Archives of Medical Reports

3(3) (2026) 24-30

OPEN ACCESS

REVIEW ARTICLE

One Health Approaches for Strengthening Infectious Disease Surveillance Across the Human Animal and Environmental Interface

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Articleinfo
Received: 2 April 2026
Accepted: 15 May 2026

Keywords: One Health; Infectious disease surveillance; Antimicrobial resistance; Public health.

How to cite this article: Swaliho Dauda Sheriff (2026). One Health Approaches for Strengthening Infectious Disease Surveillance Across the Human Animal and Environmental Interface, 3(3), 24-30. https://doi.org/10.26524/amr.2026.3.3

Abstract

The emergence of infectious diseases is increasingly influenced by the interactions between humans, animals and the environment. Conventional surveillance systems mainly depend on clinical diagnosis and laboratory confirmation in humans. Such systems may detect transmission only after a pathogen has become established within a human population. The One Health approach provides a broader framework by connecting human health surveillance with animal health and environmental monitoring. Recent developments in wastewater surveillance, pathogen genomics, and digital epidemiology have created new opportunities for earlier recognition of infectious disease threats. Environmental surveillance has expanded substantially since the COVID-19 pandemic. Wastewater surveillance is also becoming important for monitoring antimicrobial resistance because wastewater represents an interface between human populations, animal production systems and the environment. Genomic technologies can provide additional resolution by comparing pathogens detected in humans, animals and environmental samples. Digital platforms and artificial intelligence may further support the integration of large and heterogeneous surveillance datasets. This narrative review examines recent developments in One Health surveillance across the human animal and environmental interface.

1. Introduction

The emergence of infectious diseases is closely associated with the relationship between human populations, animals and the environment. Human expansion into wildlife habitats has increased contact between people and animal reservoirs. Intensive livestock production has created conditions that can facilitate pathogen amplification. Environmental degradation and climate change can modify the distribution of vectors and alter the persistence of infectious agents (Daszak et al., 2001; Mishra et al., 2021). International travel and animal movement can further accelerate the geographical spread of pathogens. These processes demonstrate that infectious disease emergence is not restricted to the human clinical setting. The importance of animal reservoirs has been recognized in many emerging infections. However the COVID-19 pandemic provided a particularly strong demonstration of the need for surveillance beyond conventional clinical systems. Human case surveillance was essential for estimating disease burden. Wastewater surveillance provided population-level information about viral circulation. Genomic surveillance enabled the identification of new viral variants. Animal investigations were required to understand susceptibility in different species and the possibility of additional transmission pathways (Ahmed et al., 2024; Djordjevic et al., 2024; Hill et al., 2024). These experiences demonstrated the value of combining information obtained from different biological systems.

The One Health concept has developed in response to this interconnected nature of health. The One Health High-Level Expert Panel defines one health as an integrated approach that seeks to sustainably balance and optimize the health of people, animals and ecosystems. This framework extends beyond the traditional concept of zoonotic disease control. It recognizes that infectious disease risk can also be influenced by climate change, biodiversity loss, and antimicrobial use. The World Health Organization, Food

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and Agriculture Organization of the United Nations, United Nations Environment Programme and World Organisation for Animal Health have incorporated these principles into the One Health Joint Plan of Action (One Health Joint Plan of Action, 2022–2026, 2022). Surveillance is central to these priorities because pathogen emergence may first become visible in animals or environmental systems rather than in human clinical settings. A pathogen may circulate within wildlife before entering livestock populations. An unusual increase in animal mortality may therefore provide an early warning of a potential zoonotic threat. Similarly, a pathogen may be detected in wastewater before an increase in clinically diagnosed cases becomes apparent. Antimicrobial resistance genes may be identified in wastewater or agricultural environments before their wider dissemination is recognized through clinical surveillance.

Environmental surveillance has expanded considerably in recent years. Wastewater monitoring became an important tool during the COVID-19 pandemic because it provided a population-level signal without requiring individual testing. The approach has since expanded to other infectious diseases and antimicrobial resistance. The central challenge is therefore not simply the collection of additional surveillance data. The greater challenge is to connect information generated by different sectors and convert these signals into actionable evidence. A One Health surveillance system should allow an unusual signal in one sector to trigger appropriate investigation in another sector when epidemiological evidence supports such a response. This review examines recent developments in One Health surveillance across the human animal and environmental interface.

2. Literature Search and Source of Evidence

A focused narrative literature search was conducted to identify recent evidence concerning One Health surveillance and infectious disease monitoring across the human animal and environmental interface. Literature was searched using PubMed, Scopus, Web of Science and Google Scholar. Additional information was obtained from the official publications of the World Health Organization, Food and Agriculture Organization of the United Nations, United Nations Environment Programme, and World Organisation for Animal Health. The search covered publications from January 2019 to August 2026. Greater emphasis was given to studies published between 2024 and 2026 because the objective was to capture recent developments in surveillance technologies and One Health implementation. Earlier studies were retained when they provided important conceptual evidence or quantitative information that remained relevant to current surveillance practice.

3. Evolution of Infectious Disease Surveillance Toward a One Health Model

Conventional infectious disease surveillance is primarily based on clinical notification, laboratory confirmation and epidemiological investigation. These approaches remain essential because they provide direct information about disease occurrence and clinical severity. However, their effectiveness depends on infected individuals reaching healthcare facilities and being correctly diagnosed. A One Health surveillance model expands the surveillance window beyond clinical disease. Instead of beginning with a confirmed human case, surveillance can incorporate information from animal populations, wildlife, wastewater, food production systems and environmental changes. Such information can provide earlier indications of pathogen circulation and may help identify potential exposure pathways. The distinction is particularly important for zoonotic pathogens. Human surveillance may detect infection after a pathogen has crossed the species barrier, whereas animal surveillance may detect infection in a reservoir population before extensive human transmission occurs. Environmental surveillance may provide another independent signal. Integration of these observations can therefore provide a more complete representation of pathogen circulation. The recent systematic review of 202 One Health systems provides important evidence for this transition. The study showed that digital surveillance platforms increasingly support data collection, analysis and visualization, but fully integrated systems remain rare. The authors emphasized that integration across sectors is still limited despite the increasing availability of digital technologies (Basheer et al., 2025). This suggests that technological availability alone does not produce One Health surveillance. Integration requires compatible data structures, institutional cooperation, agreed surveillance objectives and mechanisms through which surveillance signals can be translated into action (Figure 1).

3.1. Human Health Surveillance as the Clinical Component of One Health

Human health surveillance remains the most developed component of infectious disease monitoring because clinical laboratories, hospitals and public health systems routinely generate large amounts of diagnostic information. Syndromic surveillance can detect changes in patterns of respiratory, gastrointestinal, neurological or febrile illness, while laboratory surveillance provides pathogen-specific confirmation. The increasing availability of molecular diagnostics has improved the sensitivity and specificity of pathogen detection. Multiplex polymerase chain reaction assays can identify multiple pathogens within a single clinical specimen, while sequencing can characterize organisms beyond the limitations of targeted diagnostic tests. These approaches are particularly useful when unusual clinical presentations occur or when the causative pathogen is not initially known. However, clinical surveillance alone cannot determine whether a pathogen has recently emerged from an animal reservoir or whether environmental conditions are contributing to transmission. This limitation makes cross-sectoral linkage important. Human clinical data become substantially more informative when they can be compared with animal infection patterns, environmental pathogen detection and genomic information. The importance of this integration was demonstrated in recent discussions of One Health epidemic intelligence. A 2025 narrative analysis of surveillance gaps in resource-limited settings emphasized that human surveillance systems frequently operate independently from animal and environmental surveillance and that this fragmentation can delay recognition of emerging zoonotic threats. The authors highlighted integrated surveillance, genomic tools, digital platforms and participatory approaches as important components of future epidemic intelligence (Kayembe-Mulumba et al., 2025).

3.2. Animal and Wildlife Surveillance for Early Detection

Animal surveillance provides information that cannot be obtained through human health systems. Domestic animals, livestock and wildlife may act as reservoirs, amplification hosts or sentinels for emerging infections. Surveillance in these populations can therefore identify pathogen circulation before or alongside human cases. Wildlife surveillance is particularly important because many emerging pathogens originate from wildlife-associated reservoirs. Nevertheless, wildlife surveillance remains technically and logistically challenging. Sampling is often opportunistic and may depend on animal mortality events, hunting activities or access to particular species. A 2024 analysis of a European general wildlife health surveillance program examined 20 years of wildlife diagnostic data together with information obtained from field partners. The study identified legal, geographical, financial and administrative factors that influenced surveillance performance and emphasized the importance of coordinated stakeholder participation in wildlife health monitoring (Heiderich et al., 2024). These findings have broader implications for One Health surveillance. Wildlife monitoring should not be treated simply as an independent veterinary activity. Information concerning unusual mortality, pathogen detection or changes in wildlife distribution can provide contextual information for human and livestock disease surveillance. The usefulness of wildlife data increases when surveillance objectives are linked to specific zoonotic risks and when information can be communicated rapidly to public health and agricultural authorities. The practical development of integrated animal surveillance also depends on local participation. A 2024 participatory study in Burkina Faso developed a planning process for an anthrax surveillance system involving human health, domestic animal and environmental components. The study emphasized that surveillance systems are often highly compartmentalized and that local stakeholders and communities should be involved in designing integrated surveillance approaches rather than being introduced only during implementation (Nana et al., 2024).

3.3. Environmental Surveillance as the Third Surveillance Domain

Environmental surveillance provides information that is often absent from conventional human and veterinary surveillance. Pathogens may be released into water, wastewater, soil, air or other environmental compartments through human activities, animal excreta and contaminated materials. These environments can therefore provide indirect evidence of pathogen circulation. The importance of environmental surveillance has increased considerably since the COVID-19 pandemic. Wastewater-based epidemiology demonstrated that population-level pathogen signals could be detected without testing individuals individually. This approach can be particularly valuable when clinical testing is incomplete or when infections are asymptomatic. Environmental surveillance also has a conceptual advantage within One Health because the environment can connect human and animal populations. Wastewater from human settlements may contain signals originating from infected individuals, while agricultural wastewater can contain organisms and resistance determinants originating from livestock production. Receiving waters can then provide pathways through which microorganisms move into broader ecosystems. A 2025 review of microorganisms in environmental systems emphasized the central role of environmental compartments in pathogen dissemination and highlighted the influence of climate change, agricultural intensification, globalization and habitat degradation on infectious disease risks (Ramirez-Plascencia et al., 2025). The challenge is that environmental detection does not automatically establish transmission to humans. Environmental surveillance should therefore be interpreted together with clinical, epidemiological and genomic information. Detection of pathogen nucleic acid in water indicates environmental presence but may not demonstrate viable organisms or infectious risk. Appropriate sampling design and confirmatory testing are therefore essential.

3.4. Wastewater Surveillance and Population-Level Early Warning

Wastewater surveillance has developed into one of the most important environmental surveillance approaches for infectious diseases. It provides a pooled signal from a defined population and can therefore complement individual-level clinical surveillance. The major advantage of wastewater surveillance is its ability to capture signals from symptomatic and asymptomatic individuals. It may also identify changes in pathogen abundance before increases in healthcare utilization become apparent. However, interpretation depends on population size, wastewater flow, sampling frequency, pathogen shedding patterns and laboratory methodology. Recent evidence has expanded the role of wastewater surveillance beyond SARS-CoV-2. A 2025 global review examined 177 reports on wastewater surveillance of antimicrobial resistance published between 2014 and October 2024. Importantly, 136 studies, corresponding to 76.8% of the identified literature, were published after 2019, demonstrating the rapid expansion of this field. The review found increasing use of qPCR and sequencing methods and emphasized wastewater treatment plants as important points connecting human activity with environmental dissemination of resistance determinants (Punch et al., 2025). This evidence supports the incorporation of wastewater surveillance into broader One Health systems. Wastewater treatment plants can function as surveillance nodes where information concerning human communities and environmental contamination can be assessed simultaneously. However, agricultural and animal-associated wastewater should receive greater attention because current surveillance remains disproportionately focused on urban wastewater systems. The recent WHO guidance on wastewater and environmental surveillance for antimicrobial resistance further demonstrates the increasing institutional recognition of this approach. The guidance emphasizes environmental surveillance as a component of AMR monitoring rather than a replacement for clinical and veterinary surveillance.

3.5. Antimicrobial Resistance as a Model for One Health Surveillance

Antimicrobial resistance represents one of the clearest examples of why infectious disease surveillance must extend beyond hospitals. Antibiotic use in humans, veterinary medicine and agriculture can exert selective pressure across connected microbial populations. Resistant organisms and resistance genes may subsequently move through wastewater, food, soil and water. Traditional AMR surveillance has largely focused on clinical isolates. This provides essential information about resistance among infected patients but gives limited information about environmental reservoirs and transmission pathways. The recent global review of wastewater-based AMR surveillance demonstrates the scale of this gap. Most studies have concentrated on wastewater treatment plants in high-income countries and have used molecular approaches such as qPCR and sequencing. The authors emphasized the need for broader geographic coverage and greater integration of human, animal and environmental surveillance (Punch et al., 2025). A 2025 systematic review using systems-thinking approaches further emphasized that AMR is shaped by feedback between human, animal and environmental systems rather than by antibiotic use alone. The review argued that socioeconomic and environmental factors should be incorporated into AMR strategies (Pham & Wozniak, 2025). The implications extend beyond resistance monitoring. Integrated AMR surveillance could identify whether resistance determinants detected in environmental samples are genetically related to organisms causing human or animal infections. Such information would help distinguish environmental contamination from plausible transmission pathways.

3.6. Genomic Surveillance Across the Human Animal Environmental Interface

Pathogen genomics provides an important bridge between surveillance sectors. Conventional diagnostic surveillance can identify the presence of a pathogen, whereas genome sequencing can characterize genetic variation and identify relationships between isolates. Whole-genome sequencing is increasingly used for outbreak investigation, pathogen evolution and antimicrobial resistance surveillance. When comparable sequences are obtained from humans, animals and environmental samples, genomic analysis can help determine whether isolates belong to related transmission networks. The expansion of viral metagenomic next-generation sequencing is particularly relevant. A 2025 review described viral metagenomic sequencing as an increasingly useful approach for untargeted detection and characterization of emerging and re-emerging viruses across the human animal environmental interface. The approach may be particularly valuable when the causative pathogen is unknown or when conventional targeted diagnostics are unable to explain unusual disease clusters (Russell et al., 2025). However, genomic surveillance must be interpreted carefully. Genetic similarity does not independently prove transmission between hosts. Establishing a transmission pathway requires integration of genomic data with temporal, geographic, ecological and epidemiological information. This reinforces the central principle of One Health surveillance: no single data source is sufficient to explain complex transmission events.

3.7. Digital One Health Surveillance

Digital technologies provide an opportunity to connect surveillance information generated by different sectors. Electronic health records, laboratory information systems, veterinary databases, environmental monitoring platforms, geographic information systems and genomic repositories can potentially be linked through interoperable architectures. The 2025 systematic review of 202 One Health systems provides an important assessment of the current state of digital integration. Although the number of digital platforms has increased, the review found that fully integrated systems containing human, animal and environmental information remain uncommon. Many systems continue to focus on one or two domains rather than providing a complete One Health representation (Basheer et al., 2025). Participatory digital surveillance provides another route for increasing the geographic coverage of surveillance. A 2025 global analysis identified 60 participatory surveillance systems and obtained detailed data from 38 active systems. These systems operated across Africa, Asia, Europe, Australia and the Americas. However, only 11 systems collected information across multiple sectors, showing that digital participation has expanded more rapidly than true One Health integration (McNeil et al., 2025). The value of digital surveillance therefore depends less on the presence of an application or database and more on whether information can move between sectors. Interoperability should be considered a core surveillance function rather than a secondary technical feature.

4. One Health Surveillance in Resource-Limited Settings

The need for integrated surveillance is particularly important in low- and middle-income countries where zoonotic disease burdens may be high but diagnostic and

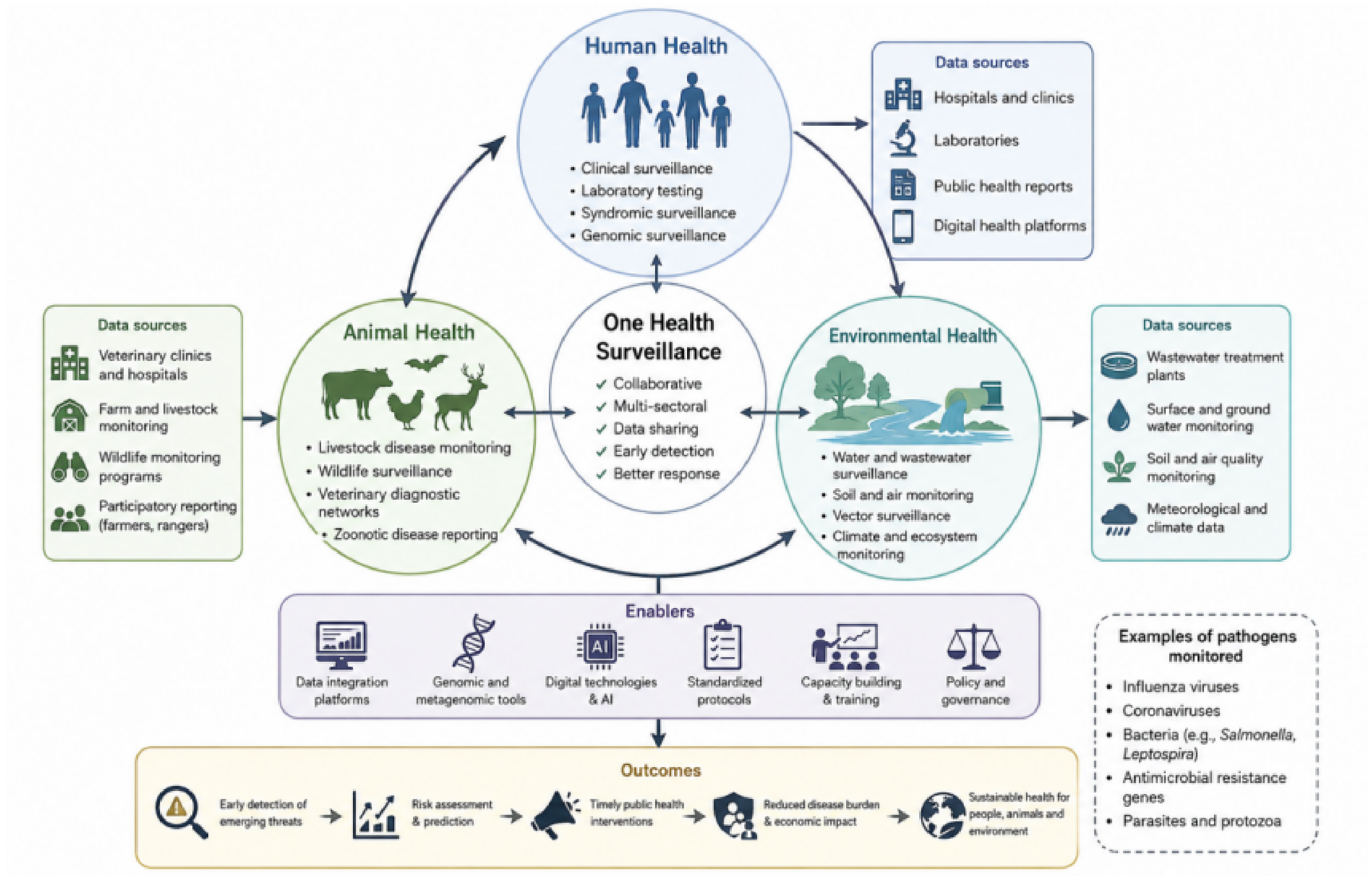

Figure 1. One Health surveillance framework for integrated infectious disease monitoring. The figure illustrates the integration of human health, animal health and environmental surveillance through technologies to support early detection and timely public health intervention.

surveillance resources remain limited. A 2025 analysis of integrated One Health surveillance in Sub-Saharan Africa highlighted funding limitations, insufficient infrastructure, limited diagnostic capacity and weak multisectoral and cross-border collaboration as continuing barriers. The authors proposed multisectoral laboratory working groups, environmental sampling, wastewater surveillance and decentralized molecular diagnostics as approaches that could strengthen surveillance capacity (Gashema et al., 2025). Digital technologies may provide opportunities to bypass some infrastructure limitations. However, digital surveillance cannot be sustained without reliable laboratory systems, trained personnel, data connectivity and institutional ownership. A 2025 analysis of digital One Health surveillance in low- and middle-income countries identified challenges involving users, data, infrastructure, capacity building, policy, impact, networks and sustainability (Nguyen-Tien et al., 2025). Therefore, the most appropriate surveillance model for resource-limited settings may not be the most technologically complex system. A practical system that combines syndromic surveillance, targeted animal sampling, environmental monitoring, basic molecular diagnostics and structured data sharing may provide greater value than an advanced platform that cannot be maintained locally.

5. Major Gaps in Current One Health Surveillance

Despite rapid progress, current One Health surveillance remains fragmented. The recent review of 202 systems provides perhaps the clearest evidence that fully integrated human animal and environmental platforms remain uncommon (Basheer et al., 2025). The problem is therefore not simply insufficient surveillance but insufficient connection between surveillance systems. Environmental surveillance is also geographically uneven. The global review of AMR wastewater surveillance showed a strong concentration of studies in high-income countries (Punch et al., 2025). Similar inequalities exist in genomic sequencing capacity and advanced molecular diagnostics. Another limitation is the difficulty of demonstrating causality. Detection of a pathogen in wildlife, wastewater or soil does not necessarily mean that the environmental source caused human infection. One Health surveillance must therefore avoid interpreting correlation as transmission. Stronger studies combining longitudinal sampling, genomic epidemiology and exposure assessment are required. Data governance represents another major challenge. Clinical information may be subject to privacy restrictions while animal and environmental data may be controlled by separate institutions. Clear agreements regarding data ownership, access and sharing are therefore necessary before an outbreak occurs. Finally, surveillance systems are often evaluated according to whether they detect cases rather than whether they improve decisions. Future evaluation should examine whether integrated surveillance actually reduces the time between emergence, detection and intervention.

6. Future Perspective

The future of infectious disease surveillance should move from isolated sector-specific monitoring toward an integrated early warning architecture. Such a system would continuously collect signals from humans, domestic animals, wildlife and environmental compartments and analyze them within a shared epidemiological framework. Human clinical surveillance would remain the foundation for identifying disease burden and clinical severity. Animal and wildlife surveillance would provide information concerning potential reservoirs and amplification hosts. Wastewater and environmental surveillance would provide population-level and ecological signals. Genomic sequencing would provide information concerning pathogen identity, evolution and genetic relationships. Digital platforms would connect these datasets, while artificial intelligence could assist with signal detection and risk prediction. The most important development will therefore not be the replacement of conventional surveillance with new technology. Instead, future systems should combine established surveillance methods with complementary technologies. A clinically detected outbreak should be traceable to animal and environmental information where relevant. Conversely, an unusual signal in wildlife or wastewater should be capable of triggering targeted human health surveillance. This approach is consistent with the broader direction of the One Health Joint Plan of Action, which identifies zoonotic disease, food safety, antimicrobial resistance, environmental health and health-system capacity as interconnected priorities.

7. Conclusion

The emergence of infectious diseases is increasingly influenced by interactions between humans. Animals and the environment. Conventional human surveillance remains essential. However, it may identify disease only after transmission has become established within human populations. One Health surveillance provides an opportunity to detect infectious threats through multiple biological and ecological pathways. The evidence reviewed here indicates that One Health surveillance should not replace established surveillance systems. It should connect them. Such integration offers one of the most practical pathways for strengthening infectious disease preparedness in an increasingly interconnected world.

Declarations

Ethics approval statement

Not applicable

Consent to participate

Not applicable

Consent to publish

Not applicable

Data Availability Statement

The data are available from the corresponding author upon reasonable request

Competing Interests

The authors declare that they have no conflict of interest

Funding

Not Applicable

Author contribution

Conceptualization, Data curation: Robert Kogi. Investigation, Formal analysis: Kazu Nsaman Buel Zorine. Supervision, Software, Visualization, Project administration, Writing, review, and editing: Swaliho Dauda Sheriff. All authors have read and agreed to the published version of the manuscript

Acknowledgements

Not Applicable

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