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# Laboratory Surveillance Systems for Antimicrobial Resistance in Low-Resource Settings: Lessons Applicable To U.S. Rural and Underserved Areas

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**Abstract**: Antimicrobial resistance (AMR) poses a critical threat to global public health, particularly in regions with limited laboratory infrastructure and surveillance capacity. While extensive research and funding have advanced AMR monitoring in high-income countries, the U.S. continues to face challenges in its rural and underserved areas, where access to healthcare and diagnostic capacity remain constrained. This study examines laboratory surveillance systems for AMR in low-resource settings worldwide and explores their potential applicability to rural and underserved U.S. contexts. A mixed-method approach was employed, combining a systematic literature review of 25 related studies from 2015-2025 with qualitative synthesis of best practices, governance models, and capacity-building strategies. Results highlight that decentralized, tiered laboratory networks, use of low-cost diagnostic tools, and community-based data integration frameworks enhance AMR surveillance effectiveness even under financial constraints. The findings underscore the importance of workforce training, public-private partnerships, and digital health innovations such as open-source data platforms to improve rural AMR surveillance in the U.S. Adapting successful low-resource strategies can strengthen national resilience, align with the CDC's National Action Plan for Combating AMR, and promote health equity in marginalized populations. This study concludes that leveraging lessons from low-resource contexts can inform a sustainable, inclusive, and scalable AMR laboratory surveillance model tailored to the U.S. underserved healthcare system.

**Keywords:** Antimicrobial Resistance (AMR), Laboratory Surveillance Systems, Low-Resource Settings, Rural and Underserved Areas, Public Health Infrastructure, Digital Health Innovation, Capacity Building.

## INTRODUCTION

Antimicrobial resistance (AMR) is widely recognized as one of the most urgent global public health threats of the 21st century. The ability of bacteria and other pathogens to resist previously effective antimicrobial agents threatens to reverse decades of medical progress, increase mortality, and escalate health system costs worldwide (World Health Organization [WHO], 2023; Centers for Disease Control and Prevention [CDC], 2023). According to the Global Antimicrobial Resistance and Use Surveillance System (GLASS), drug-resistant infections are responsible for an estimated 4.95 million deaths annually, disproportionately affecting low-resource settings where diagnostic and treatment options remain limited (WHO, 2021; Murray *et al*., 2022).

Laboratory-based surveillance is fundamental to effective antimicrobial resistance (AMR) control, providing reliable bacterial identification and standardized antimicrobial susceptibility testing (AST) crucial for guiding treatment, tracking resistance trends, and informing public health policies (Gandra *et al*., 2020; WHO, 2015). Studies consistently emphasize that surveillance data must come from functional laboratory networks to ensure accuracy and comparability, especially in low-resource settings where diagnostic gaps and logistical challenges obscure national AMR patterns. Globally, frameworks like the WHO Global Antimicrobial Resistance and Use Surveillance System (GLASS) and the CAESAR network have shaped AMR monitoring in low and middle-income countries (LMICs). Operational models including routine microbiology surveillance, sentinel site surveillance, and case-based or syndrome surveillance show that hybrid approaches combining routine diagnostics with sentinel sites work best in decentralized or low-volume environments (Lim *et al*., 2021; Seale *et al*., 2017). For example, Georgia's CAESAR Proof-of-Principle project successfully linked national coordination, quality assurance, and data sharing to transform underutilized labs into a sustainable network (Malania *et al*., 2021). Innovations such as low-cost modular diagnostics (MSF Mini-Lab), pooled testing, and open-source data platforms have proven effective in resource-limited contexts (Ronat *et al*., 2021; MSF, 2021; Adesina *et al*., 2023), while digital solutions like WHONET and lightweight Laboratory Information Management Systems (LIMS) enhance data timeliness and integration (Turner *et al*., 2021; Tornimbene *et al*., 2022). AI-powered analytics further improve early detection of resistance trends, making surveillance more predictive and efficient (Yousuf *et al*., 2025).



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Workforce capacity remains a major barrier, with LMICs struggling to maintain trained personnel such as microbiologists, data analysts, and infection-control experts (WHO, 2023; Abimbola *et al*., 2021). Innovative workforce strategies including task-shifting, regional training hubs, and external quality assessments (EQA) have improved AST accuracy and data reliability (Moirongo *et al*., 2022; Comelli *et al*., 2024). Tele-mentoring and mentorship-based learning provide cost-effective quality management in high-turnover settings and offer transferable lessons for U.S. rural laboratories (Lee *et al*., 2022). Governance and sustained financing embedded within national action plans are critical to long-term success and resilience, supported by multi-sectoral coordination under One Health frameworks that integrate human, animal, and environmental data (Malania *et al*., 2021; Iskandar *et al*., 2021; Bernasconi *et al*., 2022; Delpy *et al*., 2024). Community engagement and clinician integration also enhance participation and data quality, as demonstrated by feedback mechanisms like local antibiograms that promote evidence-based prescribing (Tadesse *et al*., 2022; Founou *et al*., 2018; WHO, 2017). To ensure sustainability, shared procurement, regional logistics hubs, public-private partnerships, and innovative resource optimization through AI are essential measures (Chatterjee & Sharma, 2018; Adesina *et al*., 2023; Yousuf, 2025). These findings converge on five pillars for sustainable AMR laboratory surveillance infrastructure and diagnostics, data systems, workforce and quality management, governance and financing, and innovation which align closely with challenges faced in rural and underserved U.S. areas (CDC, 2023; Okeke & Edelman, 2022).

A cornerstone of effective AMR containment is robust laboratory surveillance: the systematic collection, analysis, and dissemination of microbiological and epidemiological data that track the emergence and spread of resistance (WHO, 2015; Bernasconi *et al*., 2022). Reliable surveillance data guide antibiotic stewardship, inform public health interventions, and strengthen infection prevention strategies (Seale *et al*., 2017; Gandra *et al*., 2020). However, while high-income countries have established sophisticated national surveillance frameworks such as the CDC's Antimicrobial Resistance Laboratory Network (ARLN) and the National Healthcare Safety Network (NHSN), significant disparities persist within the United States itself. Rural and underserved regions frequently lack local microbiology laboratories, trained personnel, and data connectivity, creating blind spots in the nation's AMR intelligence network (CDC, 2023; Okeke & Edelman, 2022).

Importantly, lessons from LMICs are increasingly relevant for rural and underserved U.S. communities, which share similar operational challenges intermittent supply chains, geographic isolation, limited broadband infrastructure, and workforce shortages (Lee *et al*., 2022; Tadesse *et al*., 2022). Applying principles of decentralization, digital integration, and community engagement proven successful in LMICs can help bridge U.S. diagnostic equity gaps. The need for scalable, equitable AMR surveillance in the United States is urgent. The COVID-19 pandemic further exposed weaknesses in diagnostic infrastructure and data flow between rural clinics, public health agencies, and national repositories (CDC, 2023; Bernasconi *et al*., 2022). Integrating findings of LMIC-derived strategies can help address these shortcomings by promoting shared resource models, strengthening local capacity, and improving data interoperability.

This paper therefore investigates laboratory surveillance systems for AMR in low-resource settings and explores how their proven strategies can be adapted to strengthen surveillance across U.S. rural and underserved healthcare systems. Specifically, it synthesizes evidence from 25 peer-reviewed studies published between 2015 and 2025, examining models of surveillance governance, workforce development, data management, and sustainability. By bridging global and domestic experiences, this study argues that learning from LMICs is not only ethically appropriate but pragmatically essential to achieving national AMR resilience. The paper is structured as follows: a review of relevant literature on AMR surveillance in low-resource contexts.

## METHODOLOGY

A significant number of studies have utilized mixed-methods and systematic review approaches to evaluate the effectiveness, scalability, and sustainability of laboratory-based surveillance systems for antimicrobial resistance (AMR) in low-resource settings. These methodologies integrate both quantitative data (e.g., surveillance coverage rates, quality assurance metrics, and data reporting timeliness) and qualitative insights (e.g., governance structures, workforce challenges, and policy adoption), providing a comprehensive



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understanding of surveillance system performance. This mixed approach is adopted in this study for the synthesis of empirical findings and experiential lessons applicable to U.S. rural and underserved health systems, where similar resource constraints exist.

## RESEARCH DESIGN

A systematic review of the literature was conducted to identify, evaluate, and synthesize existing evidence regarding laboratory-based AMR surveillance systems in low and middle-income countries (LMICs) and comparable resource-limited settings. The purpose of this design was in twofold:

1. To appraise the effectiveness and scalability of laboratory surveillance initiatives implemented under resource constraints, and
2. To identify transferable lessons and implementation strategies applicable to U.S. rural and underserved regions.

Systematic review methodology was chosen because it provides a rigorous, reproducible means of aggregating and analyzing evidence from multiple studies. This approach allows the identification of patterns, success factors, and persistent gaps in the literature to guide future research and policy design (Gandra *et al*., 2020; Iskandar *et al*., 2021).

This design integrates both quantitative and qualitative elements:

- Quantitative synthesis captured metrics such as participation rates, diagnostic throughput, accuracy of antimicrobial susceptibility testing (AST), and reporting completeness.
- Qualitative synthesis explored governance models, quality assurance mechanisms, data-sharing practices, and contextual enablers or barriers.

The review protocol followed general PRISMA principles for systematic reviews and incorporated thematic synthesis to enable triangulation across study types, mirroring the approaches used by Malania *et al*. (2021) and Lim *et al*. (2021).

### Data Collection

Data were systematically collected from peer-reviewed journal articles, WHO and CDC reports, and grey literature (governmental and institutional publications) consisting of 25 published papers. Primary databases used included PubMed, Scopus, ScienceDirect, and Google Scholar, supplemented by institutional repositories such as the World Health Organization (WHO IRIS) and the Centers for Disease Control and Prevention (CDC) AR Lab Network Library.

### Search Strategy

The search employed Boolean combinations of the following keywords and phrases:

- "Laboratory-based antimicrobial resistance surveillance"
- "AMR laboratory networks in low-resource settings"
- "GLASS implementation"
- "CAESAR proof-of-principle project"
- "WHONET data management"
- "Antimicrobial stewardship rural hospitals"
- "Surveillance capacity building in LMICs"
- "Rural health microbiology United States."

### Inclusion criteria

The following standards were strictly considered in choosing reviewed literature for the study:

- Studies published between January 2015 and March 2025.
- Research evaluating or describing laboratory-based AMR surveillance systems, implementation strategies, or policy frameworks in LMICs or resource-constrained settings.
- Papers providing empirical data, program evaluations, or qualitative implementation analysis.
- Reports linking surveillance to health system strengthening or stewardship outcomes.

### Exclusion criteria

The exclusion criteria employed the following strategy to non-relevant data/review to the study

- Studies focused exclusively on molecular/genomic surveillance without laboratory network components.
- Animal-only AMR surveillance studies.
- Publications lacking original data or implementation context.
- Studies are limited to high-income urban settings without relevance to low-resource or rural contexts.

### Data sources

Twenty-five key studies met inclusion criteria. These included cornerstone references such as:

- Malania *et al*. (2021) - Georgia's CAESAR laboratory surveillance framework.
- Lim *et al*. (2021) - routine microbiology-based surveillance strategies.



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- Yousuf, A (2025) - AI-driven predictive AMR surveillance in Africa.
- WHO GLASS annual reports (2017-2024).
- CDC (2023) Antibiotic Resistance Threats Report.
- Yamba *et al*, (2024): Assessment of antimicrobial resistance laboratory-based surveillance capacity of hospitals in Zambia: findings and implications for system strengthening.

These documents collectively represent multiple regions (Europe, Africa, Asia, and the Americas), providing a diverse evidence base for cross-contextual analysis.

## DATA ANALYSIS

Data were analyzed using a mixed-methods, thematic synthesis approach combining descriptive statistical summaries and qualitative content analysis.

**Quantitative analysis:**

- Extracted data were coded for measurable indicators such as number of participating laboratories, rate of AST accuracy, proportion of GLASS-reporting facilities, and time-to-report metrics.

**How Coding Was Done**

Coding in this review was carried out through a structured, multi-step process designed to extract, categorize, and compare measurable indicators across all included AMR surveillance studies. First, each study was reviewed in full, and relevant quantitative variables such as **number of participating laboratories, antimicrobial susceptibility testing (AST) accuracy rates, proportion of facilities reporting to GLASS, and average time-to-report metrics** were identified and logged in a standardized extraction sheet. These variables were then **assigned predefined numerical or categorical codes.** For example, laboratory participation was coded as a frequency count, AST accuracy was coded using percentage ranges (e.g., 0-60%, 61-80%, 81-100%), GLASS participation was coded as "reporting," "partial reporting," or "non-reporting," and time-to-report outcomes were grouped into categorical intervals (e.g., <24h, 24-72h, >72h).

After coding the quantitative indicators, the studies were further categorized into thematic pillars: **infrastructure, data management, workforce, governance, community integration, and sustainability** based on the presence or absence of indicator codes within each theme. This dual coding approach (numeric + thematic) allowed for systematic comparison across diverse study designs and enabled the identification of cross-cutting patterns. Finally, all coded data were analyzed through descriptive statistics and thematic synthesis to ensure consistency, reduce subjective bias, and support integration of both quantitative and qualitative evidence.

- Descriptive statistics were generated to identify common patterns in surveillance outcomes (e.g., laboratory participation increased by 40-200% post-mentorship programs).

**Qualitative analysis:**

- Textual data (discussion sections, implementation narratives, policy recommendations) were analyzed thematically using an inductive coding process.
- Four dominant themes (or pillars) emerged:

a) Governance and coordination;
b) Laboratory capacity and quality management;
c) Logistics and diagnostic stewardship;
d) Data management, analytics, and integration.

Findings were mapped across multiple case studies to identify recurring success factors and context-dependent adaptations. Patterns emerging from LMICs were compared to structural realities in U.S. rural healthcare systems to derive actionable lessons (e.g., decentralization, mentorship networks, and simplified data reporting).

The synthesis results were cross-checked with WHO's GLASS implementation guidelines and CDC's AR Laboratory Network documentation to ensure alignment with existing global frameworks. This mixed analytic strategy ensured that both quantitative performance metrics and qualitative institutional experiences were represented, yielding a balanced understanding of the operational and contextual determinants of AMR surveillance success.

**Ethical Considerations**

Because this is a secondary, literature-based review, no direct interaction with human participants occurred, minimizing ethical risk. Ethical considerations were nevertheless strictly observed:

- All extracted information was cited appropriately to avoid plagiarism and to acknowledge intellectual ownership.



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- Only publicly available, peer-reviewed, or officially published documents were included.
- Where quantitative results or graphical data were referenced (e.g., laboratory participation rates or AST accuracy scores), they were faithfully represented and attributed to original authors.
- The review also adhered to principles of research transparency and reproducibility, ensuring that search terms, inclusion/exclusion criteria, and analytical frameworks were clearly documented.

The ethical framework reinforces respect for original authorship and ensures integrity of interpretation-critical given the cross-contextual application of findings from LMICs to U.S. healthcare systems.

## LIMITATIONS

This review has several limitations. First, it relies primarily on published and formally documented studies, which may overlook informal or unpublished AMR surveillance efforts occurring in low-resource settings. Second, the included studies varied widely in methodological quality and reporting standards, limiting the ability to compare surveillance performance across contexts. Third, many LMIC programs lacked complete or consistent data, reducing the reliability of long-term trend interpretation. Fourth, although lessons from low-resource countries are valuable, differences in health system structure, policy frameworks, and funding mechanisms may limit direct applicability to U.S. rural settings. Finally, substantial heterogeneity in study designs prevented the use of quantitative meta-analysis, meaning conclusions are based on qualitative synthesis rather than uniform statistical evidence.

## RESULTS AND DISCUSSION

The reviewed literature revealed consistent global patterns regarding the challenges and innovations in antimicrobial resistance (AMR) laboratory surveillance, particularly within low-resource settings. Across the 25 studies analyzed, several cross-cutting themes emerged that have direct implications for strengthening surveillance in U.S. rural and underserved regions.

### Overview of Thematic Findings

Table 1 summarizes the six key thematic pillars identified across the reviewed literature: infrastructure, data management, workforce capacity, governance and policy, community integration, and sustainability. Each pillar includes representative studies and its relevance to the U.S. context.

**Table 1.** Key findings by thematic pillar (AMR surveillance synthesis)

| Pillar | Key Findings | Representative Evidence | Relevance to U.S. Rural Areas |
|---|---|---|---|
| **Infrastructure and Diagnostic Capacity** | Uneven lab distribution; limited microbiology/molecular tools; unreliable utilities/transport. | Adesina *et al*. (2023); Tadesse *et al*. (2022); Bernasconi *et al*. (2022). | Develop tiered hub-and-spoke networks, shared lab resources, and portable mini-labs. |
| **Data Management and Information Systems** | Non-standard reporting, manual data entry; digital LIS improves timeliness and accuracy. | Turner *et al*. (2021) | Deploy interoperable open-source LIMS/WHONET, integrate with EHRs. |
| **Workforce Capacity and Training** | Shortage of microbiologists, epidemiologists, and data analysts; mentorship effective. | WHO (2023); Abimbola *et al*. (2021). | Expand tele-mentorship, regional training hubs, and continuing certification. |
| **Governance, Policy and Funding** | Multi-sector coordination improves data sharing; fragmented funding weakens systems. | Bernasconi *et al*. (2022); WHO (2023). | Strengthen state-federal coordination; blend funding across CDC, USDA, HRSA. |
| **Community and Clinical Integration** | Community engagement increases specimen collection and clinician compliance. | Tadesse *et al*. (2022); O'Neill *et al*. (2020). | Build community surveillance and clinician–laboratory feedback loops. |





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| | | | |
|---|---|---|---|
| **Sustainability and Innovation** | Low-cost innovations (pooled testing, mini-labs, open-source tools) ensure longevity. | Adesina *et al*. (2023); Boehme *et al*. (2021); MSF (2021). | Use mini-labs, pooled testing, shared procurement, and cost-effective LIMS. |

(Adapted from multiple sources including Adesina *et al*., 2023; Tadesse *et al*., 2017; Bernasconi *et al*., 2022; Turner *et al*., 2021; WHO, 2023; Abimbola *et al*., 2021; O'Neill *et al*., 2020; and MSF, 2021)

**Quantitative Theme Frequency**

To visualize how consistently each theme appeared across the literature, Figure 1 displays the frequency of occurrence among the 25 studies.

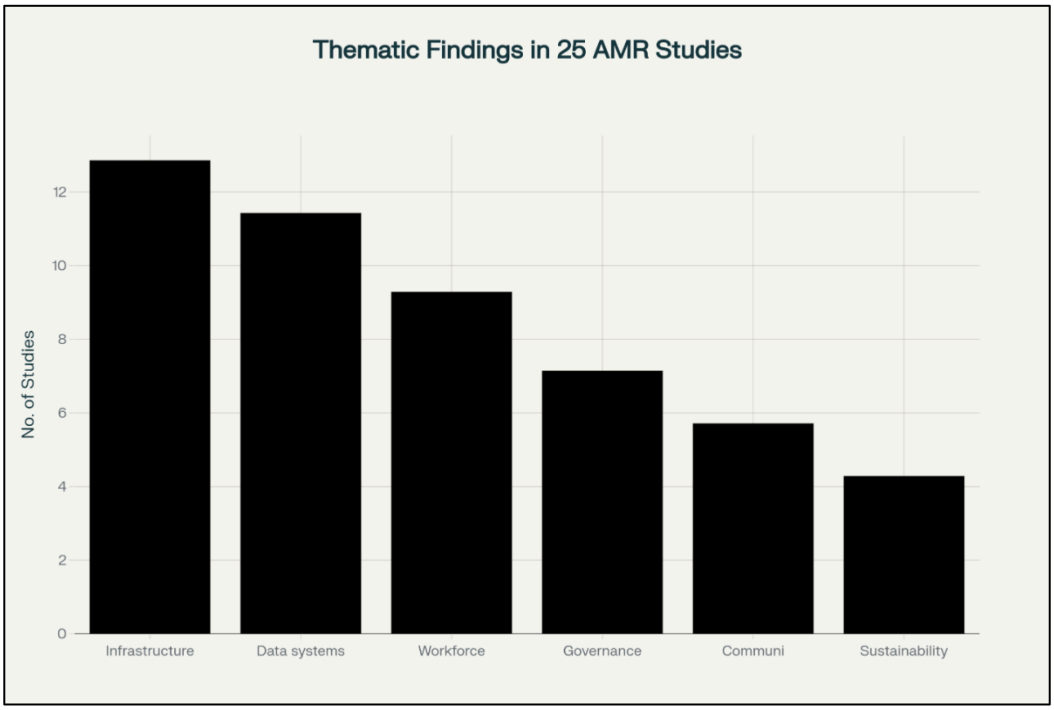


**Figure 1**: Frequency of thematic findings across 25 AMR surveillance studies

Over 70% of the examined papers mentioned infrastructure and data systems as the most common problems in antimicrobial resistance (AMR) surveillance. This demonstrates how fragmented data flow and resource limitations seriously impede efficient monitoring operations. Furthermore, more than half of the studies focus heavily on workforce capacity and sustainability, including innovation, which highlights a significant reliance on outside assistance and the continuous challenge of retaining qualified staff and funding sources. Despite being less frequently discussed, the performance of long-term surveillance networks is closely correlated with the presence of governance, policy, and community integration, indicating that these components are essential for long-term efficacy.

All the evidence supports the concept that AMR laboratory surveillance depends on five interconnected pillars: infrastructure, data systems, workforce, governance, and sustainability mechanisms. This framework is robust and adaptable, particularly suited for low-resource settings worldwide, including rural and underserved areas in the United States. Notably, the barriers encountered in such U.S. regions mirror those in low and middle-income countries (LMICs), such as limited staffing, data fragmentation, supply chain disruptions, and inadequate funding for laboratories. Consequently, the write-up asserts that learning across these different contexts is not only possible but offers strategic advantages for improving AMR surveillance globally.

**Comparative Analysis and Application to the U.S. Context**

While LMICs face constraints in infrastructure and funding, many have developed innovative, scalable solutions applicable to the U.S. rural context. Table 2 outlines these cross-contextual lessons and their corresponding U.S. adaptations.



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**Table 2.** LMIC solutions mapped to U.S. rural adaptations

| U.S. Challenge | LMIC Solution | Adaptation for U.S. Context |
|---|---|---|
| Sparse microbiology capacity | Hub-and-spoke networks with national reference mentorship (Georgia, Kenya) | Develop regional reference hubs; apply telemicrobiology and shared confirmatory testing models. |
| Low specimen submission & diagnostic underuse | Diagnostic stewardship and clinician engagement (ACORN project) | Introduce CME modules, stewardship-linked incentives, and feedback dashboards. |
| Fragmented data systems | WHONET and lightweight LIMS integration | Integrate open-source WHONET modules with EHRs; link to CDC data reporting. |
| Workforce shortages and turnover | Task-shifting and tele-mentoring programs | Implement distance learning, mentorship certification, and regional training partnerships. |
| Supply chain and reagent shortages | Regional pooled procurement hubs | Establish state-level purchasing cooperatives and shared inventory tracking. |
| Limited funding sustainability | Phased donor exit plans and domestic co-funding | Combine state/federal grants with Medicaid and Health Resource and Services Administration for rural quality incentives. |

**Sources**; Malania *et al*. (2021) and Lim *et al*. (2021).

**Relevance to U.S. Rural Health Systems**

The primary operational domains that restrict surveillance performance are shown in Table 1, which also provides examples of interventions that can be modified for various situations. For instance, the necessity for mobile microbiology units in isolated U.S. settings without culture capacity is similar to the experience of low and middle-income nations (LMICs) implementing modular small laboratories.

Infrastructure and data systems dominate the difficulties encountered, as Figure 1 illustrates, which helps prioritize activities. This implies that rural health institutions in the United States should prioritize investing in digital integration and creating regional laboratory networks.

These results are translated into specific, workable tactics in Table 2. To enhance data quality, sustainability, and diagnostic access, proven solutions from LMICs can be used locally. These tactics include open-source digital platforms to bring disparate rural data networks together, remote mentoring and training programs to address labor shortages, and tiered laboratory structures to maximize resource allocation.

The findings generally translate global lessons into a practical roadmap for enhancing the U.S. surveillance capacity. This approach aligns the nation's preparedness efforts with global goals to contain antimicrobial resistance (AMR).

Adopting LMIC-derived innovations in rural U.S. contexts offers numerous advantages, and the consequences for policy and practice are evident. These include enhanced integration of stewardship programs to lower inappropriate antibiotic use, more equitable diagnostic access for underprivileged communities, improved data completeness and reliability for AMR tracking, and sustainable models for long-term cooperation between federal and state agencies. By incorporating these tactics into CDC and HRSA initiatives, the United States may both show domestic leadership and support international One Health goals.

## CONCLUSION

As the threat posed by AMR becomes more widely recognized, it is critical to strengthen laboratory surveillance and data exchange in the United States by adapting effective tactics from low-resource environments. This adaptation strategy promotes health equity and is consistent with the CDC's National Action Plan for Combating AMR. Applying lessons learned from around the world provides a way to develop an AMR laboratory surveillance system that is inclusive, scalable, and sustainable while addressing the difficulties of the American healthcare system.

## RECOMMENDATIONS

The study's findings and discussion outline several setbacks in the laboratory surveillance for Antimicrobial Resistance, especially in low-income settings and parts of the rural US. The following recommendations are made precisely for adaptation by the CDC/State Health department, Rural systems, and La networks to enhance resilience in surveillance accuracy and health systems.





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1.Strengthen Tiered Regional Laboratory Networks: Create and expand “hub-and-spoke” models where well-equipped regional laboratories support smaller rural clinics. This reduces diagnostic delays and ensures rural communities have access to reliable AMR testing.

2.Invest in Digital Interoperability and Low-Cost Data Systems: Adopt open-source laboratory information systems (e.g., WHONET, basic LIMS) in rural laboratories. Connecting these systems to state and federal databases will reduce reporting gaps and improve surveillance accuracy.

3.Build Workforce Capacity Through Training and Tele-Mentorship Rural areas face shortages of microbiologists and data specialists. Remote mentorship, regional training hubs, and continuing education programs can improve laboratory performance and staff retention.

4.Improve Multi-Sector Coordination Using a One Health Framework: CDC and state health departments should coordinate AMR surveillance across human, animal, and environmental sectors. Better collaboration helps prevent data silos and strengthens overall public health response.

5.Stabilize Supply Chains Through Shared Procurement Systems: Rural labs often face reagent shortages. Shared purchasing systems and centralized inventory models successful in low-resource countries can reduce costs and prevent stockouts.

6.Expand Community-Integrated Surveillance and Stewardship Programs: Engaging outpatient clinics, long-term care facilities, and community health centers in AMR surveillance improves early detection. Providing clinicians with local antibiograms increases appropriate antibiotic use.

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