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Transforming Rabies Surveillance in Endemic Regions: A Narrative Review of Surveillance Gaps, Emerging Innovations, and one Health Strategies for Real-Time Detection and Reporting

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Abstract

Rabies remains one of the most fatal zoonotic diseases worldwide, causing almost certain death once clinical symptoms develop. Despite the availability of highly effective preventive measures, including post-exposure prophylaxis (PEP) and mass dog vaccination, rabies continues to claim approximately 59,000 human lives annually, with the overwhelming burden occurring in low- and middle-income countries. The persistence of rabies is driven by inadequate canine vaccination coverage, weak surveillance systems, delayed diagnosis, limited access to healthcare services, and insufficient coordination between human and animal health sectors. This thematic review examines the epidemiology of rabies, current surveillance and diagnostic validation pathways in both human and animal populations, key challenges affecting surveillance effectiveness, and emerging innovations that may strengthen rabies prevention and control efforts. Particular attention is given to the role of One Health approaches and Integrated Bite Case Management (IBCM) in improving case detection, risk assessment, and response mechanisms. The review identifies several critical gaps in existing surveillance systems, including substantial underreporting and misclassification of cases, delays in laboratory confirmation and specimen referral, fragmented and non-interoperable data systems, inadequate workforce capacity, weak community participation, and policy barriers limiting cross-sectoral information sharing. Emerging innovations include mobile-based reporting platforms, SMS and event-based alert systems, real-time surveillance dashboards, participatory community surveillance, integrated data platforms linking human and veterinary health services, rapid diagnostic technologies combined with molecular confirmation techniques such as reverse-transcription polymerase chain reaction (RT-PCR), and genomic surveillance for tracking viral transmission dynamics. Evidence suggests that strengthening surveillance within a One Health framework can significantly improve early case detection, optimize the use of post-exposure prophylaxis, enhance outbreak response, and facilitate targeted canine vaccination strategies in high-risk settings. The integration of digital technologies, laboratory strengthening, and multisectoral collaboration represents a promising pathway toward achieving the global target of zero human deaths from dog-mediated rabies by 2030. Future research should evaluate the cost-effectiveness, scalability, and equity implications of digital and genomic surveillance approaches in resource-limited settings.

Keywords: Rabies, Surveillance, One Health, Integrated Bite Case Management, Zoonoses, Dog-mediated rabies

1. Introduction

Rabies is one of the oldest recognized zoonotic diseases and remains a major public health concern despite being entirely preventable through effective vaccination and timely post-exposure prophylaxis (PEP). The disease is caused by neurotropic viruses belonging to the genus *Lyssavirus* and is transmitted primarily through the saliva of infected mammals, most commonly via bites or scratches ^[7].

Once clinical symptoms appear, rabies is almost invariably fatal, making prevention and early intervention the cornerstone of disease control [8]. Globally, rabies is responsible for an estimated 59,000 human deaths each year, although the true burden is believed to be substantially higher because of underreporting and diagnostic limitations [1].

More than 95% of human rabies cases result from bites by infected domestic dogs, highlighting the central role of canine populations in disease transmission and persistence [2]. The burden of rabies is disproportionately concentrated in low- and middle-income countries, particularly in South and Southeast Asia and sub-Saharan Africa, where inadequate access to healthcare services, diagnostic facilities, vaccines, and surveillance infrastructure continues to hinder effective disease control [3]. The persistence of rabies in endemic regions reflects a complex interplay of biological, socioeconomic, environmental, and health-system factors. Inadequate dog vaccination coverage, poorly managed free-roaming dog populations, poverty-related barriers to healthcare access, and delayed or incomplete PEP administration remain major drivers of transmission [4]. Furthermore, many exposed individuals fail to seek medical attention because of treatment costs, geographical barriers, limited health literacy, and poor awareness of the fatal consequences of rabies infection [5]. Human rabies deaths are also frequently misdiagnosed as encephalitis or other neurological disorders, resulting in substantial underestimation of disease burden and weakened public health response [6]. Consequently, rabies continues to be classified as a neglected tropical disease and remains a marker of profound health inequities within and between countries.

Rabies exemplifies a classic One Health challenge because its transmission dynamics are shaped by the interconnected health of humans, animals, and their shared environment. Domestic dogs serve as the primary reservoir and source of human infection in most endemic settings, while environmental factors such as urbanization, population growth, waste accumulation, and increased human-animal interactions contribute to sustained transmission [7]. Effective rabies control therefore requires coordinated interventions that extend beyond clinical management to include mass canine vaccination, responsible dog ownership, population management strategies, public education, and environmental health measures. Among the essential pillars of rabies prevention and elimination, surveillance occupies a central role. Public health surveillance encompasses the systematic collection, analysis, interpretation, and dissemination of health-related information needed to guide public health action [9]. In the context of rabies, surveillance enables timely identification of exposures, rapid detection of suspected cases, monitoring of disease trends, assessment of vaccination coverage, and evaluation of intervention effectiveness [1]. Robust surveillance systems are also critical for directing limited resources toward high-risk populations and geographic hotspots. Despite its importance, rabies surveillance remains inadequate in many endemic countries. Weak reporting mechanisms, limited laboratory capacity, poor specimen transport systems, fragmented information platforms, and insufficient integration between veterinary and human health sectors contribute to delayed case detection and incomplete reporting [6,7]. As a result, the actual burden of rabies often remains hidden, impairing evidence-based policymaking and resource allocation. These deficiencies are

particularly problematic in resource-constrained settings where surveillance data serve as the foundation for targeting vaccination campaigns, optimizing PEP use, and monitoring progress toward elimination goals. To address these challenges, Integrated Bite Case Management (IBCM) has emerged as an effective surveillance and response strategy that strengthens collaboration between medical and veterinary services. Through coordinated investigation of animal bite incidents, observation or laboratory testing of suspect animals, and risk-based decision-making for PEP administration, IBCM enhances case detection while reducing unnecessary treatment costs [10]. Furthermore, advances in digital health technologies, rapid diagnostic testing, molecular epidemiology, and genomic surveillance are creating new opportunities to strengthen rabies surveillance systems and improve outbreak response.

Although numerous studies have examined individual aspects of rabies epidemiology, canine vaccination, diagnostics, or disease control, the available evidence remains fragmented regarding how surveillance systems function across human and animal health sectors and how emerging innovations can address persistent implementation barriers. Existing literature often focuses on isolated components of surveillance rather than providing a comprehensive synthesis of surveillance pathways, diagnostic validation processes, operational challenges, and integrated One Health solutions. This represents an important knowledge gap, particularly at a time when countries are striving to achieve the global goal of eliminating dog-mediated human rabies deaths by 2030 under the "Zero by 30" initiative. Given the central role of surveillance in rabies prevention, elimination, and health-system strengthening, a comprehensive assessment of current surveillance approaches and emerging innovations is needed. Such an assessment can identify critical system weaknesses, highlight evidence-based best practices, and inform policies that will promote stronger multisectoral collaboration. Therefore, this review aims to examine the epidemiology and persistence of rabies, evaluate existing surveillance and diagnostic validation systems, explore the role of surveillance within a One Health framework, identify key operational challenges, and synthesize evidence-based strategies that can strengthen national rabies control programmes and accelerate progress toward the global target of zero human deaths from dog-mediated rabies by 2030.

2. Literature Review

2.1. Rabies Epidemiology: Transmission Pathways Across Species and Ecosystems

Viruses in the genus *Lyssavirus*, most frequently the classical rabies virus (RABV), cause rabies, a deadly zoonotic encephalitis. The main way that the virus is spread is by bites, scratches, or mucosal contact that introduces virus-laden saliva into tissues [11]. A complex human-animal-environment interface is reflected in the epidemiology of rabies, which is defined by interrelated transmission cycles that affect domestic, wildlife, and human populations. About 99% of human rabies infections worldwide are still caused by domestic dogs, making them the primary reservoir and source of the disease [1]. The majority of human infections in endemic areas of Africa and Asia are caused by persistent transmission within populations of free-roaming dogs. When there is inadequate vaccination coverage and poor dog population management, these domestic cycles are

maintained. However, wildlife species like skunks, foxes, raccoons, and bats, especially in the Americas and parts of Europe, have distinct sylvatic cycles^[12]. Different viral strains that can spread across species are maintained in these wildlife reservoirs.

Rabies transmission paths are greatly influenced by anthropogenic and environmental variables. Increased contact between domestic animals, wildlife, and humans is facilitated by habitat fragmentation, agricultural growth, and urban encroachment^[4]. For instance, vampire bat-cattle contacts have grown due to deforestation and intensified livestock in Latin America, perpetuating bat-associated rabies cycles^[13]. Additionally, host density, breeding cycles, and mobility patterns may all be impacted by climate variability, which could have an impact on the dynamics of transmission^[14]. Viral spread throughout ecosystems is further facilitated by human-mediated dog mobility, including trade, migration, and transboundary travel^[15]. Therefore, the spread of rabies is a multi-host, multi-ecosystem process influenced by biological, environmental, and socio-behavioral factors. Designing successful One Health solutions requires a fundamental understanding of these pathways.

2.2. Regional Epidemiology in Endemic Settings

There are significant regional differences in rabies epidemiology, which are mostly caused by variations in post-exposure prophylaxis (PEP) availability, surveillance capabilities, and vaccine coverage. Despite being avoidable by vaccination, rabies is thought to kill 59,000 people each year, with Asia and Africa bearing the brunt of this burden^[1]. Due to insufficient mass dog vaccination, scant laboratory confirmation, and ineffective surveillance systems, endemic canine rabies continues to exist in sub-Saharan Africa. With sporadic overflow into humans and livestock, transmission is mostly maintained within populations of dogs that are allowed to wander freely. Increased dog reproduction during seasonal peaks frequently results in the introduction of vulnerable juvenile cohorts into the population^[16]. Access to timely PEP is often delayed or prevented by a lack of knowledge and financial constraints, which raises the risk of death (5). Similar high rates of rabies occur in South and Southeast Asia, especially in locations with high densities and a high number of stray dogs. Under-reporting and dispersed surveillance make it difficult to estimate the burden of rabies in India, which is responsible for a significant amount of the world's rabies deaths^[17]. In contrast, canine rabies has been eradicated in many regions of North America and Europe thanks to well-coordinated dog vaccination campaigns and wildlife rabies control initiatives. However, enzootic transmission cycles are still maintained by wildlife reservoirs, such as red foxes in Eastern Europe and raccoons in the United States^[18]. In Latin America, regional elimination initiatives have markedly reduced dog-mediated rabies; however, bat-associated rabies variants remain a public health concern in Amazonian regions.

2.3. Reservoir Dynamics, Wildlife Interfaces, and Spillover Risk

Rabies persistence depends on competent reservoir hosts capable of maintaining transmission within populations. Domestic dogs serve as the primary maintenance reservoir in

most low-income settings, whereas multiple wildlife species act as independent reservoirs in higher-income countries^[19]. Distinct viral variants often adapt to specific host species, although cross-species transmission can occur when ecological interfaces facilitate contact.

Spillover risk is influenced by host density, movement ecology, and environmental aggregation points. High-density dog populations promote sustained intraspecific transmission, while migratory or wide-ranging wildlife species can disseminate virus across large geographic areas^[20]. Urban expansion and food waste availability may increase wildlife congregation near human settlements, intensifying interaction rates. A notable illustration of reservoir dynamics is bat-associated rabies. Hematophagous vampire bats (*Desmodus rotundus*) in Latin America sustain cycles of transmission that occasionally spread to humans and animals^[13]. Bat feeding behaviour is altered by ecological disturbances, which are frequently linked to such spillover events. Therefore, knowledge of host ecology, reservoir competency, and environmental factors that influence spillover potential at wildlife-domestic-human interfaces is necessary for effective rabies prevention.

2.4. Implications for Integrated Surveillance Design

Rabies surveillance needs to include an integrated One Health approach that connects the environmental, veterinary, and human sectors due to its complex ecology. Data on animal bites, laboratory-confirmed rabies cases, dog vaccination coverage, wildlife monitoring, and PEP use are all combined in effective systems^[21]. Sharing information across sectors facilitates targeted intervention and improves early outbreak detection. By enhancing the identification of bite episodes and suspicious animal cases, community-based reporting systems can improve surveillance in environments with limited resources^[5]. Risk mapping and resource allocation are further improved by including ecological data, such as animal migration corridors and land use change, and GIS techniques. In addition to enhancing epidemiological knowledge, integrated surveillance promotes targeted immunisation efforts and advances the worldwide objective of eradicating dog-mediated human rabies.

3. Rabies Surveillance System

Rabies surveillance systems are critical components of national and global public health strategies aimed at preventing human deaths and achieving the goal of zero human rabies deaths from dog-mediated transmission by 2030, as endorsed by the World Health Organization, the World Organisation for Animal Health, the Food and Agriculture Organization, and the Global Alliance for Rabies Control^[2,2,3]. Effective rabies surveillance integrates human and animal health data within a One Health framework, recognising that over 99% of human rabies cases result from bites by infected dogs^[22]. Surveillance systems aim to detect cases promptly, guide post-exposure prophylaxis (PEP) administration, monitor trends, evaluate vaccination campaigns, and inform resource allocation. However, underreporting remains a major challenge, particularly in low- and middle-income countries, due to limited laboratory capacity, weak health information systems, and poor coordination between human and veterinary sectors^[1].

3.1. Human Rabies Surveillance Frameworks

Human rabies surveillance frameworks are typically embedded within national notifiable disease reporting systems and coordinated by ministries of health. Rabies is classified as a legally notifiable disease in many countries, requiring clinicians to report suspected and confirmed cases to district and national authorities [22]. Surveillance begins at the point of care, where healthcare providers assess patients presenting with animal bites or symptoms suggestive of rabies, such as hydrophobia, aerophobia, and progressive encephalitis. Standardised case definitions, often aligned with WHO guidelines, are used to classify suspected, probable, and confirmed cases to ensure consistency in reporting. Integrated Disease Surveillance and Response (IDSR) frameworks in African countries provide structured reporting channels from health facilities to district and national levels, facilitating aggregation and analysis of data [24]. In addition to case-based reporting, many countries monitor the number of animal bite cases and PEP administrations as proxy indicators of rabies risk and service utilisation. Mortality surveillance systems, including verbal autopsy tools in community settings, also contribute to identifying probable rabies deaths where laboratory confirmation is unavailable [1]. Nevertheless, stigma, limited diagnostic confirmation, and misclassification of encephalitis cases continue to undermine the accuracy of human rabies surveillance data.

3.2. Animal and Wildlife Surveillance Systems

Animal and wildlife surveillance systems are central to rabies control, given that the disease is primarily zoonotic. Veterinary services typically oversee animal rabies surveillance, which includes monitoring domestic dogs, livestock, and wildlife reservoirs. In many endemic regions, dog-mediated rabies remains the dominant transmission pathway; therefore, canine surveillance is prioritised through reporting of suspected rabid dogs, bite investigations, and monitoring of mass dog vaccination campaigns [23]. Veterinary officers investigate reported animal bite incidents, quarantine or observe suspected animals, and collect brain samples from animals that die or are euthanised for laboratory testing. Wildlife surveillance is particularly important in regions where rabies is maintained in wild reservoirs such as foxes, raccoons, bats, and jackals. In Europe and North America, oral rabies vaccination programmes targeting wildlife species have been supported by structured surveillance networks coordinated by organisations such as the World Organisation for Animal Health, enabling monitoring of rabies elimination progress [25]. Animal surveillance data are reported through international platforms such as the World Animal Health Information System managed by WOA, facilitating cross-border information sharing. However, challenges persist, including limited field investigation capacity, poor community awareness leading to underreporting of suspect animals, and inadequate collaboration between veterinary and human health authorities, particularly in resource-limited settings [1].

3.3. Laboratory Diagnostics and Confirmation Pathways

Laboratory confirmation of rabies is essential for accurate surveillance and epidemiological monitoring. The gold standard diagnostic method for animals and humans post-mortem is the direct fluorescent antibody (DFA) test performed on brain tissue samples, which detects rabies virus

antigen with high sensitivity and specificity [26]. In recent years, molecular techniques such as reverse transcription polymerase chain reaction (RT-PCR) have enhanced diagnostic capacity by enabling viral RNA detection and strain typing, supporting molecular epidemiology and tracking of transmission pathways [18]. Antemortem diagnosis in humans is more complex and may involve testing saliva, cerebrospinal fluid, or skin biopsy samples using RT-PCR or immunofluorescence assays [18]. Reference laboratories, often designated as national rabies laboratories, provide confirmatory testing, quality assurance, and technical support to peripheral laboratories. International collaboration is facilitated through networks supported by WHO and WOA to standardise protocols and ensure biosafety compliance [10]. Sample transport systems, cold chain maintenance, and trained laboratory personnel are critical components of effective confirmation pathways. However, in many endemic countries, limited laboratory infrastructure and biosafety concerns restrict diagnostic confirmation, leading to reliance on clinical diagnosis and epidemiological linkage, which can compromise surveillance accuracy [1]. Strengthening laboratory capacity is therefore integral to improving the sensitivity and reliability of rabies surveillance systems.

3.4. Passive, Active, and Sentinel Surveillance Models

Rabies surveillance systems utilise a combination of passive, active, and sentinel surveillance models. Passive surveillance relies on routine reporting of suspected cases by healthcare providers, veterinarians, and community members. While cost-effective, it often underestimates disease burden due to incomplete reporting [26]. Active surveillance involves proactive case finding, such as community surveys, contact tracing following suspected rabies deaths, and targeted investigations in high-risk areas. This approach provides more accurate incidence data but requires substantial resources. Sentinel surveillance uses selected health facilities or geographic areas to monitor trends and detect outbreaks, offering a practical compromise in resource-limited settings [27]. Integrating these models within a One Health framework enhances early detection and coordinated response.

3.5. Data Flow, Notification, and Feedback Mechanisms

Effective rabies surveillance depends on efficient data flow, timely notification, and feedback mechanisms across sectors. Data typically originate at community or facility level and are transmitted through district and national reporting systems using paper-based or electronic platforms. Digital health information systems have improved real-time reporting and data aggregation in some countries [28]. Confirmed human cases are reported to national authorities and, where required, to WHO through the International Health Regulations framework [26]. Animal cases are reported to WOA through its global reporting system. Feedback mechanisms, including surveillance bulletins, stakeholder meetings, and performance reviews, are essential for informing frontline workers and guiding policy adjustments [23]. However, fragmentation between human and animal health data systems often impedes comprehensive analysis. Strengthening interoperable data platforms and fostering intersectoral communication are therefore vital to achieving effective rabies surveillance and elimination goals [26, 23].

4. Surveillance Gaps and Systemic Challenges

Despite global commitment to eliminate dog-mediated

human rabies by 2030 under the “Zero by 30” strategy led by the World Health Organization, the Food and Agriculture Organization, the World Organisation for Animal Health, and the Global Alliance for Rabies Control, substantial surveillance gaps persist in endemic regions^[10, 29]. Surveillance systems in many low- and middle-income countries remain under-resourced, fragmented, and heavily dependent on passive reporting mechanisms, resulting in chronic underestimation of disease burden^[3, 30]. While global modelling studies suggest tens of thousands of annual deaths, officially reported figures are far lower, reflecting systemic weaknesses in detection, confirmation, and reporting processes^[17, 31]. Surveillance challenges are multidimensional, encompassing underascertainment, sectoral fragmentation, limited diagnostic access, weak data integration, and contextual barriers that disproportionately affect rural and underserved populations^[32]. Addressing these structural gaps is essential to ensure accurate epidemiological intelligence, guide vaccination strategies, and optimise post-exposure prophylaxis (PEP) allocation.

4.1. Underascertainment and Reporting Biases

Underascertainment remains one of the most critical weaknesses in rabies surveillance. Many rabies deaths occur outside formal healthcare systems, particularly in rural communities where access to medical services is limited and fatalities occur at home without laboratory confirmation^[3, 31]. Verbal autopsy studies have demonstrated that rabies deaths are frequently misclassified as other neurological conditions such as cerebral malaria or unspecified encephalitis^[7]. Passive surveillance systems, which rely on healthcare worker reporting, are inherently dependent on care-seeking behaviour and clinical suspicion, leading to systematic underreporting^[10]. Cultural beliefs and stigma associated with neurological symptoms may discourage families from reporting suspected rabies deaths^[33]. In addition, inconsistencies in applying standardised case definitions contribute to reporting bias across districts and countries^[26]. Animal rabies surveillance is similarly affected by underreporting, as community members may fail to notify veterinary authorities about suspected rabid animals, particularly where compensation mechanisms for livestock losses are absent^[29]. These cumulative reporting gaps produce distorted epidemiological data, limiting the reliability of national surveillance statistics and impeding effective public health planning.

4.2. Human–Animal Health Sector Fragmentation

Rabies epitomises the need for a One Health approach; however, fragmentation between human and animal health sectors continues to undermine surveillance^[34]. Ministries of health and veterinary authorities frequently operate separate reporting chains, databases, and funding streams, with limited routine data sharing^[30]. This structural division hampers coordinated outbreak response and risk assessment. For example, human bite case data may not automatically trigger veterinary investigations or dog vaccination campaigns, while animal surveillance findings may not inform PEP stock forecasting^[9]. Studies have shown that countries with formalised intersectoral coordination mechanisms demonstrate stronger rabies control outcomes

compared to those with siloed systems^[33]. Funding imbalances further exacerbate fragmentation, as investments often prioritise human PEP procurement over sustained canine vaccination programmes, despite evidence that dog vaccination is the most cost-effective long-term control strategy^[4]. Legal and policy barriers may also restrict cross-sectoral data sharing, particularly where privacy regulations or institutional mandates are unclear. Strengthening joint surveillance platforms, shared indicators, and integrated data dashboards is therefore fundamental to operationalising One Health principles in rabies elimination strategies^[29, 23].

4.3. Diagnostic Access and Laboratory Delays

Diagnostic limitations significantly weaken rabies surveillance sensitivity and timeliness. Although the direct fluorescent antibody (DFA) test remains the gold standard for post-mortem confirmation, its availability is largely restricted to central reference laboratories in many endemic countries^[22]. Peripheral health facilities often lack the infrastructure, biosafety equipment, and trained personnel required to process brain tissue specimens^[31]. Specimen referral systems are frequently constrained by transportation challenges, cold chain interruptions, and administrative delays, resulting in prolonged turnaround times or sample degradation^[29]. Molecular diagnostics such as reverse transcription polymerase chain reaction (RT-PCR) offer enhanced sensitivity and enable viral lineage tracking, but they require advanced laboratory capacity and sustained reagent supply chains^[18]. In human cases, ante-mortem diagnosis is technically complex and rarely performed in resource-limited settings, contributing to reliance on clinical classification rather than laboratory confirmation^[26]. Wildlife surveillance faces additional diagnostic barriers, including carcass decomposition and limited field sampling capacity. Collectively, these diagnostic gaps reduce the proportion of laboratory-confirmed cases, limit strain surveillance, and delay outbreak detection. Expanding decentralised laboratory networks, strengthening quality assurance systems, and investing in rapid diagnostic technologies are therefore essential for improving surveillance robustness^[18, 23].

4.4. Data Integration, Interoperability, and Quality Challenges

Data fragmentation and limited interoperability remain persistent challenges within rabies surveillance systems. Human health information platforms and veterinary databases frequently use incompatible data structures, preventing seamless integration and cross-sectoral analysis^[34]. In many endemic countries, paper-based reporting systems remain prevalent at peripheral levels, increasing risks of transcription errors, incomplete datasets, and delayed aggregation^[10]. Even where electronic systems exist, they may lack standardised case definitions or automated validation checks, reducing data quality^[30]. Inconsistent geographic coding and absence of unique identifiers complicate longitudinal case tracking and outbreak mapping. Furthermore, limited analytic capacity at district and national levels restricts the translation of surveillance data into actionable insights. Weak feedback mechanisms can demotivate frontline health workers, reducing reporting compliance^[33]. Addressing these issues requires harmonised reporting standards, interoperable digital

platforms, routine data quality audits, and investment in workforce capacity for epidemiological analysis and interpretation.

4.5. Contextual Constraints in Endemic Regions

Contextual factors in endemic regions further compound surveillance challenges. Many high-burden countries face competing public health priorities, limited domestic financing, and fragile health systems, constraining sustained investment in rabies infrastructure ^[4,26]. Rural populations often encounter geographical barriers that delay healthcare access and specimen referral, while large free-roaming dog populations complicate animal surveillance and vaccination coverage estimation ^[29]. Political instability, humanitarian crises, and cross-border population movement disrupt surveillance continuity and data reporting. Socioeconomic inequities also influence care-seeking behaviour, particularly where PEP costs remain a financial burden despite policy commitments to free provision ^[31]. Limited community awareness regarding rabies transmission and reporting requirements further weakens surveillance sensitivity. Sustainable improvement therefore demands context-specific, community-engaged approaches aligned with the Zero by 30 framework and supported by long-term multisectoral investment.

5. Innovation in Rabies Surveillance

5.1. Digital and Mobile-Based Reporting Systems

A comprehensive and sensitive Animal Disease Surveillance System (ADSS) is vital for determining disease status, monitoring epidemiological trends, and planning effective animal health interventions, including a national rabies control program ^[35]. Strengthening Nigeria's ADSS is therefore critical to building a resilient framework capable of detecting, diagnosing, reporting, and responding to outbreaks in real time. The long-term vision is to transform the ADSS into an epidemiological intelligence system that functions as an early warning mechanism, provides risk estimates, evaluates state-level preparedness, and tracks changes in the distribution and determinants of rabies within source populations ^[35]. Achieving this requires modernization of the data reporting framework at community, state, and national levels to accommodate technological innovations and ensure interoperability. Digital and mobile-based reporting systems provide a practical pathway toward this transformation. Mobile applications, SMS alerts, and cloud-linked dashboards can facilitate rapid case reporting by frontline health workers, veterinarians, and community members, even in rural areas with limited infrastructure ^[36]. These tools reduce reporting delays, improve data accuracy, and enable timely interventions.

Equally important is capacity building among healthcare and veterinary personnel to ensure readiness for digital adoption. Training, technical support, and sustained investment in mobile technologies will enhance efficiency and accountability ^[36]. Embedding digital systems into rabies surveillance will strengthen outbreak response, improve decision-making, and accelerate progress toward rabies elimination

5.2. Community-Based and Participatory Surveillance Approaches

In Nigeria, mass advocacy on rabies is limited, with most activities concentrated around World Rabies Day on

September 28 ^[36]. Yet, awareness promotion remains a cornerstone of rabies elimination strategies ^[37]. Effective advocacy campaigns, particularly in rural communities, are as critical to rabies control as technical interventions such as dog vaccination ^[36]. To maximize their impact, advocacy should be organized alongside canine mass vaccination drives, ensuring that preventive and curative measures reinforce one another. The development of e-learning modules for stakeholders including children, para-medical staff, and veterinarians offers an avenue to extend outreach, while the circulation of information through social media platforms enables faster and broader dissemination ^[35]. Nigeria's multi-lingual and multi-ethnic context presents challenges for program implementation, but the involvement of local NGOs, community clubs, and grassroots organizations can help bridge communication gaps and foster inclusivity ^[35]. Public education and enlightenment campaigns should emphasize preventive practices, first-aid actions following dog bite incidents, the necessity of seeking post-exposure prophylaxis (PEP), and the importance of responsible pet ownership ^[35]. Embedding these themes within advocacy and education efforts empowers communities to take ownership of rabies prevention, thereby strengthening participatory surveillance approaches and ensuring that control strategies remain sustainable, culturally responsive, and widely accepted.

5.3. Geographic Information System (Gis), Spatial Modeling, And Risk Mapping

Geographic Information Systems (GIS) provide a powerful means of integrating geographical factors and diverse datasets into spatial formats that can be applied in both epidemiology and public health ^[38]. In the context of rabies, studies have demonstrated that environmental variables such as temperature and rainfall significantly influence disease occurrence ^[38]. Researchers have utilized GIS to map rabies cases, assess risk levels, and predict patterns of spread across regions, thereby offering valuable guidance for prevention efforts and vaccination strategies ^[39]. Spatiotemporal models further enhance these applications by predicting outbreaks through indices derived from epidemiological datasets. Evidence from China highlights the use of Bayesian hierarchical models to identify high-risk areas, with findings indicating that Poisson models more accurately capture the temporal and spatial distribution of rabies incidence ^[40]. Analytical tools such as SaTScan and Moran indices have gained popularity due to their accessibility in both commercial platforms like ArcGIS and MapInfo, and free software such as GeoDa and TerraView, which are supported by extensive didactic resources ^[38]. The integration of these spatial approaches strengthens understanding of rabies transmission dynamics and supports the design of more effective surveillance and intervention strategies.

5.4. AI, Machine Learning, and Predictive Analytics

Artificial Intelligence (AI) encompasses a range of computational techniques designed to enable machines to imitate human ^[41]. Its applications are expanding rapidly across diverse fields, including medicine and public health, where AI is increasingly recognized as a tool for improving disease surveillance and management ^[41]. Within this domain, machine learning (ML), a subset of AI that enables computers to learn from data and make predictions, has emerged as a transformative approach to outbreak prediction

and control. By analyzing large and heterogeneous datasets, ML can uncover complex patterns that traditional epidemiological method often misses, positioning it as a cornerstone of modern public health surveillance [42]. Its predictive capabilities allow for the early detection of disease hotspots and the design of dynamic response strategies, thereby strengthening preparedness and intervention efforts [42].

Recent studies have demonstrated the utility of ML frameworks in rabies control. For instance, models have been developed to predict rabies outcomes using case histories and clinical signs from animals suspected of exposing humans to the virus [43]. Extreme gradient boosting combined with logistic regression has proven effective in estimating the probability of rabies in animals investigated under the WHO-recommended integrated bite case management program. To address data imbalance, techniques such as random oversampling and synthetic minority oversampling were employed [43]. Similarly, the imbalanced-XGBoost model integrated with kriging has yielded promising results in predicting rabies incidence [44]. These innovations are expected to significantly enhance rabies control strategies by guiding targeted interventions, improving the identification of high-risk patients, and supporting the equitable distribution of pre- and post-exposure prophylaxis [45].

5.5. Event-Based and Syndromic Surveillance Integration

Syndromic and event-based surveillance systems are increasingly recognized as vital tools for the early detection of emerging zoonotic threats [46]. Syndromic surveillance focuses on the real-time or near-real-time collection of clinical symptom data, often preceding formal diagnosis, thereby enabling faster responses to potential outbreaks [46]. In Nigeria, where surveillance resources remain limited, innovative approaches are required to strengthen case detection. One practical solution is the use of free short text messaging systems, allowing dog bite victims or local leaders to report incidents directly to central authorities such as the Nigerian Centre for Disease Control (NCDC) and the Federal Veterinary Department [47]. This approach could expand reporting coverage and improve understanding of the geographical distribution of rabies exposures [47].

6. Operationalizing One Health Surveillance for Rabies

6.1. One Health Surveillance Frameworks and Models

Rabies One Health surveillance will need integrated structures to mediate the linkage of human, animal, and environmental health sectors to enable real-time identification and reporting in endemic areas where resources are limited. A good example of a systems-based approach is the Joint Risk Analysis (JRA) framework that was assembled by the World Organisation for Animal Health (WOAH) and its partners. It has integrated risk assessment between various silos and also facilitated the sharing of data due to standardized protocols that gather syndromic indications of veterinary and clinical information [48,49]. Complementing this, the Integrated Surveillance for Zoonoses (ISZ) model promotes cross-sectoral platforms where animal bite reporting from community sentinels feeds into human syndromic surveillance systems, leveraging digital tools for bidirectional data flow and early anomaly detection [50,51]. Emerging paradigms, such as the HealthMap/One Health Intelligence platforms, incorporate event-based surveillance by aggregating unstructured data from social media,

veterinary alerts, and laboratory networks into real-time dashboards, enhancing predictive analytics via machine learning algorithms tailored for low-bandwidth environments [52]. The FAO-OIE-WHO Tripartite Guide further operationalizes these through scalable, participatory models that embed intersectoral coordination mechanisms, including joint outbreak verification committees and shared electronic case-based reporting systems [53,48].

6.2. Cross-Sector Coordination and Governance Mechanisms

The existing cross-sector coordination and governance structures on which One Health rabies surveillance relies is tainted by structural flaws that have remained intact to hinder timely detection and reporting in the endemic areas. The existing cross sector coordination and governance structures on which One Health rabies surveillance relies is tainted by structural flaws that have remained intact to hinder timely detection and reporting in the endemic areas. Despite frameworks such as the FAO-OIE-WHO Tripartite collaboration and Integrated Bite Case Management (IBCM), institutional silos between human health ministries, veterinary services, and environmental agencies perpetuate fragmented data flows, with veterinary surveillance often capturing animal trends while human health systems underreport cases due to disjointed risk assessments and PEP decisions [54,55]. Coordination failures manifest in ad hoc multi-sectoral committees lacking formal mandates, resulting in delayed joint investigations and poor feedback loops, as evidenced by weak linkages between bite notifications and animal tracing, which exacerbate underreporting cycles [56,54]. Power asymmetries further undermine efficacy, with human health sectors dominating resource allocation and agenda-setting, thereby marginalizing veterinary inputs on reservoir dynamics and sidelining environmental monitoring of wildlife interfaces, which distorts surveillance priorities toward reactive human cases over proactive zoonotic threat mapping [57]. The governance weaknesses that are offset by the absence of harmonized legal frameworks, inadequate data-sharing guidelines, and decentralized funding streams lead to the suboptimal timeliness, representativeness, and completeness of surveillance data.

6.3. Integrated Data Platforms and Joint Outbreak Investigations

The existence of regional variations in the rates of rabies notification highlights discrepant reporting practices and constrains intersectoral relationships, hence establishing an accountability vacuum under which the leadership is unclear and continues to put a region at risk of a spill-over event in resource-deprived environments [1]. One Health rabies surveillance is an essential but underdeveloped area of integrated data platforms and collaborative outbreak investigations, whereby the ineffective information systems used by human and veterinary agencies facilitate the continued erosion of real-time detection and response efficacies in resource-constrained endemic situations. Platforms such as HealthMap and ProMED exemplify event-based surveillance by aggregating syndromic alerts from veterinary reports, clinical notifications, and social media into centralized dashboards, offering strengths in timeliness through machine learning-driven anomaly detection [59,60]. However, their limitations emerge in poor interoperability with national electronic Integrated Disease Surveillance and

Response (IDSR) systems, resulting in data silos that delay cross-sectoral validation and underrepresent rural animal reservoirs ^[51]. Similarly, the FAO-OIE-WHO Tripartite's joint outbreak verification protocols facilitate coordinated investigations by mandating multi-sectoral teams for bite case-animal tracing linkages, enhancing representativeness via shared case definitions, yet coordination challenges manifest in asynchronous reporting cycles and incompatible data formats compromise actionability, as veterinary laboratory results often arrive post-human PEP decisions ^[62]. In rabies-endemic settings, these platforms struggle with bandwidth constraints and heterogeneous data standards, yielding incomplete epizootic profiles that obscure spillover dynamics, while joint investigations falter due to mismatched jurisdictional priorities, overburdened personnel, and absent governance for real-time data-sharing agreements ^[54,55]. Comparative analyses reveal that while digital tools like IBCM apps streamline bite notifications, scalability remains elusive without harmonized ontologies, perpetuating discrepancies in timeliness metrics, human cases reported within 48 hours versus animal confirmations lagging weeks, thus exposing systemic vulnerabilities in achieving seamless One Health integration for proactive rabies control ^[64].

6.4. Case Studies from Endemic Regions

Case studies from rabies-endemic regions illuminate the variable efficacy of One Health surveillance implementations, revealing both transformative potential and entrenched operational hurdles in integrating human-animal data for real-time detection. In Tanzania, the rollout of Integrated Bite Case Management (IBCM) across 20 districts quadrupled rabid animal detections within one year by linking bite registries to veterinary investigations, demonstrating enhanced cross-sectoral communication and PEP optimization, yet it faltered due to health worker training deficits and livestock officers' resource shortages that delayed field responses ^[65]. Similarly, Kenya's community-based reporting in rural Laikipia confirmed five rabid dogs from 14 alerts via field diagnostics and sequencing, underscoring localized transmission chains akin to Tanzanian variants, but exposed underreporting from fragmented diagnostics and low PEP access ^[66]. The Philippines' Albay Province IBCM initiative boosted case ascertainment by 4-fold amid high bite incidence (>600/100,000), highlighting surveillance skewed by PEP proximity rather than the true burden, with scalability impeded by paper-based systems and jurisdictional silos ^[67]. Uganda's participatory IBCM form design addressed siloed tools like EMA-i and IDSR through multi-stakeholder REACT apps, improving data completeness, though persistent funding gaps for sample transport perpetuated under-notification ^[68]. Indonesia's Minahasa Regency efforts and Bali's decade-long campaigns achieved coordination gains via mass vaccination and surveillance, yet grappled with educational shortfalls and uneven stakeholder buy-in ^[69]. Collectively, these cases affirm IBCM's strengths in focal detection and intersectoral alerts, but critique persistent limitations in interoperability, rural scalability, and sustainability amid bandwidth and capacity constraints, yielding lessons on context-tailored adaptations while exposing gaps in equitable resource distribution for holistic rabies control.

6.5. Role of Communities, Veterinarians, and Frontline Workers

Communities, veterinarians, and frontline workers constitute critical yet underutilized sentinels in One Health rabies surveillance within endemic regions, where their localized insights could bridge human-animal interfaces for real-time detection. However, fragmented training and role ambiguity marginalize veterinarians' animal case investigations, while overburdened community health workers prioritize reactive bite management over proactive syndromic reporting, perpetuating under-ascertainment of wildlife reservoirs ^[70]. Missed opportunities abound in untapped community networks for event-based alerts and veterinarians' exclusion from human-centric data loops, undermining cross-sectoral integration ^[4]. These silos compromise timeliness and completeness, revealing systemic failures to empower frontline actors as co-equal surveillance pillars in resource-constrained settings.

7. Strengthening Real-Time Detection and Reporting

7.1. Real-Time, Interoperable Surveillance Architectures

Rabies surveillance in Nigeria remains fragmented and underdeveloped, with neither adequate national validated data on the burden of human rabies nor active monitoring of dog bite incidents in humans or rabies in animals, including dogs and wildlife ^[35]. The rabies control program is constrained by insufficient data, weak surveillance systems, and inadequate funding for innovations and interventions. Financial limitations have reduced mass vaccination campaigns to symbolic one-day events, such as the annual World Rabies Day celebrations, rather than sustained, nationwide efforts ^[35]. A critical weakness lies in the lack of effective communication, coordination, and collaboration, the "3Cs" of One Health between human and animal health sectors. Limited interaction among sector specialists, policymakers, and stakeholders has hindered the establishment of a unified surveillance framework capable of generating real-time, interoperable data ^[35]. Strengthening rabies control in Nigeria requires improving surveillance infrastructure at all levels. Key actions include expanding laboratory diagnostic capacity, enhancing monitoring of dog-mediated transmission, strengthening community-based surveillance, and improving human health reporting systems. When integrated, these measures can produce timely, reliable data to support evidence-based interventions. Ultimately, robust and interoperable surveillance systems are essential for effective rabies prevention and for achieving national and global rabies control goals.

7.2. Laboratory Network Optimization for Rapid Confirmation

Rabies diagnostics in Nigeria are constrained by a limited laboratory network. Currently, the National Veterinary Research Institute (NVRI), Vom serves as the sole facility for dog rabies diagnosis, while the African Centre of Excellence for Neglected Tropical Diseases and Forensic Biotechnology (ACENTDFB) at Ahmadu Bello University, Zaria is the only centre with capacity for human rabies diagnostics ^[35]. This restricted infrastructure creates significant logistical challenges, as samples including dog heads and human specimens, must be transported across long distances for confirmation, often resulting in delays and reduced efficiency.

The reliance on just two laboratories, neither of which operates at optimal capacity, undermines national rabies control efforts. Strengthening these facilities through upgrading regional infrastructure, expanding diagnostic capacity, and ensuring adequate funding and staffing would markedly improve Nigeria's rabies surveillance system [70]. Furthermore, establishing additional regional laboratories across geopolitical zones would decentralize diagnostic services, reduce turnaround times, and enhance accessibility for both veterinary and human health sectors [70]. Optimizing the laboratory network is therefore critical for rapid case confirmation, timely interventions, and effective integration within a One Health framework. Without such improvements, Nigeria's rabies control program will continue to struggle with delayed diagnoses and insufficient surveillance coverage.

7.3. Digital Notification and Feedback Systems

Digital notification and feedback systems play a critical role in enhancing the responsiveness and efficiency of disease surveillance frameworks. These systems enable real-time communication between healthcare providers, veterinary officers, public health authorities, and community members, thereby facilitating timely reporting, response, and follow-up. In the context of rabies control, digital platforms can be used to notify central health authorities of suspected cases, track vaccination coverage, and monitor post-exposure prophylaxis (PEP) administration [35].

Mobile-based applications and SMS platforms are particularly valuable in low-resource settings like Nigeria, where internet access may be limited. These tools allow for rapid data collection and dissemination, enabling bite victims, local leaders, or health workers to report incidents directly to agencies such as the Nigerian Centre for Disease Control (NCDC) or the Federal Veterinary Department [36]. Feedback mechanisms integrated into these systems can provide users with guidance on next steps, such as seeking medical attention or initiating PEP.

Moreover, digital dashboards and automated alerts can support decision-making by visualizing trends, identifying hotspots, and prompting timely interventions [35]. By fostering two-way communication and improving data flow, digital notification and feedback systems strengthen surveillance networks and contribute to more effective and coordinated rabies prevention and control strategies.

7.4. Scalability and Sustainability Considerations

Ensuring the scalability and sustainability of rabies surveillance in Nigeria requires a clear understanding of system capacity and the factors influencing effective case detection. Identifying these determinants enables the design of interventions that strengthen timely diagnosis, reporting, and response [71]. A structured needs assessment of existing infrastructure is essential to highlight gaps, prioritize resources, and generate actionable learning outcomes. Such assessments will inform strategies for long-term sustainability, ensuring that surveillance systems remain adaptable, resilient, and capable of supporting rabies control, eradication, and eventual elimination across diverse population settings.

8. Future Direction for One Health Rabies Surveillance

8.1. Research Gaps and Methodological Priorities

Future directions for One Health rabies surveillance demand rigorous addressing of persistent research gaps and methodological shortcomings that impede real-time integration across endemic settings. Foremost among these is the paucity of longitudinal studies evaluating cross-sectoral data interoperability, where disparate electronic systems for human syndromic surveillance and veterinary laboratory networks fail to yield harmonized epizootic profiles, necessitating standardized ontologies and validation frameworks for machine-readable zoonotic event streams [72]. Methodological weaknesses in current event-based surveillance, reliant on unstructured social media and clinician alerts, underscore the urgent need for prospective cohorts to assess predictive algorithm performance against ground-truthed rabies spillover dynamics, particularly at rural-wildlife interfaces [73,67]. Equally critical is the under-examination of spatiotemporal bias in bite case ascertainment, where probabilistic modeling of underreporting multipliers remains theoretically dominant but empirically sparse, limiting generalizability to diverse endemic ecologies [74]. Comparative effectiveness research comparing participatory IBCM platforms with centralized dashboards is conspicuously absent, as is causal inference on intersectoral capacity disparities using quasi-experimental designs [75]. Moreover, health economics analyses of scalable digital architectures tailored to low-bandwidth contexts lag, while genomic-epidemiologic integration for rabies reservoir tracking awaits robust field validations [76]. Prioritizing these gaps through multidisciplinary consortia will transition rabies surveillance from fragmented monitoring to predictive One Health intelligence, resolving methodological deficits that perpetuate surveillance inertia in resource-limited regions.

8.2. Scaling Integrated and Digital Surveillance Models

Scaling integrated and digital One Health rabies surveillance models across resource-limited endemic regions confronts profound scalability challenges that threaten their transformative potential despite evident architectural sophistication [77]. Cloud-based platforms promising real-time syndromic fusion from IBCM apps, veterinary laboratory feeds, and environmental sensors falter against infrastructural realities, intermittent connectivity, legacy paper registries, and heterogeneous data dialects that defy FHIR-compliant ontologies, yielding fragmented epizootic intelligence rather than seamless spillover forecasting [78]. Governance asymmetries exacerbate interoperability deficits, as human health ministries monopolize digital investments while veterinary networks languish on analog silos, perpetuating unidirectional data flows that undermine bidirectional rabies reservoir mapping [79]. Sustainability hinges on recurring costs for low-bandwidth edge computing and AI model retraining, yet donor-driven pilots rarely transition to national budgets, fostering boom-bust implementation cycles that erode workforce trust [80].

8.3. Equity and Coverage Expansion in Endemic Settings

Equity considerations loom largest, while urban-centric digital architectures marginalize rural sentinels, leaving

illiterate communities and under-resourced veterinarians unable to interface with smartphone-dependent systems, inadvertently amplifying ascertainment biases toward accessible human bites over occult wildlife cycles ^[81]. Strategic scaling demands hybrid architectures blending offline-first mobile tools with asynchronous synchronization protocols, coupled with federated governance vesting local ownership in multi-sectoral data stewards ^[82]. Absent such recalibrations, digital One Health surveillance risks entrenching technological elitism, diverting resources from equitable, context-rooted integration that alone can operationalize real-time rabies threat detection at the population scale. Equity challenges in One Health rabies surveillance manifest starkly across endemic regions, where urban-centric systems exacerbate rural exclusion and deepen disparities in real-time detection coverage. Frontline communities in remote settings, often illiterate or linguistically marginalized, remain decoupled from digital reporting platforms, while under-resourced veterinary outposts lack diagnostic reagents, yielding skewed ascertainment that privileges human bites over elusive wildlife cycles ^[83]. Gendered workloads further compound gaps, as female community health workers, primary bite responders, face mobility barriers and training deficits that sideline their zoonotic insights ^[84]. Coverage expansion demands decolonizing surveillance architectures through participatory co-design, vesting agency in indigenous sentinels, and hybrid analog-digital interfaces that accommodate low-literacy contexts ^[64]. The priorities of the future are based on federated data governance, ensuring that the voice of the rural areas is reflected in the national epizootic profiles, and capacity equity between veterinary and human health is also addressed ^[85]. Absent intentional recalibration toward inclusive sentinels and decentralized analytics, One Health frameworks risk perpetuating epistemic silos, entrenching underreporting among the most vulnerable populations, and undermining elimination equity in resource-limited landscapes.

9. Conclusion

Rabies elimination in endemic settings is largely constrained by weaknesses in surveillance rather than the absence of effective prevention and control tools. Major challenges include underreporting of human and animal cases, limited diagnostic capacity, fragmented human–animal health reporting systems, and inadequate resources. Strengthening surveillance through digital reporting systems, integrated bite case management, community-based surveillance, GIS mapping, and improved laboratory networks can accelerate detection and response. A One Health approach remains essential for linking human and animal health surveillance, improving data sharing, guide targeted interventions, and ensure efficient use of resources. Future efforts should prioritize interoperable surveillance systems, decentralized diagnostics, sustainable financing, and stronger national implementation frameworks to achieve the elimination of dog-mediated rabies.

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