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Integrated One Health approaches to zoonotic disease control and antimicrobial resistance: From policy barriers to practical solutions

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Abstract

Zoonotic diseases continue to pose significant threats to global health, food systems, and socioeconomic stability, driven by the intricate interdependence of humans, animals, and the environment. This review synthesizes current knowledge within a One Health framework to examine how ecological processes, environmental reservoirs, and human activities shape the emergence and transmission of zoonotic pathogens and antimicrobial resistance. Environmental compartments such as soil, water, and polluted ecosystems act as reservoirs for pathogens and resistance genes. At the same time, climate change, habitat disruption, and pollution alter disease dynamics and increase the potential for spillover. Human-driven factors—including urban expansion, deforestation, wildlife exploitation, and globalized food production—further intensify transmission pathways. The review evaluates surveillance systems, biosecurity practices, and stewardship policies across diverse settings, highlighting persistent gaps in diagnostic capacity, infrastructure, and cross-sectoral coordination, particularly in resource-limited regions. Emerging alternatives to conventional antibiotics, including bacteriophage therapy, anti-virulence strategies, and microbiome based interventions, are discussed as complementary tools to mitigate antimicrobial resistance. The analysis also integrates animal welfare and food security considerations, emphasizing that sustainable agriculture, healthy livestock systems, and environmental integrity are essential for resilient food supplies and effective zoonotic disease prevention. By unifying these domains, the review proposes a coordinated roadmap that strengthens surveillance, enhances stewardship, and promotes collaborative action across human, animal, and environmental sectors to improve preparedness and resilience against current and future infectious threats.

Introduction

Humans, animals, and the environment are tightly interconnected in the emergence and spread of infectious diseases (1). Most human infections originate from animals, and zoonoses-those naturally transmitted between vertebrate animals and humans—constitute a major global health challenge (2). Of the 1,400 known infectious diseases, 60% are animal-derived, and 75% of emerging pathogens are zoonotic. These diseases

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arise from diverse etiologies, including bacteria, viruses, parasites, fungi, rickettsiae, chlamydiae, mycoplasmas, and acellular pathogens, and circulate across synanthropic and exoanthropic ecosystems with frequent cross-flow between them (1). Transmission occurs through direct contact, vectors, contaminated food or water, inhalation, or bites, and in some cases, pathogens move from humans to animals as reverse zoonoses (3, 4). Aquatic environments also serve as reservoirs, where fish acquire pathogens from polluted waters, posing risks to humans through handling or consumption of raw or undercooked products (5). Foodborne transmission remains a major concern, with "1 in 10 people worldwide" affected annually by contaminated food or water (2, 6), Despite extensive research, understanding of zoonotic emergence remains fragmented across human, veterinary, and environmental disciplines. Existing reviews often emphasize epidemiology or control measures but rarely integrate environmental reservoirs, antimicrobial resistance (AMR), ecological disruption, and human-driven environmental change into a unified One Health analysis. Moreover, although the One Health framework is widely promoted, its implementation remains uneven, and the environmental pillar-described as "pivotal yet often overlooked"—is insufficiently embedded in surveillance and policy systems.

This review addresses these gaps by synthesizing zoonotic disease dynamics, environmental reservoirs of pathogens and resistance genes, AMR dissemination pathways, and the impacts of ecological and anthropogenic stressors within a comprehensive One Health framework. It evaluates surveillance systems, biosecurity measures, and stewardship policies across diverse settings, highlighting disparities between high-income and low- and middle-income countries. It also examines emerging alternatives to conventional antibiotics—including bacteriophage therapy, anti-virulence agents, and microbiome-based interventions—as complementary tools to mitigate AMR. By integrating these domains, the review proposes a coordinated roadmap to strengthen surveillance, stewardship, and cross-sectoral collaboration to reduce zoonotic risks and enhance global health resilience.

Impact of zoonoses

Zoonoses have numerous impacts on human and animal health. They compromise human well-being and security, with infected individuals often facing social isolation that increases their risk of mental health problems. The rise of antibiotic resistance further complicates the treatment of bacterial zoonoses, requiring costly medications and specialized care, which places a heavy burden on healthcare systems—particularly in developing nations. In animals, zoonotic infections can cause significant mortality, leading to severe economic losses in the livestock sector. Even when death does not occur, animal health and productivity are diminished, resulting in substantial reductions in products such as meat, milk, and eggs. This decline directly impacts human nutrition by limiting access to high-protein foods of animal origin. Moreover, diseases like brucellosis and toxoplasmosis can cause infertility, abortions, and weak offspring, compounding economic losses for farmers and affecting national food security.

Zoonotic diseases such as BSE, avian influenza, and anthrax pose significant barriers to the global trade of animals, animal products (meat, milk, eggs), and related byproducts. The economic impact is further compounded by the extensive measures required for their control and eradication, including surveillance, diagnostic testing, isolation and quarantine, restrictions on animal movement, therapeutic and vaccination programs, inspection of food products, and strict biosecurity practices. Beyond direct health consequences, zoonotic outbreaks also disrupt international trade and tourism, underscoring the interconnected and globalized nature of disease transmission (7). Given these wide-ranging effects, robust and coordinated control strategies are essential to limit their spread and alleviate associated economic and social burdens.

Control of zoonoses

Effective control of zoonotic diseases depends on surveillance, prevention, and education. Surveillance systems enable early detection in humans, animals, and vectors, improving health outcomes and reducing morbidity and mortality. Because zoonotic diseases can spread rapidly worldwide, surveillance must operate at local, regional, national, and international levels, using pathogen, serological, syndromic, and risk-based monitoring approaches (8).

Control measures include treatment, vaccination, decontamination, restriction of animal movement, personal hygiene, and culling when necessary. Hygiene practices, decontaminating infected materials, and protective equipment are essential to minimize transmission risks (9).

Foodborne zoonoses require special attention: animal products should come from healthy animals, undergo thorough ante-mortem and post-mortem inspections, and be processed under strict hygienic conditions. Broader strategies involve biosecurity measures, quarantine laws, disease reporting systems, mass vaccination campaigns, testing and slaughter/culling practices, and public awareness initiatives. Given the continuous emergence of new zoonotic threats, surveillance and control must be coordinated across all levels, supported by leadership, funding, and collaboration among organizations such as WHO, FAO, and WOAH (10). These measures are most effective when integrated within the One Health framework, which emphasizes cross-sectoral cooperation.

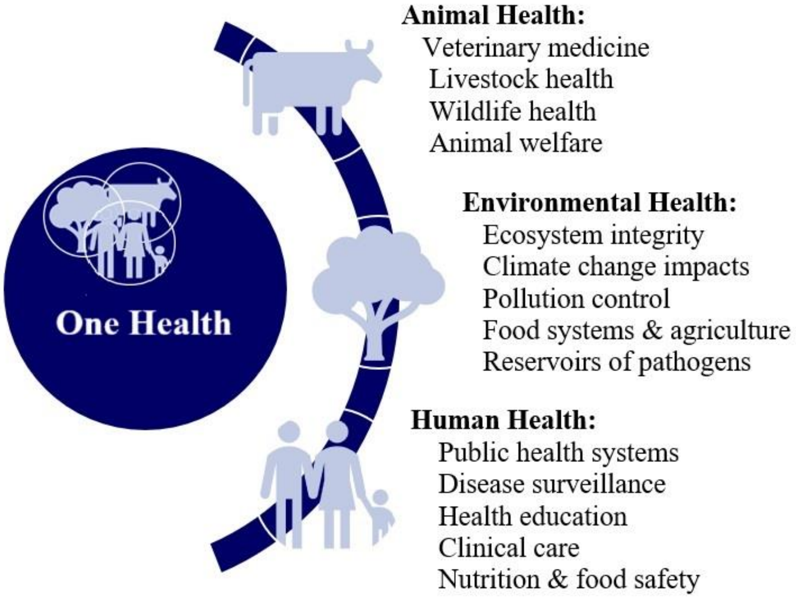

Fig. 1. The One Health interactions of human health, animal health, and environmental health.

The One Health framework

Definition and components

The One Health concept, introduced across multiple disciplines in 2006, represents a collaborative, interdisciplinary, and global initiative aimed at optimizing the health of humans, animals, and the environment (11). The American Veterinary Medical Association describes One

Health as the joint efforts of diverse sectors working at local, national, and international levels to achieve optimal health outcomes for people, animals, and ecosystems (12). This framework promotes cooperation among public health, veterinary medicine, environmental science, and agriculture to prevent and manage zoonotic diseases. By facilitating the exchange of knowledge between human and animal health domains, One Health strengthens understanding of zoonotic transmission and supports improved health outcomes (13). Fundamentally, the approach is built on the triad of human, animal, and environmental health (Figure 1). Among the three pillars of One Health, the environmental dimension plays a pivotal yet often underappreciated role in shaping disease emergence and antimicrobial resistance.

Environment and One Health

The environment represents a critical yet frequently underemphasized component of the One Health framework. It contributes to health outcomes in three principal ways: by serving as a reservoir for pathogens, resistance genes, and chemical contaminants; by hosting ecological processes that influence disease transmission; and by acting as a mediator of human and animal health (14). Growing evidence indicates that global environmental change—including biodiversity loss, land-use transformation, and pollution—heightens the probability of zoonotic spillover by altering host–pathogen interactions (15). Environmental compartments such as soil and aquatic systems not only support diverse microbial communities but also accumulate pollutants, including antimicrobial residues. Continuous exposure to low-doses of antibiotics in agriculture promotes the preservation of resistance genes, enabling environmental bacteria to function as reservoirs, capable of transferring these genes to pathogenic species (15-17). Anthropogenic contamination of air, water, and soil further amplifies this threat by mobilizing microbes and chemical pollutants across ecosystems through hydrological, atmospheric, and biological pathways. Research demonstrates that environmental AMR hotspots in soil and water bodies act as long-term reservoirs of resistance genes with the potential to disseminate into human and animal pathogens (18, 19).

Ecological interactions—including trophic relationships, competition, and symbiosis—govern the abundance and distribution of pathogens and vectors, while environmental stressors such as climate change accelerate pathogen evolution and modify transmission dynamics. As a determinant of health, the environment influences immune function and pathogen shedding in both humans and animals. Pollution, habitat degradation, and climate-driven ecological disruption weaken ecosystem stability and elevate zoonotic spillover risk (15-17). Climate-induced shifts in wildlife and vector ranges are expected to increase cross-species viral transmission, thereby intensifying zoonotic emergence (20). More broadly, climate change destabilizes ecosystems by altering the life cycles of pathogens, vectors, and reservoir hosts; facilitating the emergence of novel diseases in plants, food systems, and domestic and wild animals; triggering trophic cascades; disrupting interspecies synchrony; and transforming or eliminating natural habitats. Addressing these interconnected challenges requires the integration of environmental surveillance with human and animal health strategies to enhance resilience against emerging infectious threats. Additionally, human-modified landscapes have been shown to favor species that harbor disproportionately high numbers of zoonotic pathogens, further increasing spillover potential (21). In line with the environmental dimension of One Health, key environmental stressors contributing to zoonotic disease emergence are summarized in Table 1.

Human activity and One Health

Human activities—including urban expansion, deforestation, wildlife exploitation, and tourism—combined with long-term, human-driven climate change, profoundly alter natural ecosystems and serve as major catalysts for the emergence of zoonotic diseases, thereby intensifying the circulation of existing zoonoses. Global assessments indicate that landscapes heavily modified by humans tend to support wildlife species that harbor disproportionately large numbers of zoonotic pathogens, increasing the likelihood of spillover events (21). In addition, land-use transformation and agricultural intensification have been identified as key predictors of zoonotic emergence, particularly in rapidly developing regions (22).

Within the One Health framework, human health constitutes a central pillar, encompassing integrated health services that emphasize prevention, surveillance systems capable of detecting and responding to emerging threats, and health education initiatives that enhance public awareness of zoonotic and environmental risks. These components collectively strengthen human health resilience and improve outcomes across interconnected ecosystems. Human behaviors—including wildlife trade, hunting, and international travel—also create direct pathways for pathogen transmission between species, underscoring the importance of behavioral and social interventions within One Health strategies (23).

Integrated health services

Health care systems are vital for promoting preventive care, early disease detection, and comprehensive treatment strategies to address health issues in populations. Integrated health services focus on coordinated care that meets both physical and mental health needs through various services, which include preventive care such as routine screenings and vaccinations, early detection utilizing advanced diagnostic tools for timely disease identification, and comprehensive treatment that provides tailored care through interdisciplinary teams of healthcare professionals, veterinarians, and environmental scientists, especially for zoonotic diseases that affect both humans and animals (24). Integrated health systems are increasingly recognized as essential for managing zoonotic threats in rapidly urbanizing regions where human–animal contact is intensifying (25).

Disease surveillance

Regular surveillance of infectious diseases in wildlife and livestock populations is essential for early pathogen detection and timely response. Such monitoring may involve active surveillance programs, diagnostic testing, and structured reporting systems (26, 27). Disease surveillance also plays a central role in public health management by tracking human infections, identifying outbreaks, and responding to emerging threats. This includes detecting zoonotic infections through data collected from healthcare providers and veterinary clinics, enabling early recognition of outbreaks linked to animal-origin pathogens. However, surveillance initiatives for livestock, poultry, and wildlife often lack unified oversight and have historically received less investment than human health surveillance. Consequently, human outbreaks frequently reveal previously undetected infections in animal populations, rather than animal surveillance serving as a proactive early-warning system.

With the continual emergence of new infectious diseases, robust and coordinated surveillance systems are increasingly necessary, requiring global collaboration among organizations such as WHO and CDC to share information and harmonize responses. Surveillance at the wildlife–livestock interface remains particularly challenging due to limited ecological and epidemiological data for many wildlife species and the technical constraints associated with noninvasive sampling (28). In resource-limited settings, passive surveillance—such as the collection and examination of wildlife carcasses—

may be the only feasible approach. Control of wildlife-associated diseases often requires interventions within natural ecosystems, including fencing, habitat management, or selective culling, although these measures frequently provoke ethical and social debate (29). As a result, alternative strategies are being explored to better capture ecosystem-level variability and disease dynamics, including the use of environmental DNA to characterize host–pathogen interactions in a noninvasive and standardized manner (30). In addition to ecological stressors, human activities further exacerbate zoonotic risks and influence health outcomes across interconnected systems.

Table 1. Environmental stressors and their roles in zoonotic disease within the One Health framework

Environmental stressor	Role in One Health triad	Mechanism of impact	Zoonotic disease relevance	References
Reservoir Soil & water contamination	Environmental reservoir of pathogens and resistance genes	Diverse microbes; retains antibiotics, preserving resistance genes.	Reservoir microbes spread AMR; contaminants disperse via flows and hosts.	[15, 16]
Pollution Air, water & soil pollution	Health mediator; dispersal pathway for contaminants and microbes	Human-driven pollution spreads contaminants and microbes; impairs immunity and boosts shedding	Raises infection risk; boosts pathogen shedding and spread	[14, 15]
Ecological Food-web & ecological disruption	Ecological process shaping disease dynamics	Regulate pathogen and vector populations; disruption eliminates natural controls	Loss of regulatory species increases vector abundance and pathogen spillover risk	[14]
Habitat Habitat destruction	Health mediator; ecosystem integrity disruption	Removes natural buffers; increases wildlife–human contact; disrupts species synchrony.	Increases human-wildlife interface, raising risk of zoonotic spillover events	[16, 17]
Climate Climate change	Ecological process & health mediator; accelerates pathogen evolution	Alters pathogen, vector, and reservoir life cycles; triggers trophic cascades; disrupts species synchrony; reshapes habitats	Drives new diseases in plants, food systems, and animals; expands vector ranges	[16, 17]
Reservoir Antibiotic use in agriculture	Environmental AMR reservoir; chemical buildup in soil and water.	Continuous low-dose antibiotic use fosters resistance gene persistence in environmental bacteria	Environmental bacteria pass AMR genes to human & animal pathogens, failing treatment effectiveness.	[16, 17]
Monitoring Absence of integrated environmental monitoring	Policy & surveillance gap across all three domains	Lack of environmental–health coordination reduces system resilience.	Delays identifying emerging threats; reduces capacity to prevent cross-domain spillover.	[14,16-17]

Surveillance systems may employ a range of approaches—including active, passive, targeted, risk-based, and syndromic methods—depending on available resources and epidemiological needs. Effective surveillance requires not only data collection but also systematic analysis to detect disease patterns and emerging risks. Rapid response teams are critical for investigating outbreaks, implementing control measures, and disseminating essential information to the public and healthcare providers. Strengthening these efforts increasingly depends on collaboration with the information technology sector, which can leverage digital tools such as mobile devices, remote sensing, and online search platforms to enhance surveillance efficiency and reach (10). Moreover, human mobility, trade networks, and global transportation systems have been shown to accelerate the spread of zoonotic pathogens, underscoring the need for surveillance systems that incorporate human movement data to better anticipate and mitigate disease spread (31).

Health education

Health education plays a crucial role in raising awareness about the health risks associated with zoonoses and environmental factors. It employs various strategies to empower communities, such as targeted outreach programs for vulnerable populations, including agricultural workers and urban residents who have close contact with animals School-based education integrates health topics into the curriculum, fostering early awareness of hygiene and safe animal handling, which encourages lifelong healthy behaviors. Public health campaigns utilize diverse platforms such as pamphlets, posters, training health workers to explain to the communities, cartoons, and radio or TV adverts to spread critical information about zoonotic threats and safe food practices. Additionally, collaboration among health organizations, veterinarians, environmental agencies, and community groups further strengthens these educational efforts by sharing resources and providing coordinated training to address zoonotic health risks effectively. In recent years, communication channels have broadened to include social media platforms, mobile applications, and health ministry text messaging, driven by the global rise in mobile phone use. In low-income countries, however, access to internet-enabled devices remains constrained, and data networks often differ in reliability and affordability. Ongoing initiatives in many regions aim to address these limitations (32). Just as human behavior shapes the dynamics of zoonotic transmission, veterinary systems and animal health practices play a critical role in early detection, prevention, and responsible stewardship.

Animal health and One Health

Animal production contributes over 40% of global agricultural output and supports the livelihoods of more than 20% of the world's population (33), yet it remains highly vulnerable to infectious diseases, which account for over 20% of global production losses (34). Within this context, veterinary services form a critical frontline, integrating surveillance, antimicrobial stewardship, food safety, environmental health, animal welfare, and cross-sectoral collaboration under the One Health framework. Veterinarians monitor infectious diseases, antimicrobial resistance, and foodborne pathogens, guide prudent antimicrobial use, oversee husbandry and slaughter practices, and contribute to ecological monitoring of wildlife diseases and vector-borne dynamics, thereby strengthening public health and supporting coordinated multisectoral responses (35). One of the most urgent challenges at this interface is the rise of antimicrobial resistance.

Growing evidence shows that changes in animal behavior, movement, and stress—particularly in wildlife and intensively farmed species—significantly increase pathogen shedding and spillover risk, as stress-driven shifts in movement and behavior facilitate pathogen release and cross-species transmission (36). Modern livestock production systems characterized by high animal density and rapid turnover further amplify opportunities for zoonotic transmission, while interactions at the wildlife–livestock interface, shaped by grazing patterns, habitat encroachment, and shared resource use, represent critical hotspots for zoonotic emergence (37, 38).

Disease prevention strategies remain essential. Vaccination of domestic livestock reduces pathogen transmission between livestock and wildlife (39) and contributes to herd immunity by lowering exposure among non-vaccinated animals (24), though implementation remains challenging in low-income regions. Vector-borne diseases add further complexity: ticks, mosquitoes, and other vectors transmit more than 17% of global infectious diseases (33). Effective vector control requires context-specific approaches, including insecticides, biological control, habitat modification, structural improvements, or genetically modified mosquitoes (40), while vector-targeted vaccines offer promising environmentally friendly alternatives (41). Climate change exacerbates these risks by enabling vectors to expand into new regions and altering environmental conditions that influence pathogen persistence (42).

Strengthening farm-level biosecurity is equally critical. Most wildlife–livestock interactions are indirect (43), and measures such as restricting wildlife access, improving hygiene, managing livestock movement, and modifying habitats can substantially reduce transmission. While risks in intensive systems are well documented, extensive production systems require more systematic and context-specific biosecurity protocols (44). Although some interventions are costly, zoning and compartmentalization can reduce implementation burdens and support disease prevention, control, eradication, and safe trade. Importantly, all control measures must be accompanied by education and awareness programs for farmers, livestock owners, and local communities to ensure compliance and long-term sustainability.

Antimicrobial resistance (AMR)

Antimicrobial resistance (AMR) is a critical global health threat, particularly in relation to zoonotic diseases. By 2050, antimicrobial resistance is projected to cause 10 million deaths each year and inflict an estimated global economic loss of 100 trillion USD (45). Excessive and inappropriate use of antimicrobials, for therapeutic purposes, disease prevention and growth promotion, has accelerated the emergence and spread of resistant pathogens, undermining treatment effectiveness in both humans and animals (46). Globally, antimicrobial use in livestock is projected to increase by nearly 67% by 2030, intensifying the risk of resistance development (47). A major concern is that more than 70% of veterinary antibiotics are not fully metabolized and are excreted into the environment, where they exert selective pressure on microbial communities. This contamination promotes the emergence of resistant variants in soil and aquatic ecosystems, with potential entry into the food chain through plants and animal products (48, 49). Microorganisms develop antibiotic resistance through multiple pathways, which may be inherent to their biology or acquired from other species (Fig. 2). Deeper insight into these resistance mechanisms is expected to support the design of improved therapies for infectious diseases and to foster the development of antimicrobials capable of counteracting microbial strategies to evade treatment (50). Addressing AMR within the One Health framework requires not only surveillance and stewardship but also innovation in therapeutic strategies and policy alignment.

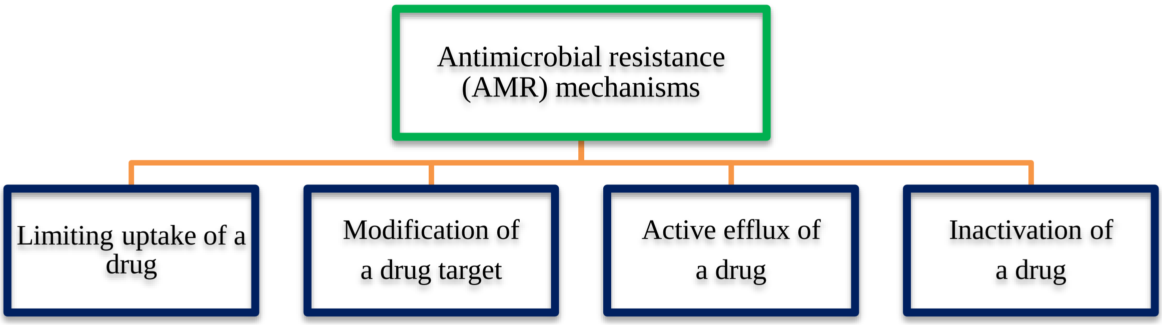

Fig. 2. The main mechanisms of antimicrobial resistance (AMR).

One Health and antimicrobial resistance

Addressing AMR requires integrated One Health strategies that emphasize prudent antimicrobial stewardship, improved surveillance, and sustainable farming practices. Figure 3 illustrates the interconnected AMR transmission routes across the One Health triad, emphasizing how antibiotic use, environmental contamination, and zoonotic spillover contribute to resistance evolution and cross-sectoral spread. Innovation beyond conventional antibiotics—such as bacteriophage therapy, anti-virulence agents, and microbiome modulation—offers promising alternatives to combat resistant pathogens. Coordinated global action is essential to mitigate AMR and protect public health, animal welfare, and food security (50). The One Health analyses highlight that AMR cannot be controlled without simultaneous interventions across human, animal, and environmental sectors, underscoring the need for unified global governance. Furthermore, the persistence and spread of AMR genes in soil, water, and agricultural systems demonstrate that environmental pathways are equally critical to AMR evolution (51). Building on this need, surveillance in animal agriculture plays a central role in detecting zoonotic outbreaks and monitoring antimicrobial resistance, serving as the foundation for informed policy and intervention.

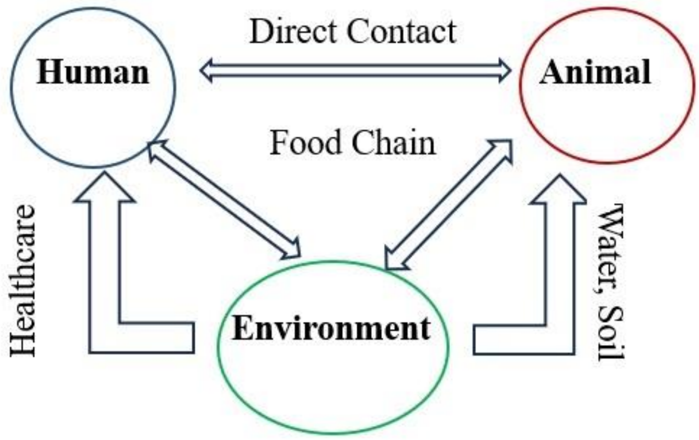

Fig. 3. Antimicrobial resistance transmission pathways across human, animal, and environmental sectors.

Surveillance

Surveillance systems in animal agriculture are vital for monitoring zoonotic diseases, antimicrobial use, and AMR trends. They provide essential data for detecting outbreaks, guiding treatment, and informing policy. Effective surveillance must integrate human, animal, and environmental health to capture transmission pathways and strengthen health systems. High-income countries have developed integrated networks, such as Canada's CAHSS and the U.S. NAHSS, which track infections and resistance across livestock and farm workers. In contrast, low- and middle-income countries (LMICs) often face challenges including limited funding, inadequate diagnostics, and weak infrastructure. These gaps highlight the need for cost-effective, scalable platforms that can operate across diverse settings. Integrated surveillance enhances resource efficiency and supports timely interventions. By linking data from humans, livestock, wildlife, and ecosystems, such systems improve understanding of zoonotic risks and antimicrobial resistance. Expanding these networks globally, particularly in LMICs, is critical for building resilience and ensuring coordinated responses to emerging threats (52, 53). Surveillance systems provide the data backbone for AMR management, but without coherent policies and stakeholder engagement, their impact remains limited.

Policy and education

Despite growing recognition of the One Health framework, implementation remains fragmented and uneven across sectors. Human health, veterinary, environmental, and laboratory systems often operate in silos, leading to duplicated efforts, surveillance blind spots, and enforcement gaps (Fig. 4). This lack of coordination undermines early detection and response to zoonotic threats and AMR.

Resource limitations further constrain progress, particularly in low- and middle-income countries (LMICs), diagnostic capacity, laboratory infrastructure, and trained personnel are often insufficient to support robust surveillance and stewardship programs. Even when policies are formally adopted, weak systems and chronic underfunding prevent their translation into practice.

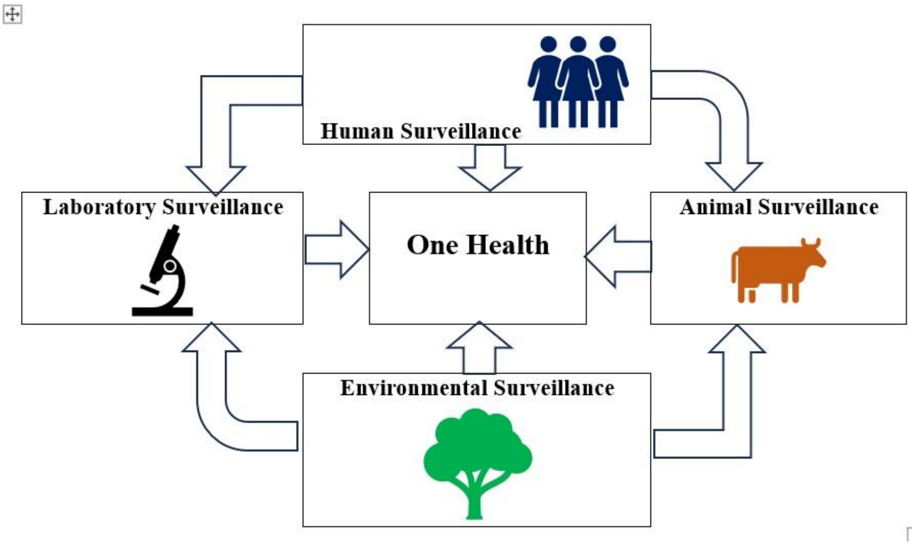

Fig. 4. Integrated surveillance policy framework for zoonotic disease control under the One Health concept.

Stakeholder engagement is another critical weakness. Farmers, veterinarians, and local communities are often excluded from policy design, resulting in low compliance and mistrust of regulations. Without farmer-centered incentives or accessible alternatives to antimicrobials, stewardship policies are unlikely to succeed.

Enforcement mechanisms also remain inadequate. Informal drug markets, unregulated antimicrobial sales, and limited monitoring capacity allow misuse to persist despite regulatory frameworks. Data gaps compound the problem: surveillance systems are fragmented, poorly integrated across sectors, and rarely shared internationally, leaving policymakers without timely evidence to guide interventions.

Socio-economic pressures further complicate implementation. In many settings, antimicrobials are viewed as essential for maintaining productivity and livelihoods. Without economic support or sustainable alternatives, farmers may resist stewardship measures. Finally, global inequities in resources and capacity create uneven implementation, weakening collective action against antimicrobial resistance. Addressing these gaps requires not only stronger governance and funding but also inclusive, cross-sectoral collaboration that integrates local contexts into global strategies. Policies must be designed with practical enforcement mechanisms, economic incentives, and transparent data sharing to ensure that One Health principles move beyond rhetoric into effective practice. To overcome these limitations, novel and alternative strategies are being explored to complement or replace conventional antibiotics.

New and alternative policies

The worldwide escalation of AMR has undermined the efficacy of many first-line antibiotics, posing serious challenges for the treatment of both human and animal infections and for controlling bacterial zoonoses. Tackling AMR demands coordinated, multi-sectoral efforts that integrate human, animal, and environmental health, rather than relying on fragmented measures. Because conventional antibiotic use exerts intense selective pressure that accelerates resistance, innovative strategies and platforms are urgently needed to advance the discovery of new antimicrobials and alternative anti-infective agents. Promising avenues include combination therapies (where certain compounds act as potentiators or synergists by enhancing membrane permeability, reducing efflux activity, inhibiting kinases, or counteracting intrinsic resistance), anti-virulence drugs (targeting regulators of pathogenicity or neutralizing virulence factors and toxins), bacteriophage-based interventions (employing lytic phages against multidrug-resistant bacteria), and microbiome-targeted modulators to prevent or treat infections. These emerging approaches may help avert a post-antibiotic era and could be adapted for use in animal agriculture to mitigate pathogenic threats.

Bacteriophage therapy has gained attention as a targeted solution against multidrug-resistant pathogens. However, its clinical feasibility remains controversial. Phages exhibit narrow host specificity, require strain-level matching, and may trigger rapid resistance development. Unlike standardized antibiotics, phages are biologically diverse, complicating mass production and quality control. Regulatory frameworks are largely absent or inconsistent across countries, with limited clinical trials and unclear safety protocols. These gaps restrict global adoption despite promising outcomes in compassionate use cases (54). As these innovations evolve, it is equally important to consider the ethical and welfare implications of animal agriculture within the One Health paradigm.

One Health and animal welfare

The integration of One Health into sustainable animal agriculture reflects growing recognition that animal welfare and health are inseparable from human well-being and environmental integrity. While improved animal health enhances productivity and sustainability, welfare considerations extend further, shaping ecological outcomes, disease dynamics, resource use, and socio-cultural systems. Current scholarship often addresses these domains in isolation, underscoring the need for integrative approaches. Economically, concentrated animal feeding operations outperform traditional systems, yet their high-density conditions elevate risks of disease transmission and welfare compromise. Moreover, reliance on processed feeds has been linked to digestive disturbances and microbiota imbalances, with implications for zoonotic spillover and antimicrobial resistance. Stakeholders—including FAO, WHO, WOAH, and welfare organizations—have prioritized welfare, though perspectives differ across farmers and the public. Advancing welfare within a One Health framework requires balancing costs and benefits, recognizing indirect gains, and generating robust empirical evidence to guide policy and practice. Ultimately, animal welfare is not peripheral but central to food production systems, global food security, and public health resilience (55).

One Health and food security

Food security refers to the sustained assurance that all individuals have physical, social, and economic access to sufficient, safe, and nutritious food that meets their dietary needs and preferences for an active and healthy life (56). It is commonly conceptualized through four interdependent pillars—availability, access, utilization, and stability—each of which is increasingly challenged by demographic pressures, environmental degradation, and emerging infectious diseases. Global food insecurity is projected to intensify as the world population approaches 9.7 billion by 2050, with food production requiring an estimated 35% to 56% increase to 2010 levels to meet future demand (57). Achieving this expansion sustainably necessitates a system-based approach, and the One Health framework provides a comprehensive lens through which the determinants of food security can be understood and addressed (58).

Within the One Health paradigm, food security is shaped by the interconnected health of humans, animals, plants, and ecosystems. Food availability depends heavily on productive and disease-free livestock, aquaculture, and crop systems. Healthy animals contribute high-quality protein sources such as meat, milk, eggs, and fish, while plant health underpins the supply of cereals, fruits, and vegetables. Recent studies show that animal diseases such as African swine fever, avian influenza, and foot-and-mouth disease significantly reduce global protein availability and disrupt supply chains (56). Animal health programs—including vaccination, improved biosecurity, vector control, and responsible antimicrobial stewardship—directly influence productivity, reduce mortality, and enhance the safety of animal-derived foods (59). Similarly, plant health surveillance and integrated pest management reduce crop losses and safeguard yields, especially as climate change increases pest and pathogen pressures (60).

Food access is also influenced by One Health factors. Outbreaks of zoonotic or transboundary animal diseases can disrupt markets, reduce household income, and increase food prices, thereby limiting economic access to nutritious foods (61). Environmental degradation—such as soil erosion, water scarcity, and biodiversity loss—reduces agricultural productivity and disproportionately affects vulnerable populations, further constraining access. Climate-related shocks are now among the leading drivers of acute food insecurity globally (56).

Food utilization, which encompasses nutritional quality, food safety, and the body's ability to absorb nutrients, is directly linked to One Health considerations. Contaminated water, unsafe food handling, and foodborne pathogens (e.g., Salmonella, Campylobacter, E. coli) compromise human health and reduce the nutritional value of consumed foods. Environmental contaminants such as heavy metals, pesticide residues, and mycotoxins also pose risks to food safety and human health. Strengthening One Health–based food safety systems- from farm to fork—helps ensure that foods are not only available but also safe and nutritionally adequate (62).

Finally, food stability—the ability of food systems to withstand shocks over time—is increasingly threatened by climate change, extreme weather events, land-use change, and emerging infectious diseases. Climate-driven shifts in vector ecology, pathogen distribution, and water availability affect both crop and livestock productivity (63). One Health approaches enhance resilience by promoting ecosystem stewardship, climate-smart agriculture, early disease detection, and coordinated responses across human, animal, and environmental health sectors.

From a policy perspective, integrating One Health into food systems enhances resilience to shocks such as pandemics, antimicrobial resistance, and climate-related disruptions (64). Coordinated surveillance across human, animal, and environmental sectors, sustainable agricultural practices, and international collaboration are essential to securing food supplies while protecting ecosystems. Thus, food security is not only about availability but also about sustainability, safety, and equity, all of which depend on the holistic integration of human, animal, and environmental health (65). Ensuring food security is also inseparable from robust food safety systems, which are critical for preventing zoonotic and foodborne infections.

One Health and food safety

Food safety faces four major challenges: microbiological risks, where bacteria such as Salmonella, Campylobacter, and Listeria cause severe and sometimes fatal foodborne illnesses; chemical hazards, including unsafe additives, pesticide residues, and heavy metals that contaminate food through poor hygiene or leaching; personal hygiene issues, as inadequate practices by food handlers increase the spread of disease despite simple preventive measures like handwashing; and environmental hygiene problems, where poor waste management and unsanitary processing conditions foster pests, contamination, and spoilage. Together, these factors highlight the complexity of ensuring safe food production and consumption (62).

Animal-derived foods are crucial for nutrition and rural livelihoods, but their production and consumption raise serious health and environmental concerns. Sustainable farming, responsible land use, and strict policies on antimicrobial resistance are key to balancing food security, public health, and ecological sustainability under the One Health framework (66), Vet medicines, including antimicrobials and other drugs like hormones and growth promoters, are widely used to treat illnesses in food-producing animals and to boost yields. However, their use can lead to drug residues in foods of animal origin, especially when off-label dosing, incomplete withdrawal periods, or poor husbandry practices occur (67, 68), Such residues pose public health risks, including hypersensitivity, cancer, mutagenicity, reproductive issues, disruption of gut flora, and antimicrobial resistance in the case of antibiotics (69). Additionally, not all administered drugs are metabolized; the leftovers exit via urine and feces, contaminating soil, surface water, and groundwater through manure and wastewater, with negative implications for wildlife and environmental health (70). To manage these risks, international and national bodies regulate veterinary drug residues. The Joint FAO/WHO Expert Committee on Food Additives (JECFA) conducts risk assessments to set maximum residue limits (MRLs), later published by the Codex Alimentarius Commission. Developing countries often adopt these MRLs, while many high-income nations establish their own standards using different criteria. Setting MRLs involves complex toxicological, pharmacological, dietary exposure, and microbiological risk assessments. Regulators also aim to improve veterinary services, supervise drug production and distribution, and expand monitoring of animal foods and the environment to encourage rational drug use and reduce public health risks (71, 72).

Conclusion

Zoonotic diseases and AMR are escalating global threats shaped by the interconnectedness of human, animal, and environmental systems. Environmental reservoirs such as soil, water, and polluted ecosystems sustain pathogens and resistance genes, while climate change, habitat loss, and biodiversity decline heighten spillover risk. Human-driven pressures—including land-use change, agricultural intensification, wildlife exploitation, and globalized trade—further expand transmission pathways and accelerate AMR evolution. Despite increasing recognition of the One Health framework, implementation remains fragmented, constrained by weak governance, limited diagnostic capacity, siloed surveillance systems, and insufficient stakeholder engagement, particularly in low- and middle-income countries. Emerging alternatives to antibiotics, including bacteriophages, anti-virulence agents, and microbiome-based strategies, offer promising complementary tools but require coordinated investment and regulatory support. Strengthening integrated surveillance, promoting prudent antimicrobial stewardship, advancing sustainable agriculture, and protecting ecological integrity are essential for building resilient health systems. A fully operationalized One Health approach is critical to safeguarding global health and food security.

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The author declares no conflict of interest.

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