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Review

Climate Change, Zoonoses, and Vaccine Equity: A One Health Framework

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Received: 11 October 2025; **Revised:** 9 November 2025; **Accepted:** 26 November 2025; **Published:** 1 December 2025

Abstract: Climate change is increasingly recognized as a driver of zoonotic disease emergence, reshaping ecological interactions and amplifying risks to human and animal health. Rising temperatures, altered precipitation patterns, and extreme weather events accelerate vector breeding cycles, disrupt habitats, and intensify human-animal contact, thereby expanding opportunities for pathogen spillover. This review aims to synthesize evidence on climate-linked zoonotic threats and examine how vaccine equity and policy integration within a One Health framework can strengthen global preparedness. A narrative literature review was conducted using PubMed, Scopus, Web of Science, and Google Scholar, covering publications from 2005 to 2025. Keywords included climate change, zoonotic diseases, One Health, surveillance, vaccine equity, and health disparities. Evidence highlights climate-sensitive diseases such as malaria, Rift Valley fever, and leptospirosis as major global health challenges. Surveillance systems, including the Global Outbreak Alert and Response Network, the Global Early Warning System, the International Pathogen Surveillance Network, and the Global Influenza Surveillance and Response System, provide critical early warning capacity but remain unevenly implemented in low- and middle-income countries. Vaccine equity challenges persist among displaced populations, rural communities, and marginalized groups, with barriers linked to infrastructure, misinformation, and systemic inequities. Embedding climate resilience, equity, and community participation into One Health strategies is essential for mitigating zoonotic threats. Strengthened interdisciplinary collaboration, digital innovation, and policy harmonization will be pivotal in advancing surveillance, prevention, and vaccine equity, thereby enhancing global preparedness against future climate-driven zoonotic disease risks.

Keywords: Climate Change; Zoonoses; One Health; Disease Surveillance; Vaccine Equity; Health Disparities

1. Introduction

Rudolph Virchow coined '*zoonoses*' in 1855 [1]. Zoonoses refer to infectious diseases that are naturally transmitted between humans and vertebrate animals [2–4]. Emerging zoonoses are characterized as infections arising from either novel pathogens or from previously recognized microorganisms that manifest in new geographic regions, host species, or epidemiological contexts where such diseases had not been previously reported [2]. Zoonotic diseases can be categorized into three principal groups [5].

i. Endemic zoonoses are those consistently present across populations, exerting a sustained impact on both humans and animals [6].
ii. Epidemic zoonoses occur intermittently, displaying irregular temporal and geographic patterns of transmission [7].
iii. Emerging and re-emerging zoonoses encompass infections that either arise from novel circumstances or reappear in expanded ranges and prevalence, reflecting shifts in ecological, climatic, or host dynamics [8].

Globally, zoonotic diseases represent a major public health burden, accounting for more than 60% of emerging infectious diseases and approximately 75% of newly identified human pathogens in recent decades [9]. Current estimates suggest that zoonotic infections are responsible for over 2.4 billion cases and 2.7 million deaths annually, with the greatest burden concentrated in low- and middle-income countries (LMICs) where surveillance and healthcare infrastructure remain limited [10]. Beyond health impacts, zoonotic outbreaks have caused severe economic and social damage. The World Bank reports that zoonotic epidemics such as SARS, Ebola, and COVID-19 have collectively resulted in trillions of dollars in global economic losses, disrupting trade, tourism, and food systems [11]. The COVID-19 pandemic alone led to a global economic contraction of 3.5% in 2020, underscoring the scale of disruption caused by zoonotic spillovers [12]. The ongoing climate crisis exerts profound effects across planetary systems, with notable consequences for both human and animal health [13]. Among its most critical public health implications is the alteration of zoonotic disease dynamics, wherein infections are transmitted between vertebrate animals and humans by diverse pathogens including parasites, viruses, and bacteria [13]. Particularly concerning is the impact on vector-borne disease transmission, as rising temperatures and shifting precipitation patterns generate increasingly favorable ecological niches for climate-sensitive vectors such as mosquitoes, sandflies, and ticks [14]. Examples of climate-sensitive zoonotic diseases include malaria, dengue, and West Nile fever, which are transmitted by mosquitoes; leishmaniasis, spread through sand fly vectors; and Lyme disease, associated with tick transmission [13]. While the influence of climate on these infections is mediated by complex, nonlinear feedbacks and varies across different vector-pathogen systems, climatic factors are widely recognized as key environmental drivers shaping their epidemiology and transmission. These impacts operate across multiple temporal scales, from short-term seasonal and annual fluctuations to longer decadal trends, underscoring the central role of climate in modulating zoonotic disease dynamics [15]. Climate change (CC) further destabilizes the equilibrium between hosts and pathogens, with altered temperature and precipitation regimes influencing animal life cycles, reproductive dynamics, and migratory behaviors [8]. Such ecological disruptions heighten the likelihood of human-pathogen encounters, altering transmission dynamics and ultimately increasing the probability of zoonotic disease emergence and spread [16]. Surrounding thermal conditions are a critical determinant of pathogen dynamics, influencing viral replication, the duration of extrinsic incubation, seasonal fluctuations in vector populations, and geographic variation in human case incidence [14]. Climatic disturbances of this kind can accelerate transmission and foster the emergence of novel infectious diseases, as illustrated by malaria expansion in West Africa. Shifts in rainfall, humidity, and land-use patterns have been directly linked to malaria transmission [17,18]. Rising global temperatures also enable tropical species to extend their ranges into higher latitudes and altitudes, establishing themselves in previously non-endemic regions [8]. Consequently, improved habitat suitability under warmer conditions facilitates the spread of disease vectors into new ecological niches [19].

CC accelerates ecological deterioration, driving processes such as forest clearance, habitat fragmentation, and transformations in land-use practices [20]. Environmental disruptions diminish the natural barriers between humans and wildlife, thereby increasing the probability of zoonotic spillover. As ecosystems shrink, animals are forced into closer proximity with human communities, generating new ecological contact zones that enable pathogen exchange [8]. Close human-wildlife interactions have been linked to the emergence of severe infectious diseases such as COVID-19, SARS, Ebola, and Lassa fever. These outbreaks frequently originate when human activities intrude into previously intact ecosystems, creating new interfaces that enable pathogen spillover [21]. CC unevenly burdens vulnerable groups, magnifying their exposure to infectious threats. Marginalized populations in resource-poor nations often lack reliable healthcare, potable water, and adequate sanitation systems, conditions that heighten their vulnerability to infection [22]. Refugee communities are especially susceptible, as overcrowding, insufficient hygiene facilities, and limited access to social and medical services create fertile ground for epidemic outbreaks [12]. In regions where climate variability undermines agriculture and food availability, nutritional deficiencies weaken immune defenses, thereby increasing susceptibility to disease transmission [23]. Collectively, zoonotic infections

exert cascading effects beyond the health sector, influencing human security, destabilizing wildlife commerce, and constraining tourism industries [24, 25]. The purpose of this review is to integrate current evidence on climate-associated zoonotic threats and to advance equitable, cross-disciplinary approaches for their mitigation. The added value of this review lies in its synthesis of climate change, zoonotic disease dynamics, and vaccine equity within an One Health (OH) framework. By embedding digital innovation and equity considerations, it extends current discourse beyond traditional zoonotic reviews and provides actionable pathways for policy and practice.

2. Methods

This study employed a narrative literature review approach, drawing upon peer-reviewed publications to explore the intersection of climate change, zoonotic disease risk, and vaccine equity. To capture a comprehensive spectrum of relevant literature, a structured search was conducted across four primary databases: PubMed/Medline, Scopus, Web of Science, and Google Scholar.

The search strategy targeted publications released between 2005 and 2025, ensuring coverage of both pre-pandemic and post-pandemic insights into climate-linked zoonotic risks. A combination of keywords and Boolean operators was used to maximize retrieval, including terms such as "climate change," "zoonotic diseases," "One Health," "surveillance," "vaccine equity," "vector-borne diseases," and "health disparities." In addition to peer-reviewed literature, grey literature was considered to capture policy-relevant evidence. This included policy briefs, technical reports, and case studies from reputable international health organizations. The search strategy was designed to balance breadth and specificity, ensuring representation of both empirical studies and policy frameworks.

Eligibility criteria were defined to guide the inclusion and exclusion of sources. Included materials comprised scholarly publications such as peer-reviewed research articles, systematic syntheses, meta-analytical studies, policy briefs, and case-based investigations that examined the relationship between climate change and zoonotic disease risk. Studies linking surveillance systems, vaccine equity, or OH interventions were also eligible, as were reports from international health agencies and initiatives focused on LMICs.

Exclusion criteria were applied to filter out non-English publications, studies lacking relevance to zoonotic disease or climate-health interactions, and editorial pieces, opinion articles, or anecdotal reports that lacked empirical evidence.

Data extraction focused on key variables relevant to the study objectives. These included disease focus (e.g., malaria, Rift Valley fever, leptospirosis), climate drivers (such as temperature rise, precipitation, flooding, drought), surveillance models (e.g., GOARN (Global Outbreak Alert and Response Network), GLEWS (Global Early Warning System), IPSN (International Pathogen Surveillance Network), GISRS (Global Influenza Surveillance and Response System), national systems), equity dimensions (e.g., access to vaccines, health system capacity, vulnerable populations), and policy frameworks (e.g., WHO (World Health Organization), FAO (Food and Agriculture Organization), UNEP (United Nations Environment Programme), WOAH (World Organisation for Animal Health (formerly OIE), national One Health strategies).

Extracted data were organized into four thematic domains: (i) global trends and climate-linked risk patterns, (ii) surveillance and early warning systems, (iii) vaccine equity and preventive strategies, and (iv) policy integration and future directions. A matrix synthesis approach was applied to compare findings across diseases, regions, and intervention models.

3. Results and Discussion

3.1. Global Trends and Climate-Linked Risk Patterns

Several infectious diseases remain significant global health challenges, with cholera, dengue fever, dysentery, leishmaniasis, leptospirosis, malaria, meningitis, and Rift Valley fever (RVF) being particularly notable due to their capacity to cause widespread outbreaks and grave morbidity [26–30]. These pathogens are highly climate-sensitive and disproportionately prevalent in Sub-Saharan Africa. For example, malaria and dengue transmission intensifies as rising temperatures accelerate mosquito breeding cycles, while cholera incidence frequently increases in association with heavy rainfall and flooding events [31]. Malaria remains a major global public health challenge, with an estimated 229 million cases reported worldwide in 2019 [26,27]. More than 200 protozoan species have been identified, of which at least 13 are pathogenic to humans. Diagnosis can be established through clinical evaluation

of characteristic signs and symptoms, while management strategies encompass both preventive and therapeutic interventions. Importantly, untreated uncomplicated malaria has the potential to progress to severe disease, underscoring the need for timely detection and appropriate treatment [32]. Rift Valley fever (RVF) virus, a vector-borne pathogen belonging to the *Phenuiviridae* family within the order *Bunyavirales*, affects both humans and animals. While most human infections are self-limiting, clinical manifestations can include prolonged febrile illness, hemorrhagic fever, hepatic injury, and in severe cases, death. Surveillance data have attributed RVF outbreaks to 72,960 animal cases with 17,810 fatalities, alongside 5,228 suspected human infections resulting in 987 deaths during the reporting period. Veterinary vaccines are available and have been licensed in endemic regions such as Rwanda, Kenya, and Tanzania; however, their deployment is typically restricted to periods when predictive risk models indicate heightened transmission potential [33]. Leptospirosis is recognized as a major zoonotic bacterial disease of global significance, responsible for an estimated one million infections and approximately 58,900 deaths annually, with a case fatality rate of 6.85%. The disease exhibits high prevalence in tropical regions, accounting for nearly 73% of reported cases, particularly across South-East Asia, East Sub-Saharan Africa, the Caribbean, and Oceania. Although global incidence has remained relatively stable, recurrent large-scale outbreaks have been documented in several countries, often triggered by natural disasters such as flooding events [34]. Elevated temperatures are associated with increased mosquito activity and reproduction, resulting in higher vector densities. In parallel, pathogens that utilize mosquitoes as hosts tend to reach maturity more rapidly under warmer conditions, thereby enhancing transmission potential. Consequently, climate change is anticipated to drive further encroachment into animal habitats and intensify human-animal interactions, ultimately increasing the risk of zoonotic disease emergence [28]. **Figure 1** illustrates the interconnected pathways through which climate change influences zoonotic disease dynamics. It highlights ecological disruptions, vector expansion, and human-animal interactions, situating these within a OH framework to emphasize cross-sectoral impacts.

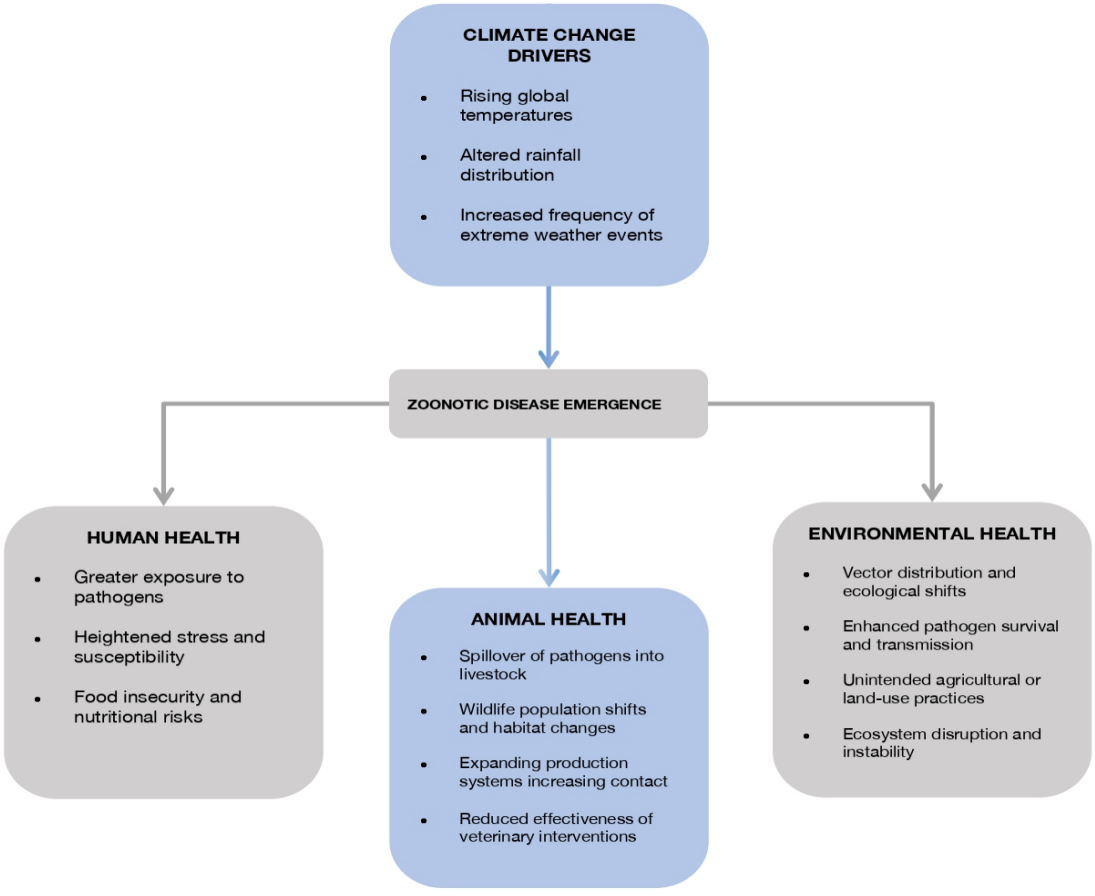

Figure 1. Pathways linking climate change to zoonotic disease emergence: A One Health perspective.

3.2. Community Engagement and Indigenous Knowledge

Community engagement constitutes a fundamental pillar of effective OH implementation, particularly within regions highly susceptible to climate-associated zoonotic diseases [35]. Local populations frequently act as the front-line of detection, observing shifts in animal behavior, vector activity, and environmental conditions that may indicate emerging health threats [36]. Incorporating indigenous knowledge systems into surveillance frameworks enhances sensitivity to ecological dynamics while fostering trust between communities and health authorities. Rural and indigenous groups possess generational expertise regarding seasonal cycles, wildlife interactions, and traditional health practices, which can complement scientific data by providing context-specific insights into disease risk [37]. For example, pastoralist communities in East Africa have long recognized correlations between rainfall variability and RVF outbreaks, offering valuable early warning signals. Community health workers (CHWs) are central to operationalizing OH at the grassroots level [38]. Through household visits, vaccination promotion, and education on zoonotic risks, CHWs reinforce both surveillance and prevention [39]. Equipping CHWs with digital tools such as mobile reporting applications further strengthens their role, enabling rapid communication with national health systems. Engagement strategies must remain culturally sensitive, respecting traditional practices while addressing misconceptions that contribute to vaccine hesitancy or delayed care [40]. Collaborative initiatives involving community leaders, women's groups, and youth organizations ensure inclusivity and sustainability, while tailored communication delivered in local languages enhances uptake of preventive measures and resilience [41]. Beyond surveillance, community participation functions as a mechanism for equity. Involving marginalized populations in decision-making processes reduces disparities in healthcare access and strengthens social cohesion. Partnerships among governments, non governmental organizations (NGOs), and local communities should prioritize capacity-building, ensuring indigenous knowledge is integrated alongside biomedical expertise [42]. Embedding community perspectives within OH frameworks creates a more holistic and adaptive system, bridging scientific evidence with local experience to improve early detection, refine intervention strategies, and ultimately mitigate the burden of climate-linked zoonotic diseases.

3.3. Surveillance and Early Warning Systems

Surveillance and warning systems are so crucial for monitoring, tracing, alerting, and notifying outbreaks of climate-associated events or diseases. Integrated human-animal-environmental data sharing platforms should be put in place to assist in surveillance and early warning. There are available tools such as the one utilized by the WHO. The WHO maintains a number of channels for reporting pandemics and other public health crises. First, the International Health Regulations (IHR) mandate that member states use the National IHR focal point to inform the WHO within 24 h of any occurrences that could qualify as an internationally significant public health emergency [43]. Since 2017, the GOARN has conducted weekly operational calls to facilitate outbreak alerts and risk assessments. As a consortium of specialized institutions, GOARN's primary mandate is rapid response and containment, achieved by deploying experts to affected sites. These calls enhance the exchange of operational data and warnings, ensuring that stakeholders remain informed of emerging pandemic threats [44]. To strengthen early detection of epidemic risks through genomic monitoring, the IPSN was launched in 2023, bringing together governments, academia, private sector actors, civil society, and international organizations into a coordinated global framework [45]. In parallel, the GISRS, established in 1952, continues to monitor and characterize influenza viruses to identify novel strains with pandemic potential, although its scope remains limited to influenza [46]. The United States Centers for Disease Control and Prevention (US-CDC), through its global network of technical experts, has operated the Global Disease Detection (GDD) Program since 2004, with the objective of identifying and containing infectious diseases at their source before they cross international borders [47]. Similarly, the GLEWS, established in 2006 as a collaborative initiative between WHO, FAO, and WOAH, functions within the OH framework to monitor zoonotic threats [48]. Collectively, GOARN, GDD, and GLEWS provide essential structures for rapid pandemic response and containment. Evidence suggests that strengthening governance and coordination, health system infrastructure and resources, and community participation are critical priorities for enhancing global health information systems and optimizing Pandemic Preparedness and Response (PPPR) [49]. Drawing on lessons from COVID-19, experts including the former Director of the US-CDC, have emphasized the importance of international collaboration and data sharing, particularly through the prototype pathogen approach. This strategy involves proactively inves-

tigating virus families with high pandemic potential to generate foundational knowledge in virology, diagnostics, animal models, antigenic targets, vaccine platforms, and immune correlates, thereby accelerating the development of medical countermeasures (MCMs) during future pandemics [50]. **Figure 2** compares major OH surveillance models, outlining their structures, operational mechanisms, and integration across human, animal, and environmental health. It underscores similarities and differences in scope, coordination, and data-sharing practices relevant to climate-sensitive zoonotic monitoring.

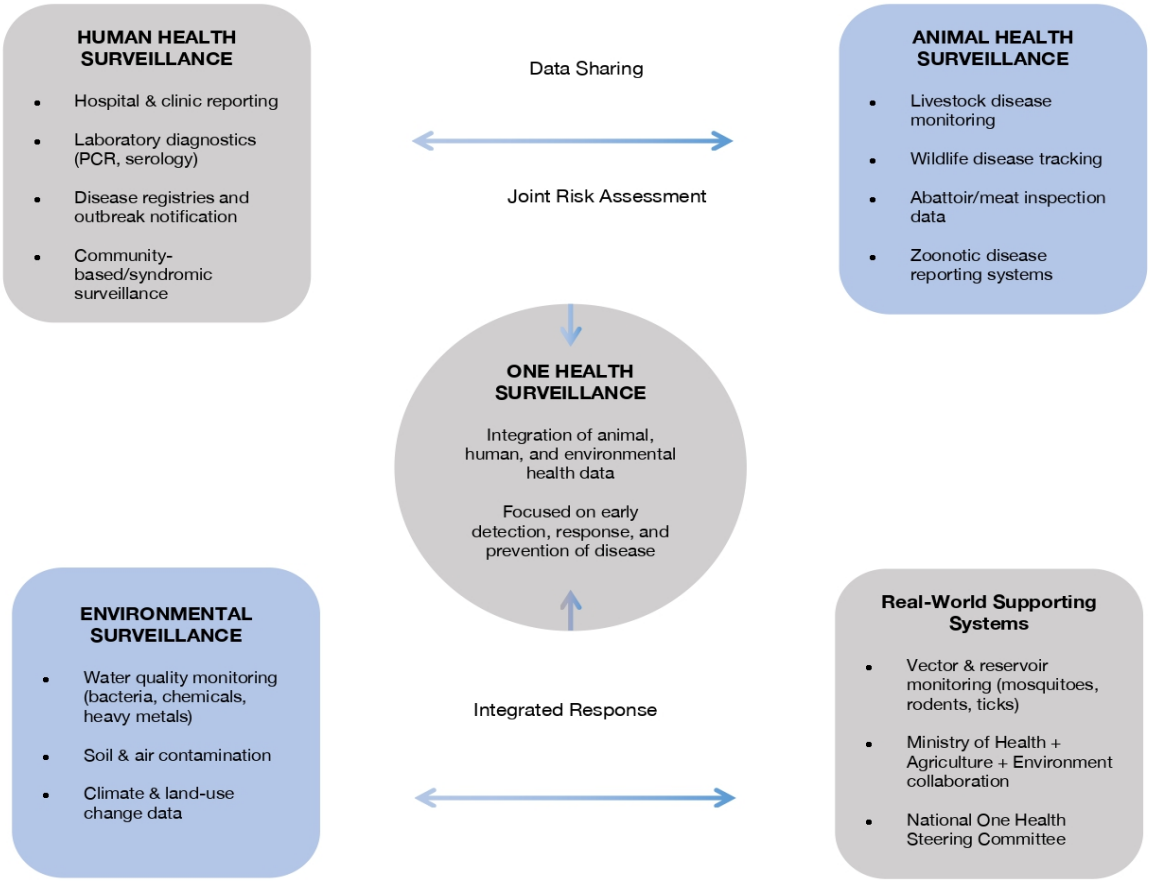

Figure 2. Comparison of One Health surveillance models.

Table 1 presents a comparative synthesis of major global surveillance systems, outlining their scope, strengths, and limitations. GOARN and GDD primarily focus on rapid outbreak detection and the deployment of technical expertise, whereas GLEWS incorporates a OH perspective by integrating human, animal, and environmental health data streams. IPSN, as a recent advancement in genomic surveillance, offers promise for the early identification of emerging pathogens, though it remains in its developmental phase. GISRS, with decades of influenza monitoring, exemplifies the importance of sustained surveillance but is constrained by its exclusive focus on influenza viruses. Collectively, these systems underscore the diversity of global surveillance mechanisms and highlight the need for enhanced harmonization, particularly in strengthening capacity within LMICs.

Table 1. Comparative strengths and limitations of global surveillance systems.

S/N	Surveillance System	Year	Scope	Strengths	Limitations
1.	GISRS	1952	Influenza only.	Long-standing influenza monitoring.	Restricted to influenza, not adaptable to other pathogens.
2.	GOARN	1997	Global outbreak response.	Rapid expert deployment, weekly operational calls.	Dependent on institutional coordination, limited LMIC capacity.

Table 1. *Cont.*

S/N	Surveillance System	Year	Scope	Strengths	Limitations
3.	GDD	2004	US-CDC global detection.	Source-level containment, technical expertise.	US-centric leadership, limited regional ownership.
4.	GLEWS	2006	FAO-OIE-WHO zoonoses.	OH integration, cross-agency alerts.	Limited funding, uneven country participation.
5.	IPSN	2023	Pathogen genomics.	Global genomic surveillance, multi-sectoral.	Still nascent, requires infrastructure investment.

3.4. Vaccine Equity and Preventive Strategies

According to WHO, health equity refers to the elimination of unjust, preventable, and remediable disparities among populations, whether these are defined by social, economic, demographic, or geographic factors, or by dimensions such as sex, gender, race, disability, or sexual orientation [51]. The state of health and equity in health outcomes is shaped by biological determinants that influence the conditions in which individuals are born, grow, live, work, and age [52]. Furthermore, access to timely, affordable, and high-quality healthcare is largely governed by sociocultural and political determinants, which are often exacerbated by discrimination and prejudice related to sex, gender, age, race, ethnicity, or disability. Achieving health equity and ensuring overall well-being requires the identification and elimination of structural inequities that drive disparities in human health outcomes [53]. These disparities are frequently associated with low socioeconomic status, limited literacy, and other social determinants. Evidence indicates that countries with well-financed health systems are better positioned to influence global policy and resource allocation, thereby shaping health outcomes more favorably [54]. The impact of such inequities becomes particularly evident during pandemics; for instance, while many developed nations secured multiple doses of COVID-19 vaccines, most African countries faced restricted access, highlighting profound gaps in global vaccine distribution [55]. Healthcare disparities arise from a complex interplay of factors operating at multiple levels [56]. Evidence indicates that an adequate supply of primary healthcare providers contributes to reducing inequities across ethnic and socioeconomic groups [57]. Sustained continuity of primary care is linked to lower risks of mortality and hospital admission, while positive patient experiences in primary care settings have been shown to mitigate the adverse health effects associated with income inequality. Conversely, individuals residing in low-income neighborhoods or those reporting poor or fair health consistently experience poorer outcomes. Moreover, voluntary enrollment models, in which patients must actively request primary care connections, can disproportionately disadvantage low-income populations and individuals with functional limitations. Multiple case studies highlight the complex interactions between conflict, displacement, and health outcomes. For example, in December 2022, the United Nations High Commissioner for Refugees (UNHCR) reported that the Russian-Ukrainian war had displaced 5.91 million people internally and created urgent humanitarian needs for 17.7 million individuals [58]. Displaced populations in such contexts often face restricted access to primary healthcare and may neglect routine immunizations while prioritizing shelter, essential goods, and employment. Building on this and similar examples, recent interventions, studies, and partnerships particularly those implemented in developing countries over the past two years have targeted pressing multilevel risk factors and offer illustrative models for future application. **Table 2** presents evidence on vaccine uptake among displaced groups, rural communities, urban informal settlements, and coastal populations. It identifies key barriers such as infrastructure deficits, misinformation, and disrupted health services, while also outlining interventions that enhance equity and resilience.

3.5. Digital Health and Innovation in One Health

Emerging digital health technologies are transforming the operational capacity of OH frameworks to anticipate, detect, and respond to climate-associated zoonotic threats [59]. Mobile health applications offer novel avenues to enhance surveillance, promote vaccine equity, and build community confidence in health systems [60]. Artificial Intelligence (AI) and Machine Learning (ML) further strengthen predictive capabilities by processing large datasets derived from climate models, genomic sequencing, and epidemiological surveillance, thereby detecting early signals of zoonotic spillover, forecasting vector dynamics, and guiding targeted interventions [61]. Blockchain technologies contribute secure, transparent, and tamper-resistant vaccine records, mitigating challenges of lost documentation among displaced populations and those in fragile ecosystems [62]. Satellite communication systems ensure continuity of data exchange during disasters and are particularly critical for LMICs, where infrastructure limitations

often impede surveillance and vaccine distribution [63]. Collectively, digital health innovations represent a transformative pathway for embedding OH principles into climate-responsive surveillance, vaccine equity, and community engagement, thereby bridging systemic gaps and enhancing resilience against future zoonotic disease threats.

Table 2. Vaccine uptake and barriers in climate-vulnerable populations.

S/N	Population Group	Setting/Climate Vulnerability	Vaccine Uptake Level	Key Barriers to Uptake	Interventions
1.	Displaced groups or refugees.	Floods, drought, conflict-driven migration.	Low to moderate	Lack of access to health facilities. Loss of vaccination records. Unstable living conditions. Language and cultural barriers.	Mobile vaccination unit. Integration of vaccines in humanitarian aid. Use of digital vaccination records.
2.	Rural farming communities.	Drought-prone and remote areas.	Low	Poor infrastructure and transport. Limited cold-chain capacity. Low health literacy. Vaccine misinformation and hesitancy.	Community outreach and health education. Solar-powered cold chain systems. Collaboration with local leaders.
3.	Urban informal setting.	Flood-prone and overcrowded cities.	Moderate	Overcrowding and poor sanitation. Distrust in authorities. Competing daily survival priorities.	Door-to-door vaccination drives. Local awareness campaigns. Partnerships with trusted community organizations.
4.	Coastal communities.	Affected by sea-level rise and storms.	Low	Displacement and health service disruption. Stockouts during disasters. Inadequate communication networks.	Emergency preparedness for vaccine delivery. Integration with disaster response plans. Use of satellite and mobile communication tools.
5.	Indigenous populations.	Living in fragile ecosystems.	Low	Geographic isolation. Cultural beliefs and traditional practices. Limited culturally sensitive health services.	Training indigenous health workers. Respectful engagement with community leaders. Tailored health communication.
6.	Low-income women, and children.	Areas affected by food insecurity and drought.	Moderate	Gender inequality. Limited mobility. Lack of childcare during clinic visits.	Women-focused vaccination programs. Integration with nutrition and maternal healthcare services. Community childcare support.

3.6. Policy Integration and Future Directions

Recognizing how knowledge gaps and policy divergences across core agencies intersect is essential to appreciating both the scope of the OH framework and the institutional limitations that shape its implementation [64]. The World Health Organization currently defines OH as 'an approach to designing and implementing programs, policies, legislation, and research in which multiple sectors collaborate to achieve improved public health outcomes' [65]. This definition closely parallels interdisciplinary models such as the socio-ecological framework of public health, which emphasizes systems-level thinking [66]. Notably, the predominance of certain disciplines particularly veterinary medicine within the adoption and application of OH may serve as its most visible hallmark [64]. Despite the experience of the COVID-19 pandemic, the role of ecosystem services and environmental sustainability within the OH framework remains insufficiently defined [66]. International stakeholders have recognized climate change as one of the most critical environmental challenges confronting humanity, yet its limited integration into OH has prompted United Nations initiatives to strengthen collaboration with UNEP [67]. Notably, on October 25, 2019, Germany's Climate and Environmental Foreign Policy Division of the Federal Foreign Office partnered with the Wildlife Conservation Society to convene the 'One Planet, One Health, One Future' conference, culminating in the adoption of the 'Berlin Principles' [68]. Collaboration across the human, animal, and environmental health sectors is essential to advancing research initiatives, designing trials, and mobilizing funding for integrated programs [65]. Interdisciplinary partnerships involving government agencies, public-private collaborations, and leadership within LMICs are critical to shaping policies that strengthen OH approaches [67]. Such coordinated efforts enable the implementation of climate-smart strategies, thereby reducing the risk and frequency of zoonotic disease outbreaks [66]. **Figure 3** illustrates an integrated policy framework that connects climate adaptation strategies with zoonotic risk reduction and vaccine equity. It highlights the role of health systems, surveillance, distribution, and biodiversity in shaping resilience, while also emphasizing social justice and affordability. The framework underscores how coordinated governance can simultaneously strengthen preparedness, reduce spillover risks, and promote equitable vaccine access.

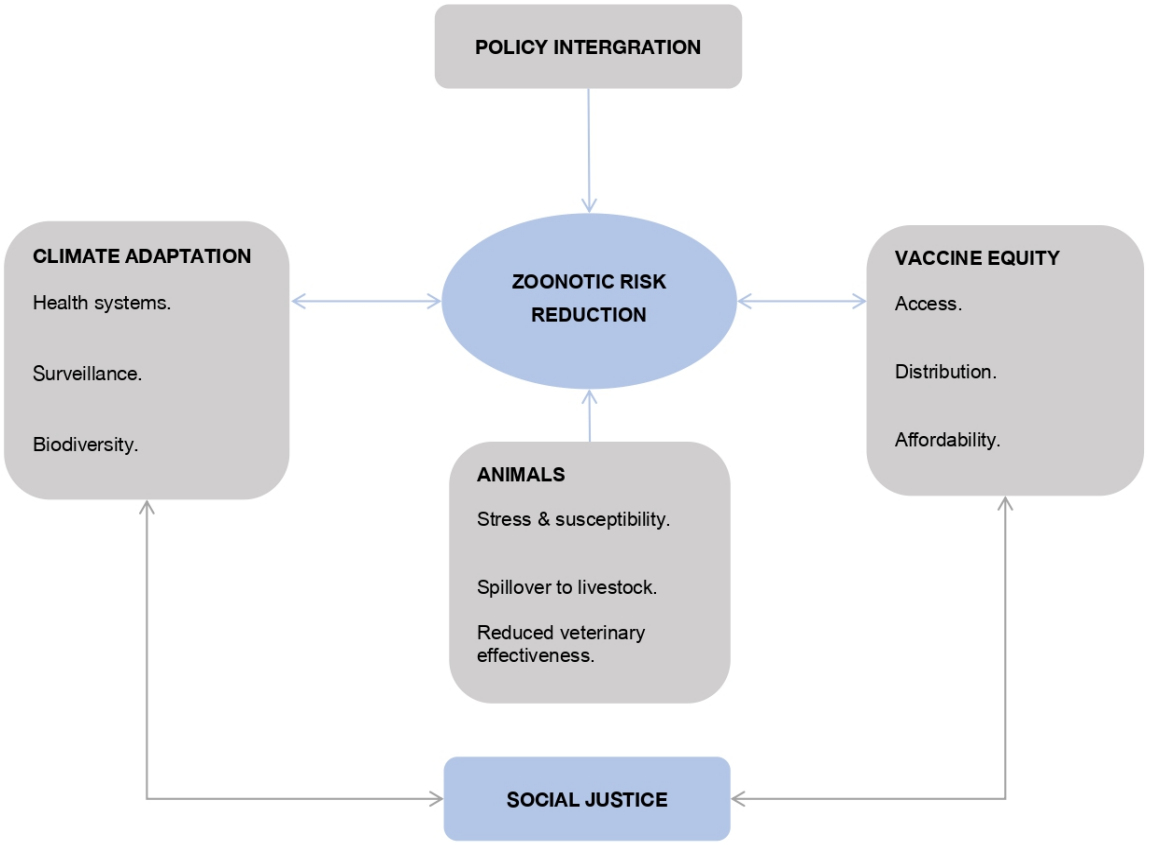

Figure 3. Policy framework linking climate adaptation, zoonotic risk reduction, and vaccine equity.

Table 3 highlights the principal policy levers necessary for advancing climate-responsive OH implementation, underscoring the multi-sectoral strategies required to mitigate zoonotic disease risks. Governance and coordination structures, such as national task forces, promote streamlined responses and reduce redundancy across institutions. Sustainable financing, derived from government allocations and donor contributions, underpins long-term surveillance and vaccine delivery programs. Active community participation, facilitated through the training and involvement of local health workers, enhances trust and enables early detection of outbreaks. Research and innovation particularly the strengthening of biomanufacturing capacity in LMICs and the application of prototype pathogen approaches, accelerate the development of medical countermeasures. Digital health integration, including mobile technologies, blockchain-enabled vaccination records, and real-time alert systems, further improves equity and accessibility. Collectively, these policy levers illustrate how integrated frameworks can align climate adaptation with zoonotic risk reduction and vaccine equity.

Table 3. Policy levers for climate-smart One Health implementation.

S/N	Policy Lever	Sector Involved	Example Action	Expected Outcome
1.	Governance and coordination	Ministries of health, environment, agriculture.	Establish national OH task forces.	Streamlined response, reduced duplication.
2.	Financing	Governments, donors, private sector.	Allocate climate-linked health budgets.	Sustainable funding for surveillance and vaccines.
2.	Community participation	Local leaders, civil society.	Train community health workers in zoonoses.	Early detection, improved trust.
4.	Research and innovation	Academia, LMIC biomanufacturing hubs.	Support vaccine R&D and prototype pathogen studies.	Faster MCM development, reduced inequities.
5.	Digital health integration	ICT ministries, NGOs.	Mobile apps for outbreak alerts, blockchain vaccine records.	Real-time data sharing, equity in access.

3.7. Future Research Directions

Future research should prioritize the integration of climate science, epidemiology, and social equity to strengthen OH implementation in addressing zoonotic disease risks. Although current evidence demonstrates associations between climate variability and disease emergence, more rigorous longitudinal investigations are required to elucidate causal pathways and forecast future burdens. Advanced modeling approaches that merge climate projections with vector ecology, pathogen genomics, and human mobility data can generate actionable forecasts to guide policymakers and health systems. Equally critical is the expansion of genomic surveillance capacity within LMICs. Strategic investments in sequencing infrastructure, bioinformatics expertise, and regional data-sharing platforms will facilitate earlier detection of novel pathogens and enhance global preparedness. Extending prototype pathogen research to virus families with high spillover potential in Africa and Asia will ensure that vaccine platforms and diagnostics are available prior to outbreak events. Community-based participatory research represents another essential avenue. Systematic documentation of indigenous knowledge related to ecological changes, seasonal disease cycles, and traditional health practices can enrich surveillance frameworks and improve cultural relevance. Collaborations with local leaders and community health workers will ensure that interventions are both scientifically robust and socially acceptable. Finally, future investigations should assess the role of digital health innovations in operationalizing OH. Mobile reporting applications, AI-driven outbreak prediction tools, and blockchain-enabled vaccine records must be evaluated in real-world LMIC contexts to determine feasibility, equity, and sustainability. Comparative studies of digital versus conventional surveillance systems will provide evidence for scaling up technology-driven solutions. Collectively, these research priorities highlight the necessity of interdisciplinary collaboration, equitable resource allocation, and innovation. Integrating climate science, community engagement, and digital health, future scholarship can enhance resilience against zoonotic threats and advance global health security.

3.8. Limitations

- Narrative reviews are subject to selection bias; however, inclusion of grey literature and triangulation across multiple databases mitigated this risk.
- Language restrictions may have excluded relevant non-English studies.
- The rapidly evolving nature of climate-health research means some emerging evidence may not yet be published.

4. Conclusions

Zoonoses are defined as diseases that are naturally transmitted between vertebrate animals and humans, with causative agents including fungi, bacteria, viruses, parasites, and prions. Rising concentrations of greenhouse gases have driven abnormal climate shifts, which in turn influence the frequency and distribution of zoonotic diseases. Establishing and operationalizing an OH platform requires the formation of an interdisciplinary team comprising public health professionals such as medical doctors, veterinarians, ecologists, biologists, and public health administrators. Leptospirosis, malaria, and RVF remain among the infectious diseases of greatest concern due to their capacity to cause widespread outbreaks and severe health impacts. Effective surveillance and early warning systems are indispensable for monitoring, tracing, and alerting in relation to climate-linked events and disease emergence. Health and health equity are shaped by biological determinants that influence the conditions in which individuals are born, grow, live, work, and age. Equally important is the recognition of how knowledge gaps and policy inconsistencies across core agencies constrain the institutional application of the OH framework. Strengthening interdisciplinary collaboration across diverse sectors is therefore essential to enable timely detection, monitoring, and intervention in response to CC events and zoonotic disease outbreaks. Governments should commit to providing financial support, fostering collaborative platforms, and promoting continuous learning opportunities for agencies such as ministries of health, veterinary services, and environmental authorities to facilitate knowledge exchange and strengthen responses to climate-related events and disease outbreaks. The OH policy must be inclusive, engaging all sectors and stakeholders including academics, students, health professionals, scientists, community leaders, and policymakers while ensuring that future generations understand and advance the concept. Particular emphasis should be placed on supporting biomanufacturing researchers in LMICs, enabling them to develop vaccines locally and minimize delays during pandemics. The inequities observed during COVID-19, when many African nations

lacked access to vaccines while developed countries secured multiple doses, underscore the urgency of such measures.

Author Contributions

Conceptualization, C.C.; methodology, A.S.; formal analysis, H.B.; investigation, C.C.; writing—original draft preparation, C.C., H.B., and A.S.; writing—review and editing, A.S.; supervision, C.C.; project administration, C.C. All authors have read and agreed to the published version of the manuscript.

Funding

We have not received any financial support for this manuscript.

Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

Not applicable.

Conflicts of Interest

The authors declare no conflict of interest.

AI Use Statement

No artificial intelligence was used in the preparation of this manuscript.

Abbreviation

Abbreviation	Full Name
AMR	Antimicrobial Resistance
CDC	Centers for Disease Control and Prevention
FAO	Food and Agriculture Organization
GDD	Global Disease Detection
GISRS	Global Influenza Surveillance and Response System
GLEWS	Global Early Warning System
GOARN	Global Outbreak Alert and Response Network
IHR	International Health Regulations
IPSN	International Pathogen Surveillance Network
LMICs	Low- and Middle-Income Countries
MCMs	Medical Countermeasures
OH	One Health
PHEIC	Public Health Emergency of International Concern
PPPR	Pandemic Preparedness and Response
RVF	Rift Valley Fever
SDGs	Sustainable Development Goals
UN	United Nations
UNEP	United Nations Environment Programme
UNHCR	United Nations High Commissioner for Refugees
UNICEF	United Nations Children's Fund
USAID	United States Agency for International Development
US-CDC	United States Centers for Disease Control and Prevention
WHO	World Health Organization
WOAH	World Organisation for Animal Health (formerly OIE)

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