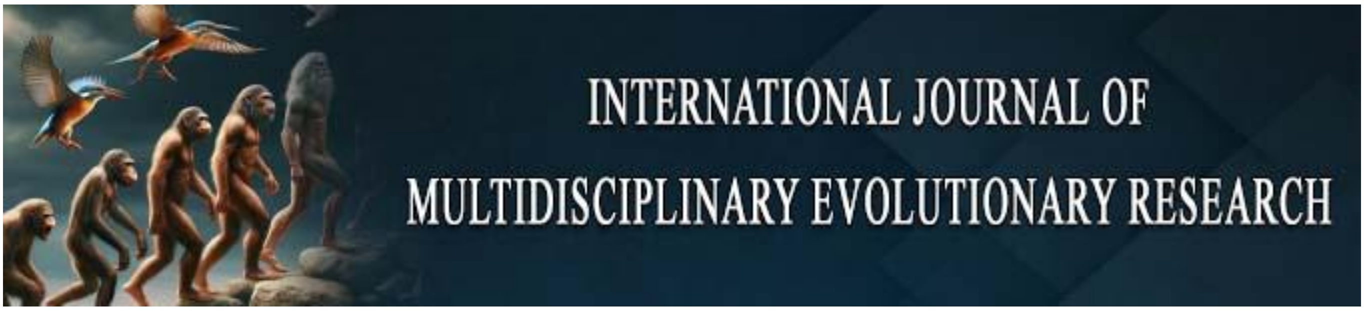

Advances in Antimicrobial Resistance Surveillance Using Multi-Laboratory National Reporting Networks

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Abstract
Antimicrobial resistance cannot be characterised from any single hospital or laboratory, and most countries have converged on a common architecture in which many clinical microbiology laboratories submit standardised susceptibility data to a national coordinating centre supported by a reference laboratory. This narrative review examines what such networks have achieved as of the 2020 reporting year, drawing on institutional reporting from the World Health Organization, the European Centre for Disease Prevention and Control, and the United States Centers for Disease Control and Prevention, alongside the applied literature on diagnostic infrastructure, facility engineering, procurement and logistics, laboratory informatics, data protection, occupational safety, medicine quality assurance, workforce competence, and monitoring across the animal, food, and environmental sectors. The advances of the preceding five years have been largely infrastructural rather than microbiological. A global data standard has reached working scale, the movement of data rather than bench competence has emerged as the binding constraint on national reporting, external quality assessment has become the mechanism that licenses aggregation rather than an optional mark of individual laboratory quality, and molecular and genomic methods have attached to the reference tier without displacing phenotypic testing at contributing sites. Reading that record together with evidence from the enabling domains that determine whether a laboratory can participate at all, which is the contribution attempted here, indicates that the principal constraints on these networks are engineering, logistical, financial, and organisational rather than technical, and that their residual methodological weaknesses concern representativeness, denominators, and data use rather than data volume. The review argues that surveillance programmes should be budgeted and evaluated as distributed infrastructure systems, and identifies the specific components on which that framing places priority.

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1. Introduction

Antimicrobial resistance is unusual among public health threats in that its measurement is inseparable from routine clinical practice. Resistance is not observed in a population; it is observed in isolates, and isolates exist only where a clinician ordered a culture, a laboratory was able to grow the organism, and a susceptibility test was performed and recorded. Every resistance statistic is therefore a statement about a healthcare system as much as about a microbe (Laxminarayan *et al*., 2013; O'Neill, 2016; World Health Organization, 2015a).

This dependence explains why the field has moved, over roughly two decades, from single-centre resistance reports to formal national networks. A single tertiary hospital can describe its own antibiogram, and that description is useful for local empirical therapy. It cannot support national treatment guidelines, cannot detect the geographic spread of a carbapenemase gene, and cannot tell a health ministry whether an investment in infection prevention worked. Those questions require many laboratories reporting comparable data into one place on a repeating schedule, which is why the value of diagnostic capacity is increasingly argued at the level of the network rather than the individual facility (Aminu-Ibrahim *et al*., 2018; Okeke *et al*., 2011).

The same reasoning appears in the wider health systems literature, where scientific and diagnostic innovation is repeatedly shown to fail at the point of delivery when the surrounding infrastructure, financing, and organisational capability are absent (Ilodigwe & Adesemoye, 2019b). The interpretive value of any resistance figure is further conditioned by the quality of the medicines circulating in the same system, since failures of manufacture and distribution contribute to the emergence and spread of resistance (Aneke & Adesemoye, 2019, 2020). Priority-setting exercises identifying the pathogens of greatest concern have sharpened the question that surveillance is expected to answer, but they have not resolved the problem of generating comparable data with which to answer it (Tacconelli *et al*., 2018).

Existing reviews of surveillance networks tend to treat the subject as self-contained, describing protocols, pathogen coverage, and reporting arrangements without reference to the physical, financial, and organisational conditions that determine whether a laboratory can participate at all (Ashley *et al*., 2018; Vernet *et al*., 2014). This omission is not trivial. A designated sentinel site with an unreliable power supply, an unserviced biosafety cabinet, a reagent order stalled at a port, an untrained technologist, or no route by which its spreadsheet can reach the national coordinating centre will appear in a network description as a participating laboratory and will contribute nothing to a national estimate. The conditions that produce this outcome are documented, but they are documented in the engineering, procurement, informatics, safety, and workforce literatures rather than in the surveillance literature, and the two bodies of work are rarely read together.

The account offered here departs from that convention by reading the surveillance record alongside evidence on diagnostic facility design and engineering, power and environmental control, procurement and specimen logistics, data architecture and protection, occupational safety and error reporting, pharmaceutical quality assurance, financing and governance, workforce competence, and monitoring across the animal, food, and environmental sectors. The objective is to establish what multi-laboratory national reporting networks have achieved as of 2020, what those achievements rest on, and which weaknesses persist.

2. Materials and Methods

This is a narrative review, appropriate to a question where the relevant evidence is dispersed across institutional reporting, applied programme documentation, and academic publication (Gandra *et al*., 2020). No formal protocol was registered, and no meta-analysis was attempted, since the source material does not consist of comparable quantitative studies. Sources were assembled in four categories.

Institutional reporting comprised reports of the Global Antimicrobial Resistance Surveillance System (GLASS) for the 2016 to 2018 data calls (World Health Organization, 2018, 2019a, 2020); annual epidemiological reporting for the European Antimicrobial Resistance Surveillance Network (EARS-Net) and its external quality assessment programme (European Centre for Disease Prevention and Control, 2020a, 2020b); reporting from the Central Asian and European Surveillance of Antimicrobial Resistance network (World Health Organization Regional Office for Europe, 2019); national threat assessment covering the United States Antibiotic Resistance Laboratory Network (Centers for Disease Control and Prevention, 2019); breakpoint standards governing interpretation (European Committee on Antimicrobial Susceptibility Testing, 2020); and sectoral reporting on antimicrobial use in animals (Food and Agriculture Organization of the United Nations, 2016; World Organisation for Animal Health, 2020).

Methodological and programme literature comprised the GLASS early implementation manual (World Health Organization, 2015b), guidance on diagnostic stewardship and on molecular methods within surveillance sites (World Health Organization, 2016, 2019b), the roadmap for participation by low- and middle-income countries (Seale *et al*., 2017), stepwise implementation models for lower-resource regions (Perovic & Schultsz, 2016), inventories of existing supranational networks (Ashley *et al*., 2018), and regional syntheses of surveillance progress (Gandra *et al*., 2020; Vernet *et al*., 2014).

Enabling-domain literature was included because network performance depends on conditions studied largely outside the resistance field. This category covers diagnostic facility design and construction, building services engineering including power and environmental control, equipment reliability and maintenance, procurement and supply chain management, enterprise data architecture and information security, occupational safety and error reporting systems, audit and financial governance, workforce development, and environmental and agricultural monitoring. Sources in this category were selected on the basis of transferable mechanism rather than subject matter, which is to say that a study was included where the process it describes recurs in a surveillance network under a different name. Such cross-domain parallels are drawn throughout as plausible structural analogies rather than as demonstrated equivalences, a distinction taken up explicitly in Section 4.2.

Extraction focused on documented network characteristics, including participating laboratory counts, data standards, quality assurance arrangements, and reporting completeness, rather than on resistance prevalence estimates. Where a finding rests on a single country programme, that limitation is stated at the point of use. No formal risk-of-bias appraisal was applied, since the source material is predominantly institutional reporting and applied programme description rather than comparative trial evidence, and readers should treat the enabling-domain material as offering plausible mechanism rather than tested effect.

3. Results

3.1. From Institutional Antibiograms To National Networks

Structured collection of susceptibility data long predates the current policy interest in resistance. Software developed to standardise the capture and analysis of routine microbiology results made it possible for individual laboratories to produce internally consistent antibiograms and, in principle, to exchange them (Stelling & O'Brien, 1997). The limitation was not analytical but organisational: individual laboratories had no obligation, incentive, or route by which to submit their data anywhere, and no common specification against which submissions could be compared.

The shift toward networks came from two directions. From below, demonstrations that routine phenotypic data already being collected could be used for operational purposes, including automated detection of clusters that had not been recognised clinically, established that the aggregate had value exceeding the sum of its parts (Stelling *et al*., 2010). From above, a sequence of global assessments framed resistance as requiring coordinated action at national and international level, and therefore as requiring data collected at that level (Laxminarayan *et al*., 2013; O'Neill, 2016). The Global Action Plan formalised the obligation, and GLASS supplied the reporting standard through which it would be discharged (World Health Organization, 2015a, 2015b).

By the time this framework was in place, a considerable number of supranational networks were already operating, many with overlapping membership and incompatible methods, and an inventory of those involving low- and middle-income countries since 2000 found that participation frequently consumed national capacity without producing outputs comparable to anything else (Ashley *et al*., 2018). Convergence on a single standard was therefore not merely a technical preference but a response to demonstrable duplication. Priority-setting for research and development ran in parallel, identifying the organisms against which new agents were most needed and, by implication, the organisms about which surveillance data were most urgently required (Tacconelli *et al*., 2018).

3.2. Architecture: the reporting laboratory

Networks that function well share a recognisable set of components, synthesised here from the GLASS manual (World Health Organization, 2015b), the roadmap for participation by lower-income countries (Seale *et al*., 2017), stepwise implementation guidance (Perovic & Schultsz, 2016), and the operating documents of established regional networks.

The first component is the set of reporting laboratories that generate primary data. Networks differ sharply in how these are selected. Comprehensive systems, typical of high-income Europe, aim for near-complete coverage of laboratories serving acute care, so that the denominator approximates the national population (European Centre for Disease Prevention and Control, 2020a). Sentinel systems, typical of low-resource settings, deliberately recruit a small number of sites with adequate capacity, on the reasoning that a few laboratories producing trustworthy data are worth more than many producing unusable data (Perovic & Schultsz, 2016; Seale *et al*., 2017). This concentration of capability also concentrates bias toward sicker, better-resourced populations, a cost of the sentinel design taken up in Section 4.2.

Whichever model is adopted, the physical and operational characteristics of the participating laboratory constrain what it can contribute. Spatial planning affects diagnostic accuracy, biosafety, and clinical throughput, since workflow separation, specimen routing, and bench allocation determine both contamination risk and the number of specimens that can be processed in a working day (Ogbete *et al*., 2018). Molecular and pathology work requires regulatory-compliant design in controlled environments, with pressure regimes, containment zoning, and unidirectional workflow specified at design stage rather than retrofitted (Ogbete *et al*., 2019). Materials and energy specification affects whether a facility remains serviceable across its working life rather than degrading into intermittent operation (Ogbete *et al*., 2020).

Where diagnostic access is being extended into underserved and rural regions, network expansion is in practice an infrastructure programme rather than a data-collection exercise, since the limiting factor is the absence of a facility capable of hosting the work rather than the absence of a reporting requirement (Aminu-Ibrahim *et al*., 2018, 2020). The constraints are severe in exactly the settings where surveillance is most needed, since routine clinical bacteriology in low-resource contexts is limited by consumable supply, equipment maintenance, and staffing before it is limited by technique (Ombelet *et al*., 2018). Automation of pattern-based detection in other diagnostic disciplines illustrates the wider shift toward standardised and reproducible interpretation that comparable reporting requires, and the same logic applies to susceptibility reading, where inter-observer variation in zone measurement is a recognised source of discordance (Ejofodomi *et al*., 2014).

3.3. Architecture: The National Reference Laboratory

The national reference laboratory performs confirmatory identification and susceptibility testing on referred isolates, characterises unusual or high-consequence resistance mechanisms, maintains the reference strain collection, and runs or distributes external quality assessment panels. Its existence is what allows a network to make claims about rare phenotypes, since without a reference tier a single site reporting an unexpected carbapenemase cannot be distinguished from a single site making a testing error.

Reference-tier capability is a design and investment question rather than an incremental upgrade to existing benches. Capital delivery models for high-risk healthcare infrastructure bear directly on whether such capacity arrives, arrives on specification, and persists, since the failure modes of these projects, including scope compression under budget pressure and commissioning without functional testing, produce facilities that satisfy an inspection but cannot sustain reference work (Aminu-Ibrahim *et al*., 2019). Once built, the reference laboratory depends on instruments whose availability is a reliability engineering problem, with failure analysis and preventive replacement policies determining whether a sequencer or an automated identification platform is available in the week an outbreak requires it (Gideon *et al*., 2019). The analytical scope of the reference tier has broadened with the incorporation of molecular methods intended specifically to support surveillance rather than clinical diagnosis (Hendriksen *et al*., 2019; World Health Organization, 2019b). Because confirmatory testing, external quality assessment provision, and genomic capability are typically concentrated in this one institution, its reliability is a network-wide vulnerability rather than a purely local one, a topological risk distinct from the instrument-level reliability question addressed above.

3.4. Architecture: The National Coordinating Centre

The national coordinating centre is an epidemiological and governance function rather than a bench function. It sets case definitions, manages the reporting calendar, deduplicates and cleans submitted data, produces national outputs, and holds the relationship with the ministry of health. Networks that place this function inside a laboratory without epidemiological staffing tend to produce data that are never analysed (Ashley *et al*., 2018).

The coordinating centre also sits at the intersection of several institutions with different mandates, including reference and clinical laboratories, hospital administrations, ministries of health and agriculture, and external funders. Governance alignment across such arrangements is a recognised failure point in multi-party ventures generally, where responsibilities that are jointly held tend to be exercised by nobody unless allocation is explicit (Eyetsemitan *et al*., 2020). The financial reporting dimension is comparable. Surveillance programmes funded through public budgets are subject to statutory reporting and budget compliance obligations that consume programme capacity and, where poorly designed, divert it from technical work (Dogbatsey & Ebhojie, 2018). Reconciliation between what was budgeted, what was disbursed, and what was delivered requires workflow design of its own (Dogbatsey *et al*., 2019), and the broader case for accounting systems that strengthen transparency and regulatory confidence applies with particular force to programmes dependent on continued external funding (Bola-Sadipe *et al*., 2019).

3.5. Architecture: The Data Standard

Comparability is the entire point of a network, and it is produced by shared specification of which specimen types and pathogens are in scope, which antimicrobials must be tested, which breakpoint system and version are used, and how a patient-level record is structured so that duplicate isolates can be removed. GLASS specified a priority pathogen list covering bloodstream, urinary tract, gastrointestinal, and gonococcal infections precisely to force this convergence (World Health Organization, 2015b), aligned with the wider priority pathogen assessment used to direct research and development effort (Tacconelli *et al*., 2018), and building on long-established practice in structured microbiology data capture (Stelling & O'Brien, 1997).

Breakpoint selection is not a neutral technical choice. The criteria for setting and revising breakpoints differ between systems and shift over time in ways that propagate directly into reported percentages, so that a national series can appear to show an epidemiological change when it records only a change in interpretive criteria (European Committee on Antimicrobial Susceptibility Testing, 2020; Turnidge & Paterson, 2007). Networks that do not record the breakpoint version applied to each submission cannot subsequently distinguish the two.

Between the site record and the national dataset lies a transformation layer that is rarely specified in surveillance documentation but always present in implementation. Extraction, transformation, and loading of records from heterogeneous source systems into a common schema is a well-described engineering problem, with characteristic failure modes including silent field truncation, inconsistent null handling, and mapping errors that survive because nobody reconciles record counts across the boundary (Badmus *et al*., 2019a). Where this layer is undocumented, discrepancies between what a laboratory believes it submitted and what the coordinating centre holds are discovered late or not at all.

3.6. Architecture: Quality Assurance

Internal quality control at each site plus periodic external assessment coordinated centrally is the mechanism converting a collection of laboratories into a network whose outputs can be pooled (European Centre for Disease Prevention and Control, 2020b). The underlying logic is shared with pharmaceutical quality systems, where risk-based decision-making concentrates scrutiny where the consequences of error are greatest, and where documented chain-of-custody integrity makes distributed outputs mutually trustworthy (Aneke & Adesemoye, 2019, 2020).

The audit literature supplies a further transferable structure. Internal audit quality improves where risk assessment is technology-enabled and continuous rather than periodic and manual (Akomolafe & Agu, 2018), risk-based internal control models allocate assurance effort in proportion to exposure rather than uniformly (Akomolafe & Agu, 2019a), and data-driven risk evaluation permits institutions with limited assurance capacity to target it (Akomolafe & Agu, 2019b). Integrated governance and compliance strategies are associated with organisational resilience rather than merely with regulatory conformity (Akomolafe & Agu, 2019c). Applied to a surveillance network, these arguments imply that a coordinating centre should target quality assessment toward sites whose submissions show statistical anomalies rather than distributing panels uniformly, and that audit findings should feed a documented improvement cycle rather than a compliance file. Integrated audit systems developed for industrial quality, health, safety, and environment functions offer a workable template for combining technical and safety assessment in a single site visit rather than duplicating logistics (Obogo *et al*., 2020a).

3.7. Physical Plant, Power, and Environmental Control

Surveillance documentation generally treats the laboratory as a given. The engineering literature does not, and its findings identify a set of conditions that determine whether a designated site can generate valid results at all.

Environmental control is the first. Incubation, refrigerated storage, and instrument tolerance all depend on maintained temperature and humidity, and the efficiency and control strategy of air conditioning systems determines whether those conditions hold through ambient extremes rather than only in favourable weather (Sunday *et al*., 2019). Building envelope design under humid tropical conditions materially affects the load such systems must carry, and design decisions taken for capital cost reasons impose recurrent energy costs that programmes later cannot meet (Nwafor *et al*., 2018b). Locally sourced materials can reduce construction cost without compromising performance where their properties are quantitatively evaluated rather than assumed (Nwafor *et al*., 2019c), and comparative study of traditional and contemporary building morphologies indicates that climate-responsive design principles available in vernacular practice are frequently discarded in favour of forms requiring continuous mechanical conditioning (Nwafor *et al*., 2018a).

Power is the second. Laboratory instruments tolerate interruption poorly, and cold chain storage tolerates it not at all. Integration of solar generation into small-scale industrial operations demonstrates both the feasibility and the sizing discipline required (Sunday & Omoegun, 2018), while load distribution optimisation for hybrid installations addresses the specific problem of matching intermittent supply to loads of differing criticality, which is precisely the problem a laboratory faces when deciding what remains energised during an outage (Sunday & Omoegun, 2019). Estimating available solar resource is a prerequisite for such sizing (Odejobi & Ahmed, 2018a), and microgrid designs that co-optimise technical performance against community affordability are directly relevant to facilities serving underserved populations, where a technically adequate system that cannot be paid for is not a solution (Komi & Adeniji, 2020). Programmatic experience from large-scale renewable integration indicates that procurement, financing, and operational responsibility, rather than generation technology, determine whether such installations continue functioning (Yeboah & Ike, 2020). Where distributed generation is connected, voltage control becomes a live concern with direct implications for sensitive instrumentation (Oshevire *et al*., 2017), and grounding system design for medium-voltage distribution in emerging markets addresses the protection failures that damage equipment during faults and lightning events (Adeniji *et al*., 2020). Longer-term energy carrier options remain under active modelling and are not yet relevant at facility scale, but they are worth flagging now because the capital planning cycles for reference-tier facilities run long enough that the power infrastructure specified today will likely still be in service when those options mature, making this a consideration for long-term infrastructure planning rather than for current procurement (Shittu *et al*., 2019).

Maintenance is the third. The transition from reactive to predictive maintenance in mechanical systems is well described, with condition monitoring permitting intervention before failure rather than after it (Sunday *et al*., 2020), and the same approach applied to critical power and energy infrastructure demonstrates measurable availability gains (Adaramola *et al*., 2018). Non-destructive testing and corrosion risk assessment provide the corresponding methods for assessing installed assets without taking them out of service (Atta *et al*., 2020), and work on corrosion inhibition indicates that protective strategies are available at modest cost where degradation mechanisms are understood (Atta *et al*., 2018). Surveillance programmes rarely budget for any of this, and the consequence is a predictable pattern in which donor-funded equipment is functional at handover and unserviceable within a few years.

Two further considerations belong here. Analytical frameworks for improving efficiency in public infrastructure delivery address the gap between capital allocated and capacity produced (Nwafor *et al*., 2019b), and resilience-oriented design, developed most fully in relation to flood vulnerability, is relevant wherever a laboratory serves a population exposed to recurrent environmental disruption (Nwafor *et al*., 2019a). Socioeconomic determinants of affordability and sustainability in the built environment apply to health facilities as much as to housing, since a facility whose recurrent costs exceed what the operating institution can sustain will be abandoned regardless of its technical merit (Gil-Ozoudeh *et al*., 2018).

3.8. Biosafety, Occupational Risk, And Error Reporting

Clinical microbiology involves the deliberate culture of pathogens, and the safety systems governing that work are also, incidentally, the systems most capable of detecting the errors that corrupt surveillance data.

Hazard identification and risk control practices constitute the foundation, and systematic review of their application indicates wide variation in whether identified hazards are actually controlled rather than merely recorded (Obogo *et al*., 2019c). Occupational safety management systems provide the governing structure (Obogo *et al*., 2020c), while risk governance models developed for settings with multiple contractors address the specific problem of accountability where several organisations operate in one facility, which is the situation in most hospital laboratories with outsourced maintenance, cleaning, and waste handling (Obogo *et al*., 2019b). Governance-oriented models of contractor safety performance address the same fragmentation from the client side (Arumosoye & Obriki, 2020), and risk management for high-consequence physical operations illustrates how low-frequency, high-severity activities are controlled through procedure rather than through experience (Obogo *et al*., 2020b).

Three findings from this literature transfer directly. First, near-miss and hazard observation data are systematically under-utilised, with organisations collecting reports and then failing to analyse them (Arumosoye & Obriki, 2019). The laboratory analogue is the discrepant result, the failed control, and the contaminated culture, which are typically resolved locally and never aggregated, although in aggregate they are the most sensitive available indicator of process drift. Second, human error causation in high-risk work is systematic rather than random, arising from predictable combinations of workload, interruption, and procedural ambiguity, which means it is addressable by design (Obriki & Arumosoye, 2020). Third, safety culture responds to the frequency and coverage of management walkthroughs, indicating that visible supervisory attention is itself an intervention rather than an overhead (Obriki & Arumosoye, 2019), a finding consistent with evidence that leadership-driven culture change alters outcomes in large distributed workforces (Obogo *et al*., 2019a). Data-driven approaches to occupational risk control in large infrastructure operations demonstrate that these mechanisms can be instrumented rather than left to judgement (Obriki & Arumosoye, 2018). Physiological exposure is also relevant in settings where laboratories operate without reliable cooling, since heat stress has been shown to degrade cognitive performance and manual precision in industrial operations generally (Arumosoye & Obriki, 2018); if this generalises to laboratory bench work, it would plausibly affect reading and recording accuracy for tasks such as zone-diameter measurement, though this has not been studied directly in a laboratory setting.

3.9. Procurement, Consumables, and Specimen Logistics

Culture media, antimicrobial discs, identification reagents, and blood culture bottles are consumables with defined shelf lives, and a laboratory without them produces no data irrespective of its staffing or accreditation. Consumable supply is among the first-order limits on routine bacteriology in low-resource settings (Ombelet *et al*., 2018), yet it is seldom treated as a surveillance variable.

The procurement literature describes the relevant mechanisms in detail. Strategic procurement optimisation addresses category management, demand aggregation, and supplier selection under conditions of volatile demand (Okonkwo *et al*., 2018a), while inventory availability and uptime modelling formalises the relationship between stock policy and operational continuity, which in a laboratory is the relationship between reagent holding and uninterrupted testing (Okonkwo *et al*., 2018b). Contract negotiation and vendor governance determine whether agreed lead times are honoured and whether cost reductions are achieved without reliability loss (Okonkwo *et al*., 2019). Supply chain risk management developed for complex engineering projects supplies a structure for identifying single points of failure, which in reagent supply is frequently a sole distributor holding an exclusive national agency (Agbabiaka *et al*., 2019).

Cross-border movement introduces further constraints. Port logistics and demurrage costs are a documented source of delay and expense in emerging economies, and temperature-sensitive consumables held at a port are frequently unusable on release (Okonkwo *et al*., 2020). Legal and administrative barriers to import participation compound this, since the licensing, documentation, and foreign exchange requirements facing importers determine what is practically obtainable rather than what is nominally registered (Jones & Ominyi, 2020). Geographic information systems integrated with procurement workflows offer a route to managing distribution across dispersed sites (Ahiaeke Patrick *et al*., 2020), and predictive analytics applied to demand forecasting reduces both stockout and expiry, the twin failure modes of reagent management (Aifuwa *et al*., 2020). Procurement analytics using widely available tools demonstrates that this capability does not require specialist platforms (Akin-Oluyomi *et al*., 2020).

Two adjacent considerations complete the picture. Sustainable procurement frameworks that incorporate environmental and governance criteria are increasingly applied to public purchasing, and laboratory consumables, being predominantly single-use plastic, fall squarely within their scope (Okojie *et al*., 2020); the practical effect for surveillance is a genuine trade-off, since environmentally and governance-compliant sourcing can raise near-term consumable unit cost precisely in the resource-constrained settings where this section has already identified stockout, not surplus, as the dominant procurement risk. Reconciling chemical safety requirements with circular economy targets is an unresolved problem for post-consumer material streams, and laboratory waste, which is simultaneously hazardous and voluminous, sits at the centre of it (Okojie & Abioye, 2020). Capability for this work depends on people, and talent development models for distributed supply chain operations address the recruitment and retention of the logistics staff on whom laboratory continuity silently depends (Falemi *et al*., 2020).

3.10. Global Harmonisation And Reporting Scale

The most consequential change of the late 2010s is that a global data standard has stopped being aspirational. GLASS was launched in 2015 as the reporting layer for the Global Action Plan (World Health Organization, 2015a, 2015b), and successive early implementation reports document steady enlargement. The first data call, reported in 2018, drew data from 729 surveillance sites in 22 countries, covering 507,923 suspected bacterial infections (World Health Organization, 2018). The second data call, closing in July 2018, drew 69 enrolled countries, of which 49 reported resistance rates (World Health Organization, 2019a). The third report records 82 countries, territories and areas enrolled in the resistance module by the close of the data call on 31 July 2019, spread across all WHO regions and including 13 low-income and 23 lower-middle-income participants; of these, 78 reported something to GLASS and 66 reported actual resistance data (World Health Organization, 2020).

Enlargement of this kind is not simply a matter of recruitment. The inventory of supranational networks operating since 2000 shows a recurring pattern of overlapping systems with incompatible methods that consumed capacity without producing comparable outputs, which is the condition GLASS was designed to end (Ashley *et al*., 2018). Comparable convergence in other regulated domains depends less on technical agreement than on implementation pathways and institutional readiness. Frameworks for regulatory clearance across jurisdictions address the practical question of how a standard agreed at supranational level is given effect under differing national legal instruments (Ominyi & Anichukwueze, 2020), and post-merger compliance integration in multi-jurisdictional settings describes the analogous problem of reconciling divergent internal procedures under a single reporting obligation (Ominyi, 2020). Cross-border compliance analytics provide the monitoring layer through which such obligations are verified rather than assumed (Lawal & Oduleye, 2018b).

Two qualifications apply. Enrolment is not reporting, and reporting is not representativeness. Between the second and third data calls, the number of countries actually reporting resistance data grew from 49 to 66, an increase of roughly 35 percent, faster than the growth in enrolled countries, from 69 to 82, roughly 19 percent, so the proportion of enrolled countries going on to report resistance data rose from about 71 percent to about 80 percent; read together with the caveat below, this is consistent with programme maturation, in which enrolment is increasingly converting into actual reporting rather than remaining a static administrative count. Many enrolled countries have submitted only a description of their surveillance system rather than data, and growth in site numbers is concentrated in countries that already had dense laboratory coverage, so global increases partly reflect deeper sampling of already well-sampled populations.

3.11. Regional Aggregation Layers

Global systems work because regional systems feed them, and the regional tier is now well developed and methodologically distinct. In Europe, EARS-Net collects invasive isolate data on eight bacterial species from European Union and European Economic Area member states, restricting scope to blood and cerebrospinal fluid isolates in exchange for depth and comparability (European Centre for Disease Prevention and Control, 2020a). The Central Asian and European Surveillance of Antimicrobial Resistance network extends deliberately aligned methods to countries of the WHO European Region outside the European Union, allowing comparison across the whole region rather than only its wealthier part (World Health Organization Regional Office for Europe, 2019).

The practical value of the regional tier is that it performs technical work national programmes cannot do alone:

maintaining protocols, running external quality assessment at scale, validating submissions, and providing a peer group against which a country can read its own numbers. Structured multi-country surveys demonstrate what this makes possible, as in the European survey of carbapenemase-producing Enterobacteriaceae, which combined standardised national sampling with central characterisation to describe the spread of high-risk clones in a way no single national dataset could (Grundmann *et al*., 2017).

Multi-country collaboration also carries organisational costs that are seldom budgeted. Networks operate across languages, professional traditions, and institutional cultures, and effective cross-cultural communication in such settings is a learned competence rather than an assumed one (Lilian *et al*., 2020). Divergent national legal frameworks governing data, consent, and publication add a further layer, comparable to the compliance problems documented for organisations operating simultaneously under multiple consumer protection regimes (Anichukwueze *et al*., 2019).

3.12. Laboratory Informatics and The Movement of Data

A single national laboratory reassembling results phoned, faxed, or emailed in from dozens of sentinel sites illustrates concretely where national reporting actually slows: assessments of surveillance networks in South and Southeast Asia describe exactly this arrangement, with one individual responsible for consolidating everything reported (Gandra *et al*., 2020). Systems of this design are slow, error-prone, and collapse when that individual is reassigned. Similar constraints have been documented across under-resourced settings more broadly (Vernet *et al*., 2014).

The response has three parts. WHONET, the free microbiology data management application in use since the 1990s, is promoted as the default entry and analysis tool for laboratories without a full laboratory information management system, since it accepts input from automated analysers, carries current breakpoint tables, and exports in the format GLASS expects (Stelling & O'Brien, 1997; World Health Organization, 2015b). Where laboratories already run a laboratory information management system, the emphasis falls on configuring exports rather than replacing working systems. Where many heterogeneous sources must be combined, middleware is used to consolidate them into a national platform.

The engineering requirements of that national platform are conventional but nontrivial. Scalable and secure cloud architecture provides the hosting model most national programmes now adopt, with the security properties determined at design stage rather than added afterwards (Ahmed & Odejobi, 2018a). Resource allocation and placement decisions determine both cost and responsiveness (Ahmed & Odejobi, 2018b), constraint satisfaction methods formalise allocation under competing demands (Ahmed *et al*., 2019), and predictive scaling using machine learning permits capacity to track demand rather than being provisioned for peak (Ahmed *et al*., 2020). Query and storage optimisation becomes material once a national dataset reaches the scale at which routine analyses would otherwise take hours (Odejobi *et al*., 2019), and performance evaluation of multi-tenant deployments under high concurrency describes the conditions arising when many sites submit simultaneously against a reporting deadline (Odejobi & Ahmed, 2018b).

Deployment discipline matters as much as architecture. Continuous integration and delivery practices reduce the incidence of changes that break existing submission routes (Badmus *et al*., 2018), comparative evaluation of deployment tooling indicates that the choice materially affects release reliability (Badmus *et al*., 2020), and infrastructure-as-code governance ensures that environments are reproducible rather than hand-configured and undocumented (Mbonu *et al*., 2020b). Platform governance frameworks developed specifically for regulated healthcare environments address the tension between rapid iteration and validated configuration, which closely mirrors the tension a national surveillance platform faces when a breakpoint update must be deployed mid-year (Badmus *et al*., 2019b). Directory services underpin the account management on which multi-site access depends (Ladapo *et al*., 2019), and digital transformation of distributed operations with embedded controls illustrates the general pattern of building governance into a system rather than around it (Mbonu *et al*., 2020a).

Connectivity is the precondition for all of it. Network quality in emerging markets is a function of deployment strategy as much as of technology (Amayo & Popoola, 2017b), and systematic review of mobile network rollout in such markets indicates that coverage extension follows commercial rather than epidemiological logic, so that the districts least served by connectivity are frequently those where surveillance sites are most needed (Sanni *et al*., 2020c).

The analytical payoff of structured data extends beyond annual reporting. Automated cluster detection applied to routine susceptibility phenotypes identifies outbreaks from surveillance data already being collected, converting a retrospective reporting exercise into an operational tool (Stelling *et al*., 2010). Where routine microbiology data are thin, alternative sources including pharmacy, procurement, and syndromic records can support surveillance objectives in the interim (Ashley *et al*., 2019). The broader implication is that informatics capacity should be treated as a first-order component of surveillance design rather than a downstream implementation detail.

3.13. Data Protection, Confidentiality, And Security Governance

A national reporting network is a distributed system carrying identifiable or re-identifiable clinical records across institutional boundaries, and it therefore inherits obligations that surveillance documentation addresses only briefly.

Consider a network spanning several countries, each with its own data protection statute. Legal and ethical risk modelling that distinguishes obligations arising from statute, from contract, and from professional duty is the necessary starting point (Mbonu *et al*., 2018), because comparative analysis of data protection regimes shows that the same patient-level dataset can be lawfully processed in one participating country and not in another (Mbonu *et al*., 2019a), a distinction that determines, isolate record by isolate record, what a national coordinating centre may legally receive from a neighbouring country's reference laboratory. The practical answer is identity and access management: a national platform, a hospital system, and a reference laboratory typically maintain separate account directories, and integration strategies for hybrid and multi-cloud environments are what let one technologist's access be granted, scoped, and revoked consistently across all three without any single institution surrendering control of its own credentials (Mbonu *et al*., 2020c; Oshoba *et al*., 2019). Blockchain-based compliance and audit trail models supply the corresponding evidence layer, letting a coordinating centre demonstrate to a sceptical ministry or funder that a submitted record has not been altered after the fact (Oshoba *et al*., 2020).

The second mechanism is detection and response, and the design tension here is specific to surveillance: a network must be defended without becoming unreachable during the emergencies, an outbreak investigation, an urgent isolate referral, in which it is simultaneously most needed and most exposed. Log analytics with automated incident response shortens the interval between compromise and containment (Mbonu *et al*., 2019b), intrusion detection and prevention supplies the monitoring layer beneath it (Dosunmu & Ogundele, 2020), and security audit combined with enterprise risk assessment establishes the baseline against which both are specified (Dosunmu & Ogundele, 2019). Because the majority of inappropriate access to health data originates with authorised users rather than external attackers, insider threat classification is the risk category a surveillance network should weight most heavily, not the one it instinctively reaches for (Akeju *et al*., 2018), and risk-based cybersecurity assurance frameworks make the resulting protection-versus-availability trade-off explicit rather than leaving it implicit in an incident response plan nobody has tested against a live outbreak (Fadayomi *et al*., 2019). Privacy-centric security engineering builds these choices in at design stage rather than retrofitting them after an incident (Okoruwa *et al*., 2020); assessment methods developed for security-critical systems that cannot be tested online describe the constrained conditions under which some reference facilities must be evaluated (Ladapo *et al*., 2018); and experience securing operational technology in electric utilities is directly instructive for laboratory environments running networked instruments that were never designed for internet exposure (Adegbite *et al*., 2020). Neither layer holds without a third: technical controls fail where staff awareness does not support them, and the everyday behaviour of the people handling records determines whether confidentiality is maintained in practice, whatever the access-control policy specifies on paper (Onche *et al*., 2020).

3.14. External Quality Assessment as A Network Function

A pooled resistance percentage is interpretable only if contributing laboratories test and interpret in the same way, and external quality assessment has accordingly moved from an optional mark of laboratory quality to the mechanism that licenses aggregation. The European programme illustrates the scale reached: the 2019 EARS-Net exercise enrolled 952 laboratories, between 1 and 95 per country, across 30 European Union and European Economic Area countries (European Centre for Disease Prevention and Control, 2020b). Exercises of this size generate two distinct products, a performance record for each participating laboratory and a characterisation of measurement error across the network that the coordinating centre can use when interpreting pooled results.

In lower-resource settings the starting point is very different, and building quality assurance provision, whether nationally or through regional providers, has become a standard early investment in stepwise implementation models (Perovic & Schultsz, 2016; Seale *et al*., 2017). Much of the conceptual machinery is borrowed from pharmaceutical quality systems, which supply the vocabulary of risk-based decision-making under good manufacturing practice and of documented traceability across custody transfers (Aneke & Adesemoye, 2019, 2020). The connection is not merely methodological, since medicine quality failures are themselves a driver of resistance, making assurance in the supply chain and assurance in the laboratory two halves of one problem.

Assurance effort is finite, and its allocation is itself a design decision; Section 3.6 sets out the general case, drawn from the audit literature, for concentrating that effort where exposure is greatest rather than distributing it uniformly (Akomolafe & Agu, 2018, 2019a) and for combining technical assessment with safety and environmental audit in a single integrated exercise (Obogo *et al*., 2020a). Applied specifically to external quality assessment, that logic argues for targeting panels at sites whose submissions show implausible susceptibility patterns, unusual completeness profiles, or discordance with peer institutions, rather than distributing them uniformly across the network. Systematic collection and analysis of near-misses and discrepant results, currently rare in laboratory practice, would provide a continuous signal between periodic panels (Arumosoye & Obriki, 2019), and treating error as systematically caused rather than individually blameworthy is the precondition for such reporting to occur at all (Obriki & Arumosoye, 2020).

3.15. Molecular and Genomic Methods At The Reference Tier

Integration of molecular and genomic methods into national networks has followed a consistent pattern. Phenotypic susceptibility testing remains the workhorse at reporting sites, since it is what clinical care requires and what most laboratories can sustain, while sequencing is concentrated at regional or national reference laboratories and applied selectively to isolates that are unusual, high-consequence, or epidemiologically linked (Hendriksen *et al*., 2019; World Health Organization, 2019b).

The United States network shows the tiered design clearly. Gonococcal surveillance within the Antibiotic Resistance Laboratory Network operates through roughly 35 local laboratories, four regional laboratories, and the national reference laboratory; local laboratories draw specimens from about 60 associated clinics, isolate organisms, and ship up to 20,000 isolates per year to regional laboratories for agar dilution susceptibility testing against seven antibiotics and whole-genome sequencing of up to 5,000 isolates, with concerning isolates examined centrally and genetic resistance markers tracked, and 8,214 and 8,628 gonococcal isolates tested in 2017 and 2018 respectively (Kersh *et al*., 2020). This is a purpose-built response to a specific problem, since the shift to nucleic acid amplification testing for gonorrhoea diagnosis eroded national culture capacity and therefore the ability to perform susceptibility testing at all (Centers for Disease Control and Prevention, 2019). The isolates actually tested amount to roughly 40 to 43 percent of the stated 20,000-isolate testing capacity, and the shortfall is informative: in a tiered network where reference-tier testing and sequencing capacity is not the binding constraint, throughput is instead set by how many isolates culture-positive sites can identify, preserve, and ship onward, which is an isolate referral and logistics problem rather than a bench capacity one, and it reinforces this review's central argument even in one of the best-resourced networks considered here.

Genomics has not replaced the phenotypic network. It has attached to it, and its value depends on the isolate referral pathways the phenotypic network already maintains, on the analytical capacity of the reference tier, and on tools that make sequence data interpretable to epidemiologists rather than only to bioinformaticians (Argimón *et al*., 2016). Multi-country genomic characterisation demonstrates the resolution available when referral and sequencing are combined at regional scale (Grundmann *et al*., 2017), and the broader movement toward automated, reproducible interpretation across diagnostic disciplines suggests where routine practice is heading (Ejofodomi *et al*., 2014).

3.16. Linking Resistance and Consumption Data

Resistance data answer only half of a policy question; the other half is what antimicrobials are being used, in what quantities, and in which categories. Global consumption rose substantially between 2000 and 2015, with the sharpest increases in low- and middle-income countries and a convergence of consumption patterns toward those of higher-income settings (Klein *et al*., 2018). Classification of antibiotics into access, watch, and reserve categories gives such data an interpretable policy meaning rather than leaving them as volume totals, and provides a target that national programmes can act on (Sharland *et al*., 2018).

Consumption data are a supply chain artefact before they are an epidemiological one, and their quality depends on the systems governing availability and distribution of medicines. Financing mechanisms and provider payment design determine what is procured and prescribed (Ilodigwe & Adesemoye, 2019a), pharmacy-led delivery models shape where medicines are dispensed and whether that dispensing is recorded (Ilodigwe & Adesemoye, 2020), and traceability across the distribution chain determines whether a recorded volume corresponds to the product actually administered (Aneke & Adesemoye, 2019). Where formal supply is unreliable, treatment sometimes falls back on locally prepared herbal or botanical preparations, compounded outside the regulated pharmaceutical supply chain rather than manufactured or imported, whose antimicrobial activity is variable and, beyond isolated laboratory characterisation of individual plant extracts, largely undocumented in surveillance systems (Gbadamosi & Obogo, 2013). Diagnostic stewardship guidance addresses the corresponding problem on the laboratory side, specifying which specimens should be collected and tested so that surveillance data reflect clinical need rather than testing habit (World Health Organization, 2016).

The fiscal dimension is frequently decisive and rarely analysed. Translating legislative and budgetary instruments into operational strategy requires mapping their sectoral impact and modelling regulatory scenarios in advance, a capability most health ministries exercise poorly (Akinola *et al*., 2020). Financial analytics that connect expenditure to outcome provide the evidence for sustaining programmes through budget cycles (Lawal & Oduleye, 2018a), executive decision systems formalise the use of that evidence in planning (Lawal & Oduleye, 2019b), and reconciliation between planned and actual disbursement determines whether a budgeted consumable allocation reaches a laboratory bench (Dogbatsey *et al*., 2019). Where medicines are supplied through multinational structures, transfer pricing arrangements influence the prices at which products enter national markets and therefore the volumes consumed (Lawal & Oduleye, 2019a).

3.17. Monitoring Across the Animal, Food, And Environmental Sectors

The Global Action Plan frames resistance as a problem spanning human health, animal health, agriculture, and the environment (World Health Organization, 2015a), with a corresponding sectoral action plan for food and agriculture (Food and Agriculture Organization of the United Nations, 2016). Reporting on antimicrobial agents intended for use in animals has become an established international series, providing the consumption denominator for the animal sector that GLASS provides for the human sector (World Organisation for Animal Health, 2020).

Surveillance on the animal and food side remains organisationally separate from human networks, and a review of European programmes covering livestock and meat found substantial variation in sampling frames, tested organisms, and reporting formats, limiting comparison between sectors even where both are well resourced (Schrijver *et al*., 2018). The exposure context in which resistance in food animals develops is supplied by husbandry and feeding research, including work on alternative and by-product feeding systems and on the physiological responses of animals maintained under different management regimes, which determine both the disease pressure prompting antimicrobial use and the physiological state in which residues are handled (Aye & Tawose, 2015, 2016). The economic structure of the producing sector matters correspondingly: access to agribusiness finance shapes the scale and intensity of production systems and therefore their antimicrobial requirements (Michael & Ogunsola, 2019a), and the competence of the producers themselves is a function of agricultural education and extension provision (Michael & Ogunsola, 2019b).

The environmental compartment is the least developed. Predictive modelling of subsurface contamination pathways provides a transferable method for tracing residues from point sources through soil and groundwater (Azeez & Badmus, 2018), spatially explicit risk modelling extends this to settings where monitoring data are sparse, which describes almost all antimicrobial residue monitoring in low- and middle-income countries (Lamidi & Olamide, 2018), and hydrological modelling of watershed vulnerability under climate variation indicates how dilution and transport assumptions shift with changing rainfall regimes (Badmus & Olamide, 2019). Chemical safety considerations for post-consumer material streams are relevant to the disposal pathways through which pharmaceutical residues enter the environment (Okojie & Abioye, 2020).

Remote sensing and unmanned aerial platforms offer monitoring capability for dispersed assets and corridors that has not yet been applied systematically to health logistics. The methods are established for linear infrastructure inspection (Dagodzo, 2018a, 2018b) and for pipeline and corridor monitoring (Dagodzo & Ahiaeke Patrick, 2020), and satellite spectral interpretation methods developed for geological survey demonstrate the analytical maturity of the underlying imagery techniques (Dagodzo, 2018c). A plausible but as-yet-untested extension to surveillance would be twofold: monitoring of dispersed production and disposal sites, and specimen transport across terrain where road logistics are unreliable; neither application has been reported for diagnostic specimens or AMR monitoring specifically, and the case made here is one of transferable mechanism rather than demonstrated practice.

3.18. Analytics, Visualisation, and Decision Support

A network producing a confidential annual report to a ministry has limited effect. The analytical layer that converts submitted records into usable output is therefore part of the surveillance system rather than an optional addition.

Cluster detection from routine phenotypes remains the clearest demonstration that existing data support operational use (Stelling *et al*., 2010), and alternative data sources extend analytical reach where microbiological coverage is thin (Ashley *et al*., 2019). Beyond outbreak detection, the relevant capabilities are conventional. Profitability and performance analytics built on widely available tools show that useful dashboards do not require specialist platforms (Akin-Oluyomi *et al*., 2020), predictive analytics improves forecasting accuracy for the consumables on which testing depends (Aifuwa *et al*., 2020), and predictive modelling of attrition and lifecycle behaviour offers a transferable method for identifying sites at risk of disengaging from a network before they stop reporting altogether (Oziri *et al*., 2020). Geospatial analytics developed for retail expansion addresses precisely the siting question a surveillance programme faces when deciding where an additional sentinel laboratory would add most information (Seyi-Lande *et al*., 2020).

Measurement of programme return is a persistent difficulty. Analytical models developed for regulated sectors address the problem of attributing outcome to investment where the causal chain is long and confounded, which is the position of any surveillance programme asked to demonstrate its value (Sanni *et al*., 2020a), and positioning frameworks for regulated professional services address the related problem of communicating that value to non-technical decision-makers (Sanni *et al*., 2020b). Executive decision systems provide the structure through which analysis reaches the people who allocate budgets (Lawal & Oduleye, 2019b), and predictive infrastructure scaling ensures that analytical workloads remain affordable as datasets grow (Ahmed *et al*., 2020).

3.19. Governance, Oversight, and Regulatory Alignment

Surveillance is a regulatory function as much as a scientific one, and the oversight literature from other safety-critical sectors is unusually transferable.

Aviation provides the closest analogue. Predictive compliance monitoring using routinely generated complaint data demonstrates that systemic risk can be detected from administrative records collected for another purpose, which is closely analogous to detecting resistance emergence from routine clinical microbiology (Adeyelu, 2018). Adaptive safety management system implementation models developed explicitly for developing economy contexts address the problem of applying an international standard where the assumed regulatory and staffing base is absent, which closely parallels the central implementation problem for GLASS participation (Adeyelu, 2019). Risk quantification models combining heterogeneous data sources illustrate how a low-frequency, high-consequence hazard can be monitored proportionately rather than either ignored or over-resourced (Adeyelu, 2020).

Governance alignment across participating institutions determines whether obligations are met (Eyetsemitan *et al*., 2020), cross-jurisdiction regulatory clearance frameworks determine how supranational standards acquire domestic force (Ominyi, 2020; Ominyi & Anichukwueze, 2020), and integrated governance and compliance strategies are associated with resilience rather than with mere conformity (Akomolafe & Agu, 2019c). Statutory reporting and budget compliance obligations shape what a programme can actually do with its allocation (Dogbatsey & Ebhojie, 2018). Compliance behaviour, finally, is trainable: ethics and compliance training frameworks designed to produce measurable behavioural change offer a route to embedding data submission and confidentiality obligations as routine practice rather than as periodic reminders (Anichukwueze *et al*., 2020).

3.20. Workforce, Training, and Competence

Every component described above is operated by people whose competence and continuity determine whether it functions. Staffing is among the primary limits on routine bacteriology in low-resource settings (Ombelet *et al*., 2018), and the surveillance-specific skills of data management, quality control interpretation, and epidemiological analysis are scarcer still.

The education literature supplies transferable findings on how such competence is built. Professional development is the mechanism through which practitioners acquire capability for tasks not covered in initial qualification, and its effectiveness depends on structure and follow-up rather than on exposure alone (Yeboah *et al*., 2019). Pedagogical strategies developed for resource-constrained settings address instruction where materials, time, and specialist support are limited, which describes most laboratory in-service training (Bobga *et al*., 2018). Digital tools can extend reach where instructors are few, provided their integration is designed rather than assumed (Boakye *et al*., 2020), and data-informed digital learning platforms applied to healthcare settings demonstrate the model most directly (Orise & Niniola, 2020). Career pathway design affects retention, since staff trained at programme expense who see no progression route leave for institutions that offer one (Ogbona *et al*., 2020a), and structured engagement with the stakeholders surrounding a learner, a principle established in the home-school partnership literature, transfers to the relationship between a coordinating centre and the hospital administrations employing its contributing technologists (Ogbona *et al*., 2020b).

Two further competences deserve explicit mention. Cross-cultural communication is a requirement in multi-country networks rather than an incidental benefit (Lilian *et al*., 2020), and information security awareness determines whether the technical controls described earlier are honoured in daily practice (Onche *et al*., 2020). Talent development models for distributed operations address the systemic problem of building capability across many sites simultaneously rather than concentrating it centrally (Falemi *et al*., 2020), and behaviourally oriented compliance training provides the mechanism for embedding it (Anichukwueze *et al*., 2020).

3.21. Comparison of Network Designs

Table 1 summarises the principal design families in operation. The categories blur in practice, and the table is included to show that "national network" describes a family of designs with different trade-offs between coverage, depth, and cost rather than a single blueprint (Ashley *et al*., 2018; Gandra *et al*., 2020; Kersh *et al*., 2020).

Table 1: Design families among multi-laboratory national and regional resistance reporting networks.

Network	Coverage model	Reference tier	Distinguishing feature
EARS-Net (EU/EEA)	Near-comprehensive, invasive isolates only	National reference laboratories	Large centrally run EQA; narrow, deep scope restricted to blood and CSF isolates
CAESAR (non-EU European Region)	Mixed, expanding	National reference laboratories with regional technical support	Methods deliberately aligned with EARS-Net to permit comparison across the region
AR Lab Network (United States)	National, with regional high-capacity laboratories	Regional laboratories plus national reference laboratory	Tiered testing with substantial sequencing capacity and outbreak response function
Sentinel networks, South and Southeast Asia	Sentinel, tertiary hospitals, staged expansion	National reference laboratory, often newly designated	Growth by capability rather than count; heavy investment in EQA and informatics

Table 2 sets out the enabling conditions identified across the preceding sections, the failure mode associated with each, and its observable effect on surveillance output.

Table 2: Enabling conditions, failure modes, and effects on surveillance output.

Enabling condition	Characteristic failure	Effect on surveillance data
Facility design and environmental control	Incubator and storage conditions outside tolerance	Invalid results, unquantified misclassification
Power supply and equipment maintenance	Outage, instrument failure without service contract	Intermittent gaps indistinguishable from low incidence
Reagent procurement and logistics	Stockout, expiry, customs delay	Testing suspended; denominator collapses silently
Data pipeline and interoperability	Manual submission, undocumented transformation	Late, incomplete, or silently truncated national datasets
Data protection and access control	Confidentiality breach or system compromise	Institutional withdrawal from reporting
Quality assurance and error reporting	Uniform rather than risk-targeted assurance	Undetected drift in a subset of contributing sites
Workforce competence and retention	Departure of the trained data manager	Reporting ceases without formal withdrawal
Financing continuity	Grant expiry without domestic budget line	Network capacity degrades toward pre-programme levels

4. Discussion and Conclusion

The advances described above are real, but they are concentrated in the parts of the system that are easiest to fund and hardest to sustain. Several observations follow.

First, the constraints that matter are engineering, logistical, and organisational rather than microbiological: the United States gonococcal network, for example, tested only around 40 to 43 percent of its stated 20,000-isolate annual capacity in 2017 and 2018 despite reference-tier testing and sequencing capacity already being built (8,214 and 8,628 isolates respectively; Kersh *et al*., 2020), a gap attributable to isolate referral and logistics rather than to bench throughput. The recurring failure points in national networks more broadly are specimen referral logistics, reagent availability, manual data submission, and dependence on a single individual for national data assembly (Ashley *et al*., 2018; Gandra *et al*., 2020; Ombelet *et al*., 2018; Vernet *et al*., 2014). None of these is remedied by better microbiology, and each is remedied by investment that surveillance budgets rarely classify as surveillance. A programme that funds training and panels but not cold chain, uninterruptible power, or a service contract has funded the visible half of a system.

Second, the reference tier is a single point of failure in most national systems. Where confirmatory testing, quality assessment, and genomic characterisation all sit in one laboratory, any interruption to that laboratory suspends the network's ability to validate its own outputs. Systems with multiple interchangeable high-capacity laboratories, as in the tiered United States design, retain capacity when individual sites are disrupted (Centers for Disease Control and Prevention, 2019; Kersh *et al*., 2020). Reliability engineering offers the appropriate framing, treating the reference function as a service with an availability requirement rather than as a building (Gideon *et al*., 2019).

A further, time-limited, consideration: the disruption to routine clinical services associated with the ongoing coronavirus pandemic is likely to affect surveillance data for the current reporting year in ways that will not be obvious in the resulting percentages. Reduced elective activity, redeployment of laboratory staff and equipment to viral testing, interruption of isolate referral, and altered healthcare-seeking behaviour each change which patients are cultured. Because resistance percentages are ratios computed on whatever isolates arrive, a change in the composition of that arriving set moves the numerator without any change in the underlying biology. Programmes should record what changed in their own operations during this period, since that record will be needed later to interpret the data the period produces. The supply chain dimension deserves particular attention, since global competition for laboratory consumables affects reagent availability for bacteriology as much as for virology (Okonkwo *et al*., 2018b, 2020).

Third, the governance layer is now as consequential as the technical layer. A network holding clinical records across institutional and national boundaries carries legal obligations that, if breached, will cause participating institutions to withdraw irrespective of the scientific value of participation (Mbonu *et al*., 2018, 2019a; Okoruwa *et al*., 2020). Security and confidentiality are therefore continuity requirements rather than compliance overhead.

4.1. Enabling Conditions Beyond the Laboratory

The findings above describe what networks do; the evidence indicates that what allows them to do it sits largely outside the microbiology laboratory.

Diagnostic networks are capital-intensive and long-lived, and the delivery model determines whether capacity arrives and persists. Capital project delivery for high-risk healthcare infrastructure, regulatory-compliant design of molecular and pathology environments, spatial planning for throughput and biosafety, and materials and energy specification for long service life are all determinants of whether a designated site can meet a reporting standard year after year (Aminu-Ibrahim *et al*., 2019; Ogbete *et al*., 2018, 2019, 2020). Extending participation beyond tertiary referral centres is an infrastructure programme before it is an epidemiological one (Aminu-Ibrahim *et al*., 2018, 2020), and delivery efficiency in public infrastructure determines how much capacity a given allocation produces (Nwafor *et al*., 2019b).

Operating conditions form a second cluster. Environmental control, power continuity, and maintenance discipline jointly determine whether a laboratory produces valid results on any given day (Adaramola *et al*., 2018; Sunday *et al*., 2019, 2020), and the engineering choices supporting them, including generation sizing, load prioritisation, protection design, and envelope specification, are made at design stage and are expensive to revisit (Adeniji *et al*., 2020; Nwafor *et al*., 2018b; Sunday & Omoegun, 2019).

At system level, the financing question is inseparable from coverage and payment design, since what is reimbursed determines what is ordered, and a culture that is not reimbursed is a culture that is not taken (Ilodigwe & Adesemoye, 2019a). The more general observation that scientific innovation fails to improve outcomes without effective delivery infrastructure applies with unusual force to surveillance, where the innovation is a data standard whose value is entirely contingent on the capacity of others to comply with it (Ilodigwe & Adesemoye, 2019b).

Medicine quality and distribution integrity constitute a fourth enabling condition. Resistance measured in a population exposed to substandard or improperly stored products is not comparable to resistance measured in a population receiving products of assured quality, which makes chain-of-custody integrity and risk-based quality decision-making relevant to the interpretation of surveillance outputs and not only to regulatory compliance (Aneke & Adesemoye, 2019, 2020).

4.2. Limitations of Current Network Data

Sentinel networks produce data about sentinel sites. Because those sites are usually tertiary referral hospitals with better laboratories and sicker patients, they systematically overestimate national resistance prevalence (Gandra *et al*., 2020; Seale *et al*., 2017; Vernet *et al*., 2014). The bias is acknowledged but rarely quantified, and pooled national or global figures inherit it; extending diagnostic access beyond referral centres is the only structural remedy (Aminu-Ibrahim *et al*., 2020).

A resistance percentage also requires a defensible denominator. Where only a small fraction of febrile patients in a catchment have a blood culture taken, the resulting isolates describe an unrepresentative slice of infection (Ombelet *et al*., 2018). Low blood culture rates limit interpretability more fundamentally than any analytical technique can repair, which makes specimen collection capacity a surveillance variable rather than a background condition.

Whether repeat isolates from the same patient are removed, and over what window, materially changes reported percentages. Networks specify this (World Health Organization, 2015b), but site-level adherence varies, and revisions to breakpoint criteria introduce discontinuities in time series that are easily misread as epidemiological change (European Committee on Antimicrobial Susceptibility Testing, 2020; Turnidge & Paterson, 2007). Undocumented transformation between site and national datasets adds a further, generally invisible, source of discrepancy (Badmus *et al*., 2019a).

The most persistent weakness is that data collection has outpaced data use. National reports are produced in more countries each year, but their translation into revised empirical therapy guidelines, procurement decisions, or infection prevention priorities remains inconsistent (Gandra *et al*., 2020; World Health Organization, 2020). Where surveillance data have been connected to an operational function, as in automated cluster detection from routine phenotypes, the return on existing collection has been demonstrable (Stelling *et al*., 2010).

This review has its own limitations. It is narrative rather than systematic, source selection was purposive, and much of the enabling-domain evidence consists of conceptual frameworks and programme description rather than comparative evaluation, so the mechanisms proposed should be read as plausible rather than demonstrated in the surveillance context specifically. Transfer of findings across sectors carries the risk that superficially similar processes differ in ways that matter. The institutional reporting on which the quantitative statements rest is itself subject to the representativeness problems the review describes.

4.3. Implications for Practice

Several practical priorities follow. Informatics should be funded as core infrastructure, with data pipelines, interoperability, and technical staffing treated as seriously as bench equipment, since a network's output is bounded by its slowest data path (Ashley *et al*., 2019; Stelling *et al*., 2010). Redundancy should be built into the reference tier, because multiple laboratories capable of the same confirmatory and characterisation work protect the network against interruption at a single site (Kersh *et al*., 2020). Denominators should be published alongside percentages, so that culture volumes, blood culture rates, and contributing site counts allow readers to assess representativeness rather than assume it (Gandra *et al*., 2020; Ombelet *et al*., 2018).

Sentinel networks should expand by capability rather than by count, since adding sites that cannot meet the data standard degrades the pooled estimate, and stepwise models exist that sequence this expansion sensibly (Perovic & Schultsz, 2016; Seale *et al*., 2017). Diagnostic stewardship should be treated as part of surveillance design rather than as a separate clinical initiative, since it determines which specimens enter the system in the first place (World Health Organization, 2016). Quality assessment effort should be risk-targeted rather than uniform (Akomolafe & Agu, 2019a), and discrepant results and near-misses should be collected continuously rather than only at panel intervals (Arumosoye & Obriki, 2019).

Programme budgets should include the operating conditions on which testing depends, specifically power continuity, environmental control, preventive maintenance, and reagent buffer stock, rather than treating these as the host institution's responsibility (Okonkwo *et al*., 2018b; Sunday *et al*., 2020). Data protection and access control should be specified at design stage, since retrofitting them after an incident is both more expensive and less effective (Mbonu *et al*., 2020c; Okoruwa *et al*., 2020). Analysed data should be returned to contributing laboratories promptly and in usable form, which remains the cheapest available intervention for data quality (Akin-Oluyomi *et al*., 2020). And where a network is established with external financing, the transition to domestic funding should be planned with named budget lines at the outset rather than at the point a grant ends (Ilodigwe & Adesemoye, 2019a).

4.4. Directions for Further Work

Three questions are unresolved and tractable. The first is quantification of sentinel bias. Paired sampling of sentinel and non-sentinel facilities in the same catchment would allow the direction and magnitude of overestimation to be estimated rather than assumed, and would permit adjustment of pooled figures.

The second is the measurement of network availability. Surveillance programmes report what was submitted but not what was possible, and instrumenting the operating conditions described above, including uptime, reagent stock position, and instrument service status, would allow reporting completeness to be interpreted against capacity rather than treated as a fixed property of a site (Adaramola *et al*., 2018; Aifuwa *et al*., 2020).

The third is evaluation of data use. There is at present no standard measure of whether surveillance output changed a guideline, a procurement decision, or a prescribing practice, and without such a measure the case for sustained investment rests on assertion. Methods developed for attributing outcome to investment in other regulated sectors offer a starting point (Sanni *et al*., 2020a).

4.5. Conclusion

The multi-laboratory national reporting network has become the standard organisational form of resistance surveillance, and the field has accumulated enough operational experience to identify what makes one work. The advances of the preceding five years have been real and largely infrastructural: a functioning global data standard with substantial uptake, mature regional aggregation layers, a shift from paper and email toward structured electronic reporting, the institutionalisation of external quality assessment, and the attachment of genomic capability to existing phenotypic networks.

What limits these systems is not microbiological capability. Facility conditions, power and maintenance, reagent supply, culture ascertainment, isolate referral, structured data submission, data protection, reference-tier redundancy, workforce continuity, and coordinating capacity determine whether a national network produces a number worth acting on, and each depends on infrastructure, financing, and organisational arrangements that surveillance programmes do not usually control and rarely budget for. Treating a surveillance network as distributed infrastructure rather than as a reporting obligation changes what gets funded and what gets measured. Investment in those components, and honesty about the representativeness of what results, remain the central tasks.

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