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Review article

Climate change accelerates antimicrobial resistance - One Health must become the operating system

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Abstract

Antimicrobial resistance (AMR) and climate change are increasingly recognized as interconnected global threats driven by shared ecological, infrastructural, and socioeconomic vulnerabilities. This review summarizes emerging mechanistic and epidemiological evidence demonstrating how rising temperatures, hydrological extremes, ecosystem disruption, and environmental pollution accelerate the selection, persistence, and spread of antimicrobial resistance genes at the human-animal-environment interface. We emphasize climate-sensitive pathways, such as heat-driven microbial evolution, hydrological mobilization of resistance factors, aerosolized transmission, and climate-stressed food systems, which collectively reshape the distribution and impact of resistant bacterial infections. Importantly, we identify practical, co-beneficial interventions including pollution control, climate-resilient water and sanitation systems, adaptive antimicrobial stewardship, AI-powered surveillance, and integrated One Health governance. Framing AMR as a climate-sensitive health outcome shifts it from a mostly reactive, downstream clinical challenge to a predictable, preventable upstream systems vulnerability influenced by climate dynamics. Incorporating climate awareness into AMR policies and actions is therefore vital to preserving antimicrobial effectiveness, bolstering health system resilience, and safeguarding climate-sensitive populations in a rapidly warming world.

Keywords: Antimicrobial resistance, Climate change, Environmental dissemination, Health system resilience, One Health, Surveillance, Wastewater

Introduction

Antimicrobial resistance (AMR) is the evolutionary process by which microorganisms adapt and survive exposure to drugs that previously were effective against them. This issue is worsening due to climate change, making these crises interconnected ecologically and systemically [1]. Rising global temperatures and shifting rainfall patterns influence microbial ecology in various ways. They increase bacterial replication rates, shorten generation times, enhance horizontal gene transfer rates, and upregulate mobile genetic elements (MGEs), thereby accelerating biofilm formation and mutation rates. Moreover, changing environmental conditions facilitate the spread of antimicrobial resistance genes (ARGs) in water, soil, and food systems. Simultaneously, extreme weather events can damage sanitation and healthcare infrastructure, leading to more infections and a higher need for antibiotics [1, 2, 3]. Environmental reservoirs such as aquaculture and agricultural runoff serve as hotspots for resistant pathogens, with higher prevalence of resistance linked to climate variables such as heatwaves and sea-level rise [4, 5, 6]. Vulnerable populations in low- and middle-income countries (LMICs) face disproportionate burdens due to weakened health systems and limited adaptive capacity [7, 8]. A coordinated One Health approach is essential, integrating human, animal, and ecosystem health to strengthen cross-sectoral surveillance, promote sustainable antimicrobial stewardship (AMS), and develop climate-resilient health systems worldwide [9].

Literature identification and synthesis approach

This brief review synthesizes current evidence on the intersections between climate change and AMR. Relevant literature was identified through structured searches in PubMed, Web of Science, and Scopus, covering publications from January 2020 to February 2026. Search terms included combinations of “climate change,” “temperature,” “extreme weather,” “hydrology,” “aerosols,” “environment,” “antimicrobial resistance,” “antibiotic resistance genes,” and “One Health.” Priority was given to systematic reviews, meta-analyses, large epidemiological datasets, and mechanistic studies that connect climatic factors to the emergence, persistence, or spread of AMR. Additional policy and modeling studies were included to illustrate practical governance and surveillance implications. The evidence was synthesized narratively and organized around key climate-sensitive pathways, including thermal stress, hydrological disruption, environmental reservoirs, atmospheric transport, and vulnerabilities in climate-sensitive health systems.

Thermal stress as a climate driver of AMR

Heat is now recognized as a potent, climate-sensitive factor that accelerates AMR [1, 2]. Analysis of over 28 million clinical bacterial isolates from 2000 to 2023 shows that average ambient temperature and extreme heat indices, such as peak daily temperatures and extended heat waves, are positively linked to higher resistance rates, even after accounting for gross domestic product (GDP) per capita, population density, antibiotic use, and water, sanitation, and hygiene (WASH) infrastructure. Conversely, colder temperatures generally display the opposite pattern [4]. These trends are consistent across various bacterial groups and regions, confirming heat as a global ecological driver of AMR. Additionally, evidence suggests that climate change is altering microbial communities in the environment and promoting thermal adaptation. Fungi such as *Candida auris* exhibit multidrug resistance (MDR) and tolerance to elevated temperatures, demonstrating how global warming and resistance development are converging [10, 11, 12].

Furthermore, several large-scale studies provide quantitative estimates of this relationship. For instance, MacFadden et al. found that each 10 °C rise in local temperature correlates with approximately a 2–4% higher prevalence of resistance in *Escherichia coli, Klebsiella pneumoniae,* and *Staphylococcus aureus* in the United States [12]. Subsequent multi-country analyses have observed similar positive associations between temperature anomalies and resistance rates across various antibiotic classes. However, the magnitude of the effect depends on the pathogen, antibiotic class, healthcare infrastructure, and regional antimicrobial use patterns [13].

Hydrological instability as a context-dependent amplifier of AMR

Hydrological instability includes droughts, floods, and changing water dynamics, which act as context-dependent amplifiers of AMR. Prolonged droughts concentrate chemical pollutants, residual antibiotics, and resistant microorganisms in soils and shrinking water sources, increasing selective pressure, particularly for members of the order Enterobacterales [14]. Conversely, moisture-dependent pathogens, such as *Acinetobacter baumannii*, may have reduced prevalence under dry conditions [11]. Heavy rainfall and flooding create “accumulate and flush” cycles that mobilize antibiotic-resistant bacteria (ARB) and resistance genes from wastewater, livestock manure, and soils into rivers, aquifers, and communities, raising human and animal exposure [14]. The runoff effects are magnified by climate-driven changes in hydrology, sediment movement, and microbial community structure. Mitigation involves targeted actions such as surge-capacity WASH measures, improved drainage and humidity control in healthcare settings, and adaptive wastewater management guided by hydrological forecasts. Integrating climate predictions with AMR surveillance and infrastructure planning is crucial to lessen environmental spread and enhance the resilience of water and sanitation systems [9].

Climate-driven environmental reservoirs and transmission pathways of AMR across aquatic and terrestrial systems

Both aquatic and terrestrial environments act as dynamic reservoirs and channels for AMR, with vulnerability strongly modulated by climate change. Coastal and estuarine ecosystems, already stressed by global warming, salinity shifts, and eutrophication, serve as hotspots for *Vibrio* species, exhibiting rising resistance prevalence, temperature-dependent virulence, and enhanced biofilm formation [4]. Climate-exposed aquaculture systems, crucial for global food security, respond to pathogen pressure by increasing antimicrobial use, further enriching local resistomes. Resistance determinants are propagated not only within microbial cells but also via extracellular DNA, storm-driven sediment mobilization, and downstream water transport, facilitating long-range dissemination of ARGs [14].

Aquaculture is a good example of how climate pressures can intensify antimicrobial selection. Rising water temperatures increase pathogen proliferation in densely stocked systems, often prompting prophylactic antibiotic use. Monitoring across the U.S. Gulf Coast and the Mediterranean showed increased resistance among *Vibrio* species and other aquatic bacteria in warm-water aquaculture environments [15, 16]. Key indicators for surveillance include antimicrobial use rates per unit of biomass produced, resistance prevalence in indicator organisms, ARG abundance in aquaculture sediments, and antibiotic concentrations in effluent discharge. Strengthening vaccination programs, improving stocking density management, and implementing effluent treatment can reduce reliance on antimicrobials while maintaining productivity [15, 17].

On land, climate-driven alterations in soil microbial communities, wildlife distributions, helminth ranges, and plant pathogen pressures intersect with intensified anthropogenic inputs of antibiotics and pesticides, particularly during seasonal heat and drought stress [14, 18], and are leading to disseminated AMR across the One Health spectrum. Meanwhile, cryospheric melting and thawing permafrost release ancient resistomes that mix with modern microbes via meltwater [19]. Although metagenomic studies confirm the presence of ancient resistance genes in glacier and permafrost environments [20, 21], the extent to which these resistomes contribute to contemporary clinical resistance remains an open research question. Consequently, interconnected water and land reservoirs emphasize the urgent need for integrated surveillance, targeted stewardship, and ecosystem-based strategies to limit resistance spread amid accelerating climate change (Figure 1).

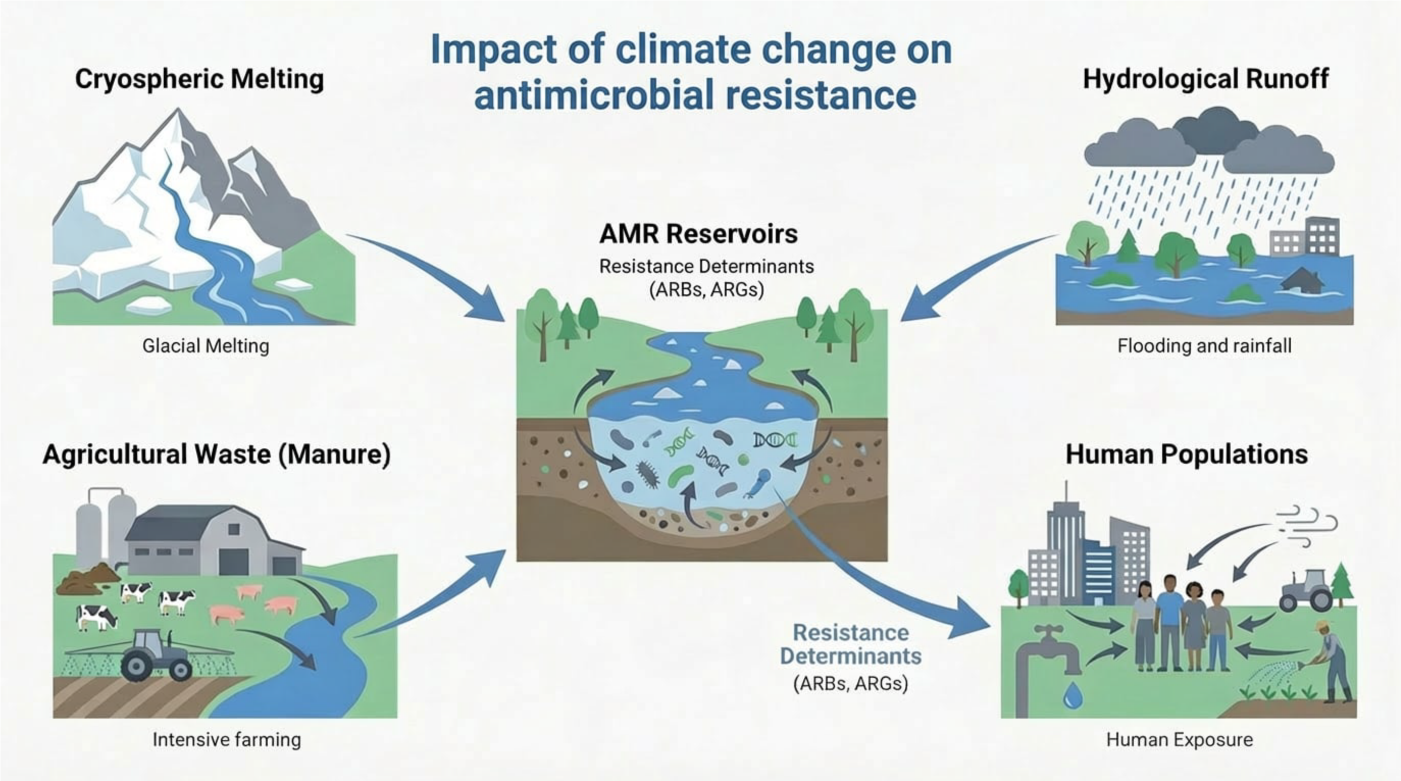

Figure 1: Conceptual model of climate-mediated AMR transmission. The diagram illustrates the mobilization of resistance determinants, i.e., antibiotic-resistant bacteria (ARB) and antibiotic-resistant genes (ARGs) from cryospheric, aquatic, and agricultural reservoirs to human populations, driven by hydrological extremes and thermal stress.

Atmospheric pathways of AMR transmission and aerozolised resistomes

Atmospheric transport is often an understudied pathway for spreading AMR. Aerosols, including dust, wildfire smoke, industrial emissions, and urban pollution, can harbour both ARB and extracellular ARGs, enabling long-range dispersal at regional and even continental scales. Climate change and human-driven land-use modifications have led to increased heatwave and wildfire frequency, prolonged droughts, and intensified desertification. This modulates aerosol generation, transport dynamics, and ground deposition patterns, effectively modifying terrestrial, aquatic, and urban resistomes.

Emerging evidence indicates that wildfire smoke plumes can transport metabolically active ARB and ARGs over hundreds of kilometers from the original source, revealing an emerging airborne dimension of AMR that overlaps with human and animal exposure routes [22]. Incorporating aerosolized resistomes into One Health surveillance, public health risk assessment, and climate-adapted emergency planning is therefore vital for predicting the spread of resistance, especially as climate extremes intensify, and highlights the atmosphere as a key global pathway for AMR amplification [23]. Although the presence of ARGs and antibiotic-resistant bacteria in aerosols has been confirmed [23, 24, 25, 26], the clinical impact of airborne AMR transmission at the population level remains unclear, underscoring the need for more longitudinal exposure research. A summary of climate-sensitive pathways affecting antimicrobial resistance, along with the current evidence strength, is provided in Table 1.

Climate-driven AMR in LMICs and vulnerable populations

Climate change-driven AMR disproportionately affects LMICs and vulnerable communities, where limited healthcare access and diagnostic capacity, poor WASH infrastructure, limited environmental enforcement, and lack of good governance increase AMR exposure [45]. Climate-driven expansion of vector-borne diseases further complicates AMS strategies, where increasing outbreaks of pathogens such as dengue, malaria, and leptospirosis amplify empiric antibiotic use for undifferentiated infections and secondary complications, thereby augmenting selective pressure for resistance. Furthermore, extreme events such as floods, cyclones, and heatwaves lead to displacement, overcrowding, and poor sanitation, creating high-risk pressure pots for the emergence of resistant pathogens [46].

A pragmatic priority package for addressing climate-sensitive AMR in LMICs should focus on strengthening fundamental health and environmental systems. Key interventions include enhancing basic WASH infrastructure and expanding wastewater treatment capacity, as well as strengthening laboratory diagnostic capacity and AMR surveillance networks in accordance with the four pillars and two foundational interventions of people-centered approaches to AMR proposed by WHO [47]. In parallel, AMS programs should be implemented and reinforced in both healthcare and agricultural sectors to reduce inappropriate antimicrobial use. Establishing climate-sensitive disease surveillance and early warning systems can further support proactive responses to climate-driven health risks. Integrating AMR monitoring into environmental and water quality surveillance programs would also enhance early detection of emerging bacterial resistance threats [18, 48]. Progress in these areas can be tracked using measurable indicators such as antibiotic consumption rates, resistance prevalence in sentinel pathogens, access to safely managed sanitation services, wastewater treatment coverage, and increased access to better-equipped microbiology laboratories.

Addressing these intersecting vulnerabilities requires integrated socio-ecological ASM strategies and alignment of AMS with the Sustainable Development Goals (SDGs), including universal health coverage, safe water and sanitation, sustainable cities, ecosystem preservation, and climate action. By tackling upstream environmental and social drivers of resistance, integrated approaches move beyond reactive containment to people- and equity-centered, prevention-oriented interventions that strengthen the resilience of health systems and ecosystems alike. Recognizing AMR as a climate-sensitive and socially mediated challenge reframes AMS as a global justice issue that demands multisectoral coordination, adaptable policies, and targeted investment in vulnerable populations [18].

Table 1: Climate-sensitive pathways influencing antimicrobial resistance and the current strength of evidence.

Pathway	Evidence strength	Type of evidence	Key indicators	Policy/Intervention leverage	Reference
Rising temperatures	High	Multi-country epidemiological datasets, experimental microbiology	Mean temperature, heatwave frequency, and resistance prevalence	Climate-adapted AMS and surveillance triggers	[1, 2, 27, 28]
Hydrological extremes	Moderate	Environmental monitoring, wastewater studies	Flood frequency, antibiotic concentration, and ARG abundance	Climate-resilient WASH and wastewater treatment	[29, 30, 31, 32, 33, 34, 35]
Aquatic food systems	Moderate	Aquaculture studies, environmental AMR surveys	Aquaculture antibiotic use and *Vibrio* resistance	Biosecurity, vaccination and effluent control	[36, 37, 38]
Atmospheric transport	Emerging	Aerosol ARG detection, wildfire smoke studies	ARG detection in aerosols	Airborne monitoring and environmental surveillance	[39, 40, 41, 42]
Cryosphere release	Emerging	Metagenomic studies of glaciers/permafrost	ARG abundance in meltwater	Environmental monitoring and exposure research	[19, 20, 43, 44]

Embedding climate-intelligent governance and One Health strategies for early detection, monitoring, and mitigation of AMR

The Lancet scoping review on the intersections between climate change and AMR identifies six recurring relationships: harmful synergies, climate driving AMR, shared solutions, shared drivers, trade-offs, and AMR influencing climate change. These relationships span aquatic, terrestrial, and health systems, providing evidence that the nexus is systemic rather than incidental [14]. A logical step is to incorporate climate indicators into AMR early warning and response strategies. This involves linking meteorological data feeds with clinical, environmental, and wastewater AMR dashboards to predict risk periods and initiate early, targeted, and integrated interventions across the One Health spectrum [14, 18]. The main obstacle in addressing climate-sensitive AMR is no longer a lack of analytical tools. Instead, the key challenge is translating existing models into routine regulatory decision-making. Advanced environmental and ecological modeling frameworks already show that AMR risks can be quantified, spatially mapped, and proactively managed under climate stress [49].

Implementing climate-sensitive AMR mitigation strategies also requires careful consideration of feasibility and trade-offs [50]. For example, intensified wastewater disinfection may reduce microbial contamination but can increase chemical loads or energy demand [51, 52]. Similarly, advanced treatment technologies such as membrane filtration or advanced oxidation processes may be difficult to implement in resource-limited settings [53, 54]. Climate-resilient AMR interventions must therefore balance environmental effectiveness, economic feasibility, and infrastructure capacity. Prioritizing low-cost measures such as improved sanitation systems, stewardship programs, and targeted monitoring can deliver substantial benefits while minimizing unintended consequences.

Environmental monitoring and wastewater surveillance are increasingly recognized as vital tools for tracking the spread of AMR across ecosystems [55]. For regulatory purposes, climate-AMR models need to be calibrated with environmental monitoring data, including antibiotic concentrations, hydrological flow patterns, wastewater discharge volumes, and antimicrobial consumption rates in humans and animal populations [56]. Model validation usually involves comparing predicted concentrations or resistance trends with actual environmental monitoring data collected over multiple seasons or under different hydrological conditions. Outputs such as spatial risk maps, exceedance predictions of predicted no-effect concentration (PNEC) thresholds, and climate-related risk forecasts can then be incorporated into decision-making dashboards that support wastewater permitting, environmental monitoring priorities, and national AMR action plan (NAP) implementation [57, 58].

Integrated hydrology exposure models, such as LF2000 WQX, connect antimicrobial prescribing patterns, human and animal excretion, and wastewater discharges to river flow dynamics to predict antibiotic levels in surface waters under varying climate conditions [59]. Simulations consistently show that frequently used compounds, especially macrolides and fluoroquinolones, can surpass PNECs in receiving waters, particularly during low-flow or heat-stress periods [60, 61]. These exceedances indicate ongoing selection pressure on aquatic microbiomes, highlighting the importance of climate-adapted discharge limits, targeted improvements in wastewater treatment plants, and risk-based permitting at hydrologically vulnerable sites [49].

In addition to existing exposure models, Lotka-Volterra and eco-evolutionary frameworks explain the competitive interactions between susceptible and resistant microbial populations in response to environmental disturbances [18]. When climate stressors, such as global warming, nutrient loading, or hydrological disruption, occur alongside antimicrobial residue contamination, these models predict a systematic shift toward the dominance of resistant pathogens unless both environmental factors and antimicrobial misuse are addressed simultaneously. This dual-control approach is crucial because AMS alone is insufficient when environmental selection pressures persist [18, 62]. Combining AMR and climate modeling into regulatory and adaptation planning enables proactive investment in advanced treatment methods such as oxidation, activated carbon, and membrane systems. Using these tools in routine decision-making reshapes resistance as a predictable and manageable risk, which can be tackled through coordinated, evidence-based infrastructure and policy actions at the intersection of climate and health [62, 63].

Health systems sit at the frontline of the climate-AMR nexus and must adapt AMS strategies to increasingly unstable conditions [45]. For example, heatwaves amplify the risk of device-associated, moisture-linked, and waterborne outbreaks, requiring stronger surveillance, improved drainage, humidity control, and environmental monitoring. Power outages threaten cold-chain integrity, risking subtherapeutic dosing and resistance selection [1]. Droughts and floods disrupt WASH systems, demanding contingency planning. As such, embedding climate scenarios into procurement, stockpiling, and formulary design helps avoid reactive reliance on suboptimal drugs. Integrating climate resilience into AMS reframes it as an adaptive systems challenge requiring anticipatory, coordinated planning [1, 45].

Furthermore, climate change impacts disease ecology, leading to increased use of prophylactic antimicrobials in livestock and aquaculture, while warming waters boost selection pressures for resistance [9]. Preventing harmful responses requires climate-smart and AMR-aware strategies such as vaccination, enhanced biosecurity, thermotolerant breeds and crops, optimized stocking densities, and integrated aquaculture protocols to limit pathogen spread and waste. Strong effluent controls and AMR-focused wastewater monitoring are crucial to avoid trade-offs and to promote productivity, sustainability, and public health in the face of climate change [1, 9].

Artificial intelligence (AI) can help anticipate and reduce AMR by integrating climate, prescribing, genomic, wastewater, and environmental data to identify hotspots, predict risks, and guide targeted interventions across the One Health spectrum [64]. These computational pipelines also accelerate antimicrobial discovery, enabling the development of drugs and biologics that remain effective under heat, humidity, and varying pH conditions, which are increasingly common in clinical and agricultural environments. Achieving this requires sustained investment in interoperable, ethical, AI-ready One Health data systems, along with robust governance to ensure quality, equity, and responsible use. Embedding AI into climate-resilient AMR surveillance can support faster response time, smarter resource allocation, and a shift from reactive containment to proactive, systems-level prevention [64].

Addressing the climate-AMR nexus relies equally on good governance and interdisciplinary strategies. Climate considerations must be integrated into national AMR plans, health adaptation strategies, and environmental policies under a unified One Health framework that tackles disseminated AMR across ecological niches [65]. Regulations should shift upstream to enforce limits on antimicrobial discharge from pharmaceutical, agricultural, and healthcare sources, aligned with PNECs and local hydrology [49]. Additionally, climate resilience strategies must climate-proof WASH and wastewater infrastructure through surge-capacity systems, decentralized treatment in vulnerable areas, and real-time monitoring that uses wastewater-based AMR surveillance as an operational decision-making tool rather than a discretionary research activity [11]. Investment should align with the SDGs, prioritizing LMIC investment in climate-resilient labs and WASH infrastructure, and improving the implementation of national AMR strategies [14]. Accountability must be embedded at all levels, with compliance accurately measured, to integrate climate and environmental AMR indicators into national dashboards and joint progress reports, ensuring transparent, enforceable stewardship [45, 64].

Climate-AMR early warning framework

Connecting meteorological signals with AMR surveillance can enhance proactive public health responses and strengthen preparedness for climate-related health threats [9]. A streamlined operational framework for climate-sensitive AMR early warning systems could combine various indicator domains, such as climate indicators (temperature anomalies, heatwave duration, and extreme precipitation events), environmental indicators (antibiotic levels in wastewater, abundance of ARGs, and river flow levels), clinical indicators (resistance prevalence in sentinel pathogens and antibiotic usage rates), and animal and food-system indicators, including antimicrobial use in livestock and aquaculture, and resistance patterns in indicator bacteria [66, 67]. By integrating these datasets within a One Health surveillance framework, it would be possible to detect emerging resistance trends earlier and enable timely policy and public health interventions.

Trigger thresholds might include sustained heat anomalies, low-flow hydrological conditions, or rapid increases in the prevalence of resistance in sentinel organisms. These signals would be evaluated by national AMR coordination units and public health authorities, prompting actions such as enhanced surveillance, targeted stewardship alerts, wastewater discharge controls, or infection prevention measures in healthcare facilities [1, 68, 69]. Incorporating these indicators into real-time dashboards and national AMR action plans would transform climate-sensitive AMR surveillance from a retrospective reporting activity into an operational decision-support system (Figure 2).

Climate change clearly accelerates AMR through interconnected pathways, including rising temperatures, extreme weather events, ecosystem disruption, and increasing pollution routes [4, 23]. These processes are no longer merely theoretical; they are observable factors that shape resistance patterns across human, animal, and environmental systems [1, 9]. The reviewed literature highlights actionable, mutually beneficial interventions such as controlling antimicrobial pollution, implementing climate-smart livestock and aquaculture practices, developing resilient water and sanitation systems, and utilizing AI-enabled surveillance to anticipate risks before resistance becomes deeply rooted [64]. Expanding these solutions requires a shift from fragmented sectoral efforts to a One Health governance approach that integrates climate intelligence into AMR policies and planning. How quickly these strategies are adopted will influence antimicrobial preservation, especially in climate-vulnerable communities facing heightened risks [1, 9, 14].

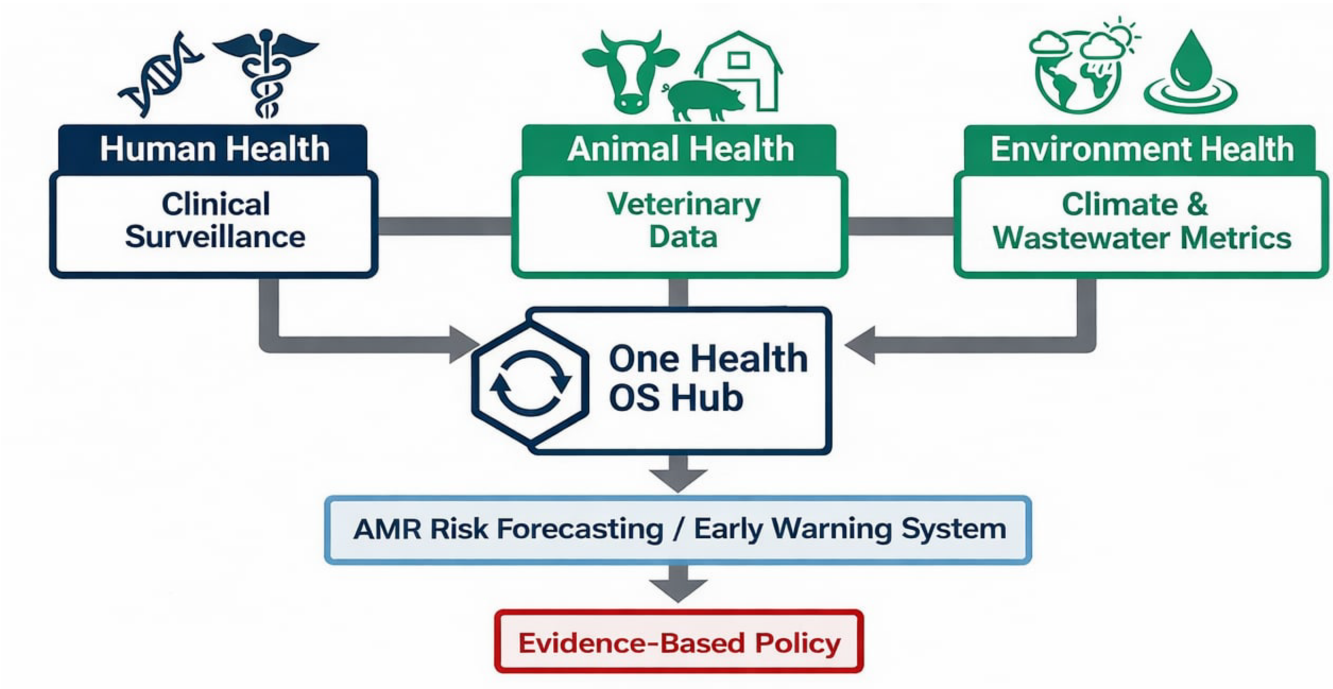

Figure 2: Climate-sensitive AMR early warning framework. Clinical surveillance, veterinary antimicrobial use data, and environmental indicators such as climate variables and wastewater metrics are integrated through a One Health operational system (OS) hub. Combined datasets enable early detection of climate-sensitive AMR risks, supporting predictive modeling and decision dashboards that inform evidence-based public health and environmental policy.

Limitations and interpretation of evidence

Much of the current evidence linking climate change and antimicrobial resistance remains observational and dependent on context. While strong associations between climate variables and resistance rates have been documented, causal relationships are affected by multiple interacting factors, including antimicrobial use patterns, WASH infrastructure, urbanization, population mobility, and socioeconomic conditions. Climate factors may therefore act as amplifiers of existing resistance dynamics rather than independent drivers. Additionally, the strength of evidence varies across pathways; large epidemiological datasets support temperature-resistance links, while atmospheric transport and cryospheric resistomes release are emerging areas with limited direct clinical connections. Future studies combining long-term environmental monitoring, genomic surveillance, and exposure assessment will be necessary to better understand causal pathways and regional differences.

The convergence of AMR and climate change signals a systems-level tipping point in global health. Shared ecological disruption, infrastructural weakness, and social inequity are accelerating microbial adaptation beyond the reach of traditional containment strategies. Without climate-informed stewardship, resilient water and sanitation systems, sustainable food production, advanced surveillance, and accountable One Health governance, antimicrobial effectiveness will decline faster than we can replace it. Climate-informed AMR policy is not a distant goal but an urgent necessity.

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