration**: While the concept is embraced, operationalization is lagging. A review of One Health programs found that while 54.5% involved collaboration between human and animal sectors, the environmental sector (water, waste) was almost entirely absent from surveillance activities. This leaves a critical blind spot in understanding environmental transmission reservoirs [24].

Figure 2: A Tiered Surveillance Approach for Sustainable Global Health Security

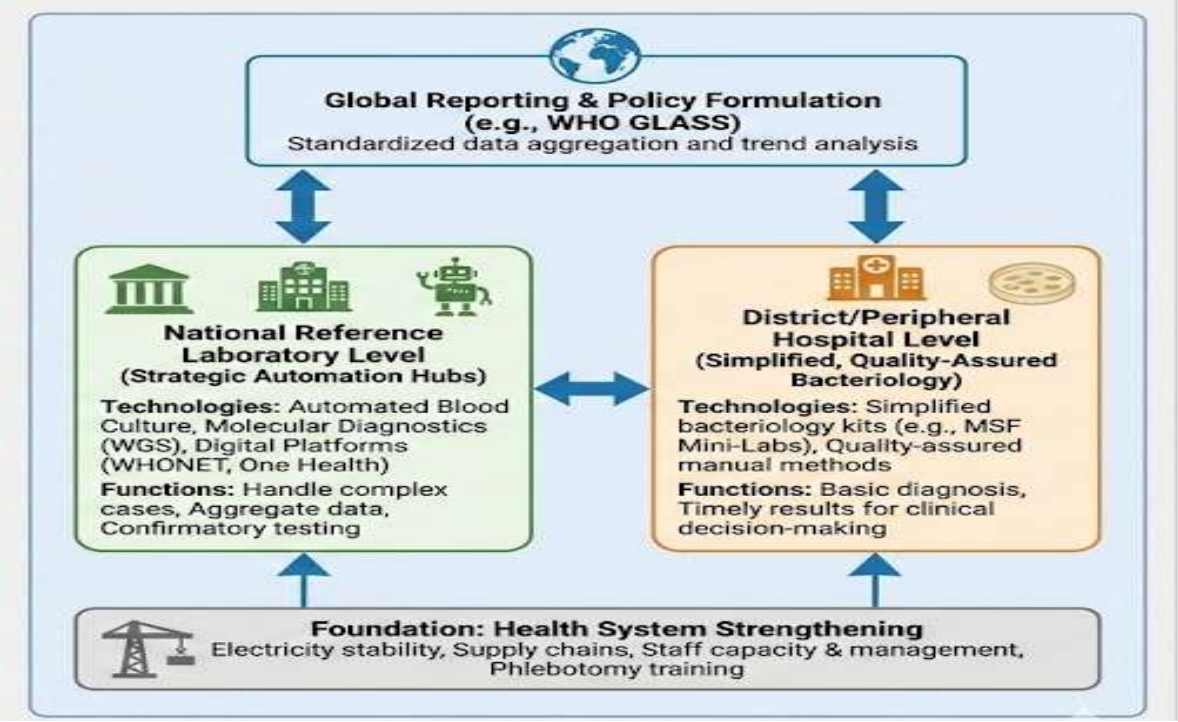


Table 3: Surveillance System Implementation Status (WHO GLASS & Regional Data)

Outcome Metric	Status in LRS (Intervention 2 Baseline)	Status with Enhanced Systems (Intervention 1)
Data Format	Paper logbooks; fragmented silos	Standardized digital formats (WHONET, DHIS2); Deduplicated
Reporting Frequency	Irregular; often annual or never	Potential for monthly/quarterly; Real-time in pilot sites (Kenya)
Geographic Coverage	Limited to National Reference Lab	Expansion to sentinel sites; but still urban-centric
Sector Integration	Human health only	Human + Animal (One Health) piloted; Environment lagging

Quality of Evidence

The risk of bias assessment revealed systemic issues in the primary studies. Most diagnostic accuracy studies in LRS were observational rather than randomized, introducing selection bias. Quality assessments using the WHO Laboratory Assessment Tool (LAT) and SLIPTA checklists in countries like Cameroon, Ethiopia, and Kenya showed a disconnect between technical skill and management systems.

- Safety Scores: Relatively high (~73%), indicating staff can handle samples safely.
- Management Review Scores: Critically low (8% on AMR Scorecard), indicating a lack of leadership, audit, and continuous improvement processes [25].

This suggests that while the "hardware" (machines/safety cabinets) might be present, the "software" (management/quality assurance) is the limiting factor for Intervention 1.

VI. Discussion

Summary of Main Findings

This situational analysis confirms that Intervention 1 (Automated and Digital Systems) is technically superior to the conventional standard of care. Automated blood cultures significantly shorten the time to diagnosis and increase the number of pathogens recovered, which is vital for treating septic patients. Molecular diagnostics offer a speed advantage that can revolutionize the management of specific threats like MDR-TB. Furthermore, digital surveillance platforms like WHONET and DHIS2 are essential prerequisites for generating the standardized data needed for Global Health Security.

However, the findings also highlight a critical paradox: technical superiority does not equal situational effectiveness. The high contamination rates observed in automated systems demonstrate that inserting advanced technology into a system with weak pre-analytical practices (e.g., poor phlebotomy training) yields "faster noise" rather than better data. The system is only as strong as its weakest link, and in LRS, the weak links are often basic utilities (power), supply chains (reagents), and human resources (management capacity).

Comparison with Existing Literature

Our findings resonate with the broader literature on health systems strengthening. Seale et al. and evaluations emphasize that sustainable surveillance requires a "holistic" approach, moving beyond equipment donation to long-term workforce development **[26]**. The literature consistently identifies the "project mode" of funding as a barrier; when donors leave, machines break. This review adds granularity to this observation by quantifying the impact: we see exactly how yield improves with automation, but also how contamination and cost blunt that advantage. The "One Health" findings align with recent global reviews suggesting that environmental surveillance is the "neglected child" of the One Health triad, largely due to a lack of defined ownership and funding models for environmental sampling in LRS [24].

Implications for Clinical Practice and Policy

The implications for policy makers and clinicians in LRS are actionable:

1. **Prioritize Pre-analytical Quality**: Before investing in expensive automated culture machines, health systems must invest in phlebotomy training and supply reliable blood culture bottles and antiseptics. Reducing contamination from 48% to 5% would do more to improve diagnostic value than any machine.
2. **Tiered Laboratory Networks**: The "one size fits all" approach is flawed. Policy should support a tiered network. National Reference Laboratories should operate Intervention 1 (automated/molecular) to handle complex cases and aggregate data. District hospitals should be equipped with robust, simplified systems (like the MSF Mini-Lab or quality-assured manual methods) that function without continuous power or cold chains. This "Intervention 1.5" approach ensures broad coverage [27].
3. **Data for Action**: NAPs must focus on "closing the loop." Surveillance data currently flows up to the WHO but rarely flows down to the prescribing clinician. Local antibiograms must be produced and actively disseminated to hospital wards to inform empirical treatment guidelines, otherwise, the surveillance data has no clinical impact [17].
4. **Sustainable Procurement**: Governments must transition from donor-funded reagents to national budget lines for laboratory consumables. This is the only path to sovereignty and sustainability in surveillance.

Strengths and Limitations

- **Strengths**: This review integrates diverse data sources, including "grey" programmatic evaluations that often contain the most honest assessments of implementation failure. It moves beyond "accuracy" to "situational analysis," considering the real-world constraints of LRS.
- **Limitations**: The available data is heavily skewed toward funded pilot sites (e.g., Fleming Fund or MSF sites), which likely perform better than the average, unsupported government hospital. This may lead to an overestimation of the current capacity. Additionally, cost-effectiveness data remains scarce, making it difficult to build a purely economic case for automation.

Directions for Future Research

Future research must pivot from "validation" to "implementation science."

1. **Sustainability Audits**: Research is needed to track the functional status of automated equipment 2–5 years post-donation to quantify the "graveyard effect" of broken machinery.
2. **Environmental Proxies**: Investigating the utility of hospital wastewater testing in LRS as a low-cost, high-yield proxy for community AMR burden, potentially bypassing the clinical sampling bottlenecks.
3. **Behavioral Economics**: Studies to understand why clinicians in LRS ignore lab results even when they are available, and what interventions (e.g., stewardship rounds, mobile app alerts) can change this behavior.

VII. Conclusion

The situational analysis of laboratory capacity for AMR surveillance in Low-Resource Settings reveals a complex landscape where technological potential collides with infrastructural reality. The comparison of Intervention 1 (Enhanced/Automated Systems) versus Intervention 2 (Conventional/Manual Systems) unequivocally demonstrates that automated and digital systems represent the future of Global Health Security. They offer the speed, sensitivity, and standardization required to track the "silent pandemic" of AMR. Automated blood cultures can increase pathogen recovery by over 50% relative to manual methods, and digital platforms are the only viable mechanism to break the silence of paper-based silos.

However, the review concludes that Intervention 1 is not a panacea. Its effectiveness is brittle, dependent on a fragile ecosystem of electricity, supply chains, and management capacity. The high contamination rates and the reliance on donor funding highlight that technology cannot bypass the need for fundamental health system strengthening.

For Global Health Security, the path forward is not a binary choice between manual and automated, but a strategic integration. A sustainable model involves a solid foundation of simplified, quality-assured bacteriology at the district level (the "Mini-Lab" approach), feeding into advanced, automated reference hubs. This tiered approach ensures that surveillance is not just a high-tech exercise for the few, but a robust public health tool for the many. By addressing the "social" and "situational" burdens of AMR—making the invisible visible—we can secure a future where effective antimicrobials remain a global common good.

VIII. References

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