



Zoonotic Spillover and Pandemic Risk: A Review of Transmission Pathways and Mitigation Approaches

Riaz Ahmed

ABSTRACT

Zoonotic diseases transmitted from animals to humans pose an escalating threat to global health, driven by rapid environmental change, wildlife exploitation, and intensive animal husbandry. The current review paper synthesizes up-to-date knowledge on the mechanisms and pathways of zoonotic spillover and examines biological prerequisites such as host range expansion, viral mutation, and viral recombination occurring in intermediate hosts. The review analyzes transmission routes, including direct contact, fomites, foodborne, vector-borne, and airborne pathways, and highlights the amplifying role of ecological disturbance, wildlife density, and “mixing vessels” like live animal markets and factory farms. Case studies of severe acute respiratory syndrome, Middle East respiratory syndrome, avian and swine influenza, Ebola, and COVID-19 illustrate common transmission dynamics and public health challenges. Furthermore, global risk mitigation strategies are evaluated, from One Health frameworks and wildlife surveillance platforms to biosecurity measures, trade regulations, and community-driven behavior change initiatives. Finally, the study identifies critical research gaps, such as the integration of ecological data, surveillance in biodiversity hotspots, AI-based predictive modeling, and data-sharing barriers, and proposed multidisciplinary recommendations to enhance early detection, regulation, and ecosystem conservation. The review paper aims to inform policy and strengthen resilience against future zoonotic pandemics by encouraging transdisciplinary collaboration and proactive prevention.

Keywords: Zoonotic spillover, Viral mutation, One health framework, Wildlife surveillance, Pandemic preparedness

Introduction

Overview of Zoonotic Spillover

Zoonoses are infectious diseases transmitted from animals to humans that pose a significant and growing threat to global public health.¹ A zoonotic spillover occurs when a pathogen overcomes the biological barriers between species, establishing almost 75% of infectious diseases in humans.² While many such events remain localized, some can ignite widespread outbreaks or pandemics, as starkly demonstrated by HIV, severe acute respiratory syndrome (SARS), H1N1, Ebola, and more recently, COVID-19. These events underscore the urgent need to understand and manage the drivers of zoonotic disease emergence (Figure 1).

The risk of spillover is intensifying due to increasing interactions at the human-animal-environment interface.^{4,5} Factors such as deforestation, biodiversity loss, global trade in wildlife, intensive farming, and urban

expansion are disrupting ecosystems and facilitating novel pathogen transmission pathways. With climate change and global mobility further accelerating these risks, pandemic preparedness now hinges on proactive, cross-sectoral surveillance and response strategies.

Research Aim and Objectives

The purpose of the current review is to explore the complicated dynamics sustaining zoonotic spillover and pandemic risks.

Research Objectives

1. To analyze the biological, socioeconomic, and ecological factors contributing to zoonotic spillover events
2. To examine common transmission pathways from animal reservoirs to human populations, including direct contact, food systems, and environmental interfaces
3. To evaluate historical and emerging examples of zoonotic outbreaks (SARS, Ebola, COVID-19) to identify shared transmission dynamics
4. To examine current global and regional mitigation strategies, including surveillance, One Health frameworks, and wildlife trade regulations
5. To propose multidisciplinary recommendations to strengthen early detection, risk prediction, and prevention of future zoonotic pandemics

Scope of Review

The current paper reviews the complex relationship of ecological, biological, and socioeconomic factors leading to zoonotic spillover and pandemic risks. The key mechanisms of cross-species transmission, like pathogen evolution, environmental disruption, and intermediate hosts, are examined in the review. It also outlines the primary pathways of transmission from animal to human and analyses primary zoonotic outbreaks like Ebola, SARS, and COVID-19 for elaborating on shared dynamics. Furthermore, it evaluates current global mitigation strategies and highlights research gaps. The study also adopted a multidisciplinary lens, emphasizing the importance of integrated One Health approaches to strengthen early detection, surveillance, and prevention of future zoonotic pandemics.

Structure of Review Paper

The current review paper is structured in sections: section “Mechanisms of Zoonotic Spillover” explores the biological and ecological mechanisms enabling cross-species transmission; section “Transmission Pathways from Animals to Humans” outlines the major pathways through which zoonotic diseases are

OPEN ACCESS

This is an open access article distributed under the terms of the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original author and source are credited.

Department of Medical Sciences,
Military College of Signals,
Rawalpindi, Pakistan

Correspondence to:

Riaz Ahmed,
riazkhattak450@gmail.com

Additional material is published online only. To view please visit the journal online.

Cite this as: Ahmed R. Zoonotic Spillover and Pandemic Risk: A Review of Transmission Pathways and Mitigation Approaches. Premier Journal of Infectious Diseases 2025;3:100003

DOI: <https://doi.org/10.70389/PJID.100003>

Received: 30 May 2025

Revised: 16 June 2025

Accepted: 17 June 2025

Published: 30 June 2025

Ethical approval: N/a

Consent: N/a

Funding: No industry funding

Conflicts of interest: None

Author contribution:

Riaz Ahmed –
Conceptualization, Writing –
original draft, review and editing

Guarantor: Riaz Ahmed

Provenance and peer-review:

Unsolicited and externally
peer-reviewed

Data availability statement:

N/a

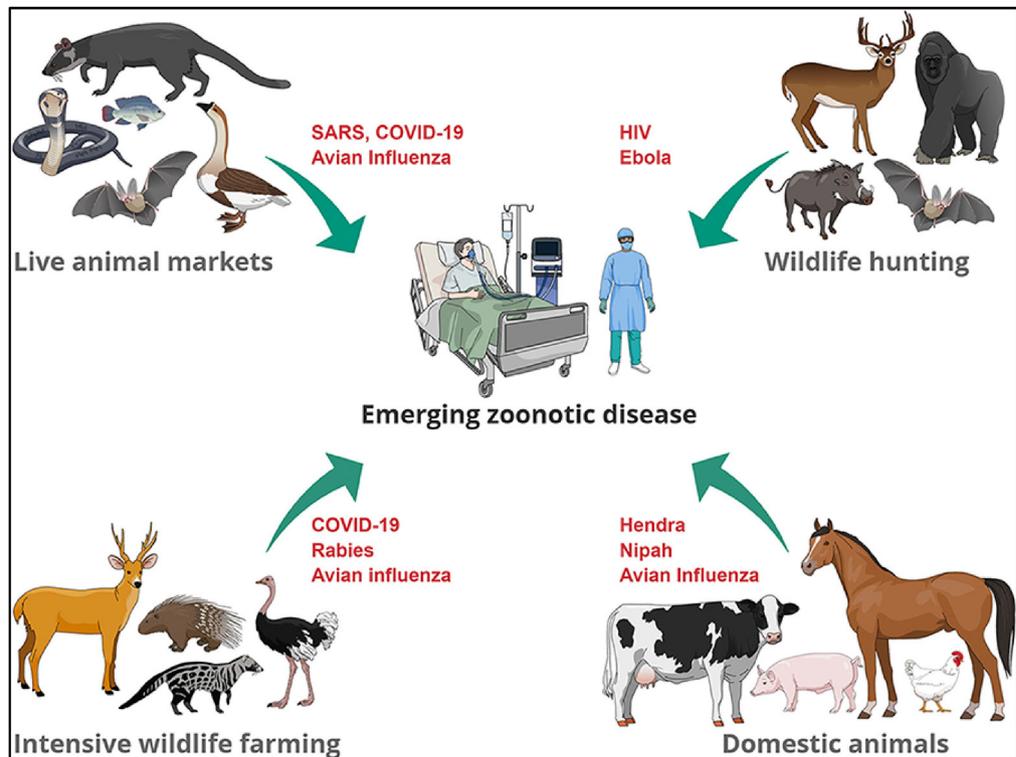


Fig 1 | Zoonotic disease examples and transmission pathways³

transmitted to humans; section “Case Studies of Major Zoonotic Outbreaks” presents case studies of major zoonotic outbreaks to identify common patterns, section “Current Global Strategies for Zoonotic Risk Mitigation” evaluates global mitigation strategies, and section “Research Gaps and Future Directions” highlights research gaps and future directions. The conclusion part summarizes the findings and advocates for integrated, preventive approaches to manage future pandemic threats.

Mechanisms of Zoonotic Spillover Biological Prerequisites for Cross-Species Transmission

Successful zoonotic spillover depends heavily on biological compatibility between pathogens and new hosts.² A pathogen’s host range its ability to infect multiple species and enhances spillover potential. Pathogen evolution, particularly viral mutations in surface proteins, can improve binding to human receptors, increase infectivity, and evade immune responses.⁶ RNA viruses, such as coronaviruses and influenza viruses, are especially prone to such mutations due to their high replication error rates.⁴ The biological changes assist the virus to bypass the species barriers, increasing infections in humans and spreading faster. In addition, emerging zoonotic risk prediction is possible by understanding these factors (Figure 2).

Role of Intermediate Hosts and Viral Recombination

Intermediate hosts act as channels facilitating the adaptation of pathogens to human biology.² Moreover, viruses frequently jump from the original wildlife

reservoirs to intermediate species. This is where they are able to mutate and recombine with other viruses.⁷ This genetic exchange can lead to novel strain development with high infectivity and transmissibility in humans. Civets acted as intermediate hosts for SARS-CoV, and dromedary camels also played the same role in Middle East respiratory syndrome (MERS-CoV).⁸ It is also assessed that viral recombination in such hosts drives evolution and the risk of human infections.

Importance of Ecological Perturbation and Wildlife Density

Ecological perturbations such as urban expansion, deforestation, and habitat fragmentation impact natural ecosystems and alter wildlife behavior.^{2,9} These changes often force animals to migrate closer to human settlements, increasing opportunities for zoonotic contact. High wildlife density in confined or degraded habitats leads to greater pathogen shedding and interspecies transmission.¹⁰ The loss of biodiversity also reduces the natural “dilution effect,” where healthy ecosystems buffer pathogen spread.¹¹ Consequently, human intrusion into previously undisturbed environments significantly elevates the likelihood of spillover events.^{3,5,8} Protecting natural habitats is, therefore, a vital element in zoonotic disease prevention.

Spillover Amplification via “Mixing Vessels”

“Mixing vessels” like wet markets and intensive animal farming systems provide ideal conditions for pathogen exchange.¹² In wet markets, diverse species are kept in crowded, unsanitary conditions that enable

interspecies transmission and viral recombination. These environments allow viruses to jump between animals and adapt to new hosts, including humans.⁵ Similarly, intensive farming, where thousands of genetically similar animals are confined, acts as a breeding ground for viral mutations. Swine and poultry farms, in particular, have facilitated the emergence of avian and swine influenza strains with pandemic potential.¹³ Improved biosecurity in these settings is essential for risk mitigation.

Transmission Pathways from Animals to Humans

Direct Transmission

Direct transmission refers to transmission by immediate physical contact with infected animals or secretions, and it can be in the form of blood, saliva, other body fluids, and bites and scratches^{5-7,12} (Figure 3). It causes diseases like rabies through animal bites; Ebola, for instance, was linked with infected primates or bats.¹⁴ People living in close contact with livestock and wildlife, like hunters, are at high risk of disease.¹⁵ A lack of

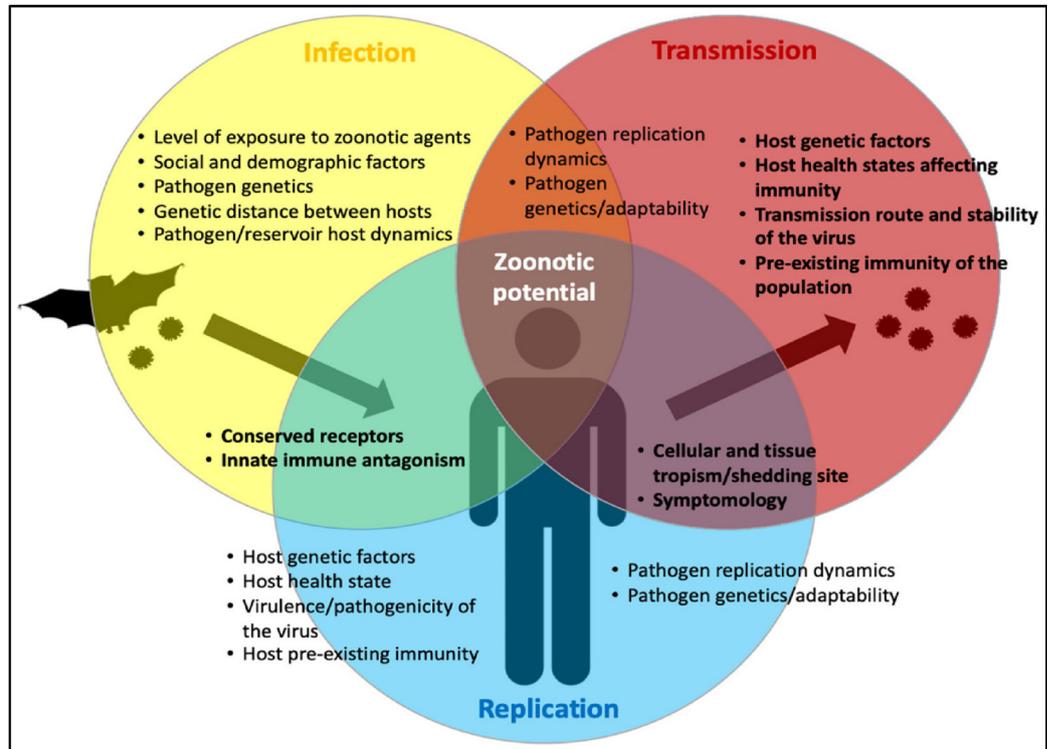


Fig 2 | Biological factors affecting zoonotic potential²

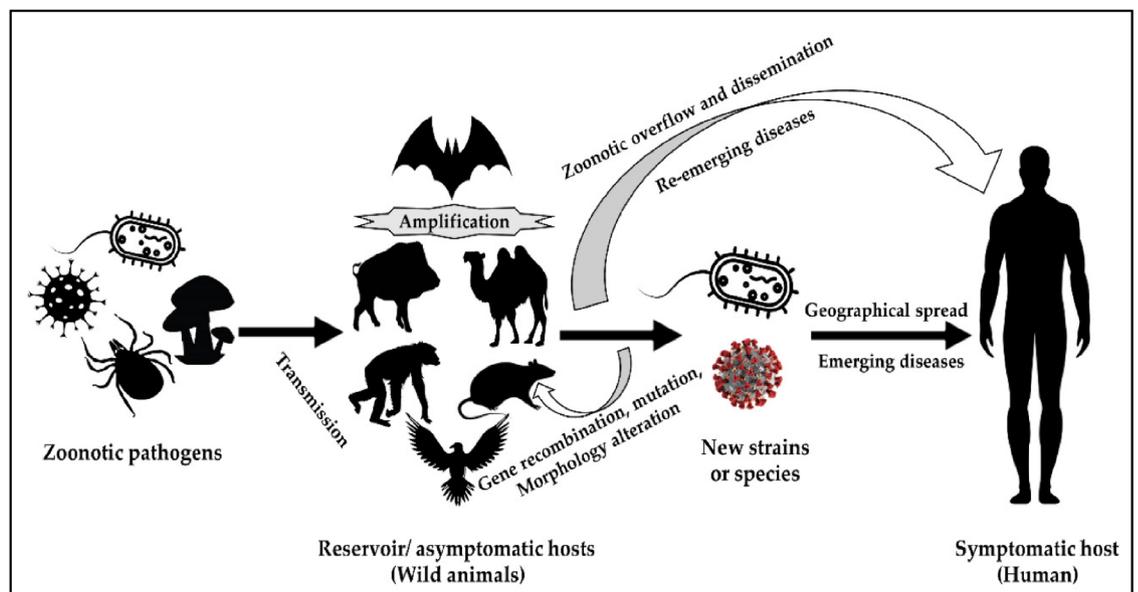


Fig 3 | Direct transmission from reservoir to host¹⁶

protective measures and poor awareness increases such risk, particularly in low-resource settings like rural environments. Furthermore, direct contact is a straightforward and deadly route for zoonotic transmission, and it needs targeted public health interventions.¹²

Indirect Transmission

The indirect transmission involves contact with the surface, contaminated environment, or objects like fomites.¹⁷ These pathogens can survive for hours or days on cages, bedding, tools, cages, and soil exposed to the animal's blood, saliva, or waste. For instance, spores of anthrax persist in the soil and infect livestock and humans through skin contact or by inhalation.¹⁸ Furthermore, human activities such as cleaning enclosures of animals and consumption of contaminated water also increase the exposure risk.⁴ Another aspect is the inadequate waste management, poor sanitation, and overcrowded living conditions that increase the risk of indirect spillover.

Foodborne Transmission

Foodborne zoonoses increase with the consumption of contaminated animal products, such as unpasteurized milk, undercooked meat, or bushmeat.¹⁹ Pathogens such as *E. coli*, *Salmonella* spp., *Brucella* spp., and prions (associated with mad cow disease) can be transmitted through improper food handling and consumption.²⁰ Moreover, the consumption and hunting of wildlife are common in specific regions that also pose risks of exposure to unique pathogens as was observed in the past outbreaks of Ebola.¹⁵

Vector-Borne Transmission

Vector-borne diseases spread through infected arthropod bites like ticks, mosquitoes, and fleas.² As biological intermediaries, these vectors carry pathogens from animals to humans. For example, West Nile virus is spread by mosquitoes from infected birds.²¹ On the other hand, Lyme disease is transmitted via tick bites. Moreover, vector-borne transmission is also dependent on ecological conditions.²² These include vector population density and climatic factors.

Airborne Transmission

Some of the most significant pandemics in history have emerged through airborne transmission of zoonotic pathogens. Viruses like influenza and SARS-CoV-2 can be spread via respiratory droplets or aerosols from infected animals or humans.¹⁹ In confined spaces like animal markets or farms, close contact with livestock increases the potential for inhalation of contaminated air.²⁰ Poultry and swine are known reservoirs for influenza viruses capable of evolving and infecting humans. Once airborne pathogens adapt to humans, they may spread rapidly and globally.

Role of Urbanization, Deforestation, and Climate Change

Urbanization, deforestation, and climate change are powerful drivers that expand human exposure to

zoonotic diseases.¹⁷ As forests are cleared for agriculture or urban development, humans and livestock move into previously undisturbed ecosystems, increasing contact with wildlife reservoirs. Climate change alters animal migration patterns, vector habitats, and disease seasonality.¹⁹ For example, warmer temperatures have extended the range of disease-carrying mosquitoes. Rapid urban growth often results in overcrowded conditions and poor infrastructure, amplifying both direct and indirect transmission.

Case Studies of Major Zoonotic Outbreaks SARS-CoV (2002–2003)

The SARS-CoV outbreak started in China and spread rapidly to nearly two dozen countries. The virus was believed to originate in bats with civet cats as these were found to be intermediate hosts before infecting live animal markets and humans.⁸ In addition, SARS-CoV was also causing respiratory illness with an increased fatality rate. It was controlled through quarantine, public health interventions, travel barriers, and by highlighting the risk of live wildlife and inadequate surveillance of disease.

MERS-CoV

MERS-CoV emerged in Saudi Arabia in 2012 as a result of confirmed human cases that had contact with intermediate hosts of the virus (dromedary camels).²³ MERS-CoV also likely originated in bats, and the virus causes severe respiratory symptoms and possesses a fatality rate of around 35%, significantly higher than SARS.²⁴ Human-to-human transmission has been limited but occurs in healthcare settings. MERS emphasized the importance of occupational exposure monitoring, especially in livestock industries, and the challenges of controlling zoonotic diseases with high mortality but limited transmission chains.²⁵ It remains endemic in the Middle East, with sporadic outbreaks globally.

H5N1 and H1N1

H5N1 (avian flu) and H1N1 (swine flu) are notable influenza viruses of zoonotic origin. H5N1 emerged from poultry in Asia in the early 2000s, causing sporadic but deadly infections in humans.²⁶ H1N1, in contrast, sparked the 2009 global pandemic and was a reassortant virus involving genes from avian, swine, and human strains.²⁷ Swine served as a mixing vessel for this genetic reshuffling. While H5N1 had high mortality and low transmissibility, H1N1 spread rapidly worldwide with moderate severity.²⁸

Ebola Outbreaks

Ebola virus disease has repeatedly emerged in Central and West Africa, with outbreaks linked to handling or consuming bushmeat, especially primates and bats.²⁹ The 2014–2016 West African outbreak was the largest in history, killing over 11,000 people.³⁰ Transmission occurs through direct contact with infected blood, fluids, or tissues, and human-to-human transmission further amplifies spread. Furthermore, cultural practices

around burial and caregiving contributed to the severity of the outbreak.²⁹

COVID-19

The COVID-19 pandemic, caused by SARS-CoV-2, is believed to have originated from a zoonotic spillover, possibly involving bats and an unknown intermediate host.³¹ The outbreak began in Wuhan, China, with early cases linked to a live animal market. Unlike earlier coronaviruses, COVID-19 spread rapidly due to asymptomatic transmission and high global mobility.³² It exposed weaknesses in pandemic preparedness, global surveillance, and healthcare infrastructure.

Commonalities in the Outbreak and Public Health Lessons

Despite differences in origin and transmission, these outbreaks share common triggers: close human-animal contact, ecological disruption, and insufficient surveillance. Markets, farms, and wildlife trade frequently serve as spillover hotspots. Delayed public health responses and weak international coordination often worsened outcomes. These case studies highlight the necessity of proactive surveillance, transparent communication, and multidisciplinary collaboration. Strengthening global health systems and addressing upstream drivers such as habitat loss and risky animal practices are essential to mitigating future pandemic risks.

Current Global Strategies for Zoonotic Risk Mitigation The One Health Approach

The One Health approach emphasizes the interconnectedness of human, animal, and environmental health.³³ By integrating veterinary, medical, and ecological sciences, One Health fosters collaboration across disciplines to detect, prevent, and respond to zoonotic threats.³⁴ It promotes data sharing, cross-sectoral surveillance, and coordinated responses to outbreaks. One Health is particularly effective in identifying early warning signs at the human-animal-environment interface.³⁵ The One Health approach is gaining traction globally as it is recognized by organizations like WHO, FAO, and OIE, though implementation varies by region. Effective adoption requires policy integration, funding, and capacity building across public health, agriculture, and wildlife sectors.

Wildlife Surveillance Programs and Pathogen Discovery

Wildlife surveillance programs and pathogen discovery platforms play a main role in the early detection of zoonotic threats.³⁶ Initiatives like PREDICT and GISAID collect viral samples from wildlife, livestock, and humans to monitor emerging pathogens, including influenza and coronaviruses.³⁷ These platforms use genomic sequencing and data sharing to track viral evolution and potential spillover. Surveillance efforts are especially critical in biodiversity hotspots where novel viruses are likely to emerge.³⁶ However, limited funding, political barriers, and gaps in global coverage remain challenges. Current advancements in portable sequence tech-

nologies like nanopore devices have enabled genomic analysis in the field, allowing for increased detection of pathogens in remote areas. Moreover, the integration of wildlife ecology integration and behavioral studies with pathogen monitoring can assist in identifying high-risk species and interactions.

Biosecurity in Livestock and Animal Markets

Enhancing biosecurity in livestock production and animal markets is crucial to preventing zoonotic spillovers.³⁸ Measures include improving hygiene, regulating animal densities, minimizing interspecies contact, and ensuring veterinary oversight. Live animal markets, especially those mixing wild and domestic species, are high-risk environments for disease transmission.³⁹ Farm-level biosecurity reduces the risk of infection in animals and potential transmission to humans.³⁸ Proper waste disposal, vaccination programs, and monitoring of animal health are key strategies.

Wildlife Trade Regulations (Convention on International Trade in Endangered Species [CITES]) and Enforcement Challenges

Wildlife trade regulations, such as those enforced under CITES, aim to curb illegal or high-risk wildlife commerce that can facilitate disease spread.⁴⁰ Regulating trade assists in reducing human exposure to exotic species that may carry unknown pathogens.⁴¹ However, enforcement remains inconsistent, especially in regions with weak governance or high market demand. Corruption, inadequate resources, and lack of public awareness hamper effectiveness. In addition to frameworks like CITES, various countries have introduced restrictions or national bans on wildlife markets based on the COVID-19 pandemic. Such efforts often face resistance because of the economic, cultural, and subsistence importance of wildlife in various countries.¹⁸ Effective regulations should be paired with alternative livelihoods, education, and community engagement.

Community-Based Awareness and Behavior Change

Community engagement is vital for reducing behaviors that promote zoonotic transmission.⁴² Awareness campaigns educate the public about safe animal handling, bushmeat risks, hygiene practices, and the importance of vaccination.⁴³ Behavior change initiatives often involve collaboration with local leaders, schools, and religious institutions to ensure culturally appropriate messaging. Programs that involve community participation tend to be more effective and sustainable.⁴² In regions with high spillover risk, empowering local populations with knowledge and resources can significantly reduce exposure.

Global Pandemic Preparedness Frameworks

Global health organizations such as WHO, FAO, and OIE have developed collaborative pandemic preparedness frameworks to improve international response capacity.⁴⁴ These frameworks include risk assessment tools, training programs, emergency response coordination, and strategic stockpiling of vaccines and

medical supplies. International Health Regulations (IHR) is an initiative promoting early reporting and standardized response to outbreaks. However, gaps remain in surveillance coverage, equitable access to resources, and response speed.⁴⁵ In addition to IHR, emerging initiatives like the pandemic fund managed by the World Bank and the Global Virome Project aim to proactively identify and prepare for the threats.⁴⁶ Joint cross-border exercises and scenario-based simulations are used to test emergency readiness and coordination across nations. The integration of digital health technologies, such as real-time data dashboards and AI-driven outbreak modeling, is promising.

Research Gaps and Future Directions

Despite growing recognition of zoonotic risks, significant research and policy gaps hinder effective prevention and response. One major shortfall is the inadequate integration of ecological data into public health systems. Many disease surveillance programs focus primarily on human and livestock populations, overlooking critical environmental indicators such as wildlife population shifts, habitat degradation, and species interactions. Bridging this gap requires interdisciplinary collaboration and tools that can translate ecological signals into actionable public health intelligence.

Another critical issue is underreporting and weak surveillance in biodiversity hotspots, particularly in low-income countries. Veterinary services and local health are under-resourced, and disease outbreaks might not be detected until they escalate. Furthermore, capacity building for on-the-ground surveillance, real-time reporting, and laboratory diagnostics are essential for early containment. In addition, there is also an urgent need for AI-driven tools and predictive models that can assist in analyzing large and complex datasets to effectively forecast spillover events. Such technologies can also assess the risk based on environmental, biological, and socioeconomic variables for preemptive actions. Moreover, early warning mechanisms and global data sharing are also crucial, as international reporting is often limited due to inconsistent reporting standards, political barriers, and concerns about data sovereignty.

Conclusion

Zoonotic spillover is driven by ecological, biological, and socioeconomic factors. The evolution of pathogens and host range is driven by viral mutations and recombination that further lead to cross-species spread. Transmission pathways, from direct contact and fomites to foodborne, vector-borne, and airborne routes, are further exacerbated by urbanization, deforestation, and climate change. Historical outbreaks, including SARS, MERS, avian and swine influenza, Ebola, and COVID-19, highlight common triggers: close human-animal interfaces, weak surveillance, and insufficient biosecurity. The complexity of these drivers shows that isolated interventions are inadequate. A transdisciplinary One Health framework that integrates human, animal, and environmental health

sciences is essential for holistic risk management. Strengthening early detection through enhanced surveillance and AI-driven predictive models, regulatory measures such as stringent biosecurity standards and wildlife trade enforcement, and environmental conservation to preserve ecosystem integrity must go hand in hand.

References

- Bhatia B, Sonar S, Khan S, Bhattacharya J. Pandemic-proofing: intercepting zoonotic spillover events. *Pathogens*. 2024;13(12):1067. Available from: <https://www.mdpi.com/2076-0817/13/12/1067>
- Escudero-Pérez B, Lalande A, Mathieu C, Lawrence P. Host-Pathogen interactions influencing zoonotic spillover potential and transmission in humans. *Viruses*. 2023;15(3):599. Available from: <https://www.mdpi.com/1999-4915/15/3/599>
- Magouras I, Brookes VJ, Jori F, Martin A, Pfeiffer DU, Dürr S. Emerging zoonotic diseases: should we rethink the animal-human interface? *Front Vet Sci*. 2020;7:582743. Available from: <https://www.frontiersin.org/journals/veterinary-science/articles/10.3389/fvets.2020.582743/full>
- Ellwanger JH, Chies JA. Zoonotic spillover: understanding basic aspects for better prevention. *Genet Mol Biol*. 2021;44(1 Suppl 1):e20200355. Available from: <https://www.scielo.br/j/gmb/a/TTzyf6tcX37QwCr7fQqQp/?lang=en>
- Clifford Astbury C, Lee KM, Mcleod R, Aguiar R, Atique A, Balolong M, et al. Policies to prevent zoonotic spillover: a systematic scoping review of evaluative evidence. *Glob Health*. 2023;19(1):82. <https://link.springer.com/article/10.1186/s12992-023-00986-x>
- Plowright RK, Ahmed AN, Coulson T, Crowther TW, Ejotire I, Faust CL, et al. Ecological countermeasures to prevent pathogen spillover and subsequent pandemics. *Nat Commun*. 2024;15(1):2577. Available from: <https://www.nature.com/articles/s41467-024-46151-9>
- Pauciuolo S, Zulian V, La Frazia S, Paci P, Garbuglia AR. Spillover: mechanisms, genetic barriers, and the role of reservoirs in emerging pathogens. *Microorganisms*. 2024;12(11):2191. Available from: <https://www.mdpi.com/2076-2607/12/11/2191>
- Al-Salihi KA, Khalaf JM. The emerging SARS-CoV, MERS-CoV, and SARS-CoV-2: an insight into the viruses zoonotic aspects. *Vet World*. 2021;14(1):190. Available from: <https://pmc.ncbi.nlm.nih.gov/articles/PMC7896889/>
- Esposito MM, Turku S, Lehrfield L, Shoman A. The impact of human activities on zoonotic infection transmissions. *Animals*. 2023;13(10):1646. Available from: <https://www.mdpi.com/2076-2615/13/10/1646>
- Goldstein JE, Budiman I, Canny A, Dwipartidrisa D. Pandemics and the human-wildlife interface in Asia: land use change as a driver of zoonotic viral outbreaks. *Environ Res Lett*. 2022;17(6):063009. Available from: <https://iopscience.iop.org/article/10.1088/1748-9326/ac74d4/meta>
- Leeson P. Ecosystem restoration and zoonotic disease risk in humans: an integrative literature review. Available from: <https://www.theseus.fi/handle/10024/867755>
- Marrana M. Epidemiology of disease through the interactions between humans, domestic animals, and wildlife. In: *One health*. Cambridge: Academic Press; 2022. p. 73–111. Available from: <https://www.sciencedirect.com/science/article/pii/B9780128227947000010>
- Kessler S, Harder TC, Schwemmler M, Ciminski K. Influenza A viruses and zoonotic events—are we creating our own reservoirs?. *Viruses*. 2021;13(11):2250. Available from: <https://www.mdpi.com/1999-4915/13/11/2250>
- Lacroix A, Mbala Kingebeni P, Ndimbo Kumugo SP, Lempu G, Butel C, Serrano L, et al. Investigating the circulation of Ebola viruses in bats during the Ebola virus disease outbreaks in the Equateur and North Kivu provinces of the Democratic Republic of Congo from 2018. *Pathogens*. 2021;10(5):557. Available from: <https://www.mdpi.com/2076-0817/10/5/557>
- Namusisi S, Mahero M, Travis D, Pelican K, Robertson C, Mugisha L. A descriptive study of zoonotic disease risk at the human-wildlife interface in a biodiversity hot spot in South Western Uganda. *PLoS Negl Trop Dis*. 2021;15(1):e0008633. Available from:

- <https://journals.plos.org/plosntds/article?id=10.1371/journal.pntd.0008633>
- 16 Rahman MT, Sobur MA, Islam MS, Levy S, Hossain MJ, El Zowalaty ME, et al. Zoonotic diseases: etiology, impact, and control. *Microorganisms*. 2020;8(9):1405. Available from: <https://www.mdpi.com/2076-2607/8/9/1405>
 - 17 Chen T. Fomites and the COVID-19 pandemic: an evidence review on its role in viral transmission. Vancouver, BC, Canada: National Collaborating Centre for Environmental Health; 2021. p. 1–24. Available from: <https://ccnse.ca/sites/default/files/Fomites%20and%20COVID-19%20March%2022%20final%20in%20template-revised.pdf>
 - 18 Rahim MF, Ahmad MZ, Naeem RF, Sohoo MU, Sindhu ZU, Tahir AH, et al. Anthrax and its impact on public health. In: *Zoonosis*. Vol. 4. Faisalabad, Pakistan: Unique Scientific Publishers; 2023. p. 502–9. Available from: <https://uniquescientificpublishers.com/wp-content/uploads/2023/zon-v4/502-509.pdf>
 - 19 Pradhan AK, Karanth S. Zoonoses from animal meat and milk. In: *Present knowledge in food safety*. Cambridge: Academic Press; 2023. p. 394–411. Available from: <https://www.sciencedirect.com/science/article/pii/B9780128194706000299>
 - 20 Shurson GC, Urriola PE, van de Ligt JL. Can we effectively manage parasites, prions, and pathogens in the global feed industry to achieve One Health?. *Transbound Emerg Dis*. 2022;69(1):4–30. Available from: <https://onlinelibrary.wiley.com/doi/abs/10.1111/tbed.14205>
 - 21 Brüssow H, Figuerola J. The spread of the mosquito-transmitted West Nile virus in North America and Europe. *Microbial Biotechnol*. 2025;18(3):e70120. Available from: <https://enviromicro-journals.onlinelibrary.wiley.com/doi/abs/10.1111/1751-7915.70120>
 - 22 Radolf JD, Strle K, Lemieux JE, Strle F. Lyme disease in humans. *Curr Issues Mol Biol*. 2021;42(1):333–84. Available from: <https://www.mdpi.com/1467-3045/42/1/11>
 - 23 Alnuqaydan AM, Almutary AG, Sukamaram A, Yang BT, Lee XT, Lim WX, et al. Middle East Respiratory Syndrome (MERS) virus—pathophysiological axis and the current treatment strategies. *AAPS PharmSciTech*. 2021;22(5):173. Available from: <https://link.springer.com/article/10.1208/s12249-021-02062-2>
 - 24 Banerjee A, Kulcsar K, Misra V, Frieman M, Mossman K. Bats and coronaviruses. *Viruses*. 2019;11(1):41. Available from: <https://www.mdpi.com/1999-4915/11/1/41>
 - 25 Peiris M, Poon LL. Severe acute respiratory syndrome (SARS) and Middle East respiratory syndrome (MERS) (Coronaviridae). *Encyclopedia Virol*. 2021:814. Available from: <https://pmc.ncbi.nlm.nih.gov/articles/PMC7837069/>
 - 26 Zadorozhna VI, Shahinian VR. Zoonotic influenza viruses and their risks for humans. *Mikrobiol Z*. 2024;86(6):92–114. Available from: <https://ojs.microbiolj.org.ua/index.php/mj/article/view/177>
 - 27 Yao-Tsun L. Emergence and evolution of reassortant highly pathogenic H5 avian influenza viruses. Doctoral dissertation, National University of Singapore. Available from: <https://search.proquest.com/openview/5cbeedfe7a8487ae9a8b98908e9001ba/1?pq-origsite=gscholar&cbl=2026366&diss=y>
 - 28 Klivleyeva N, Saktaganov N, Glebova T, Lukmanova G, Ongarbayeva N, Webby R. Influenza A viruses in the swine population: ecology and geographical distribution. *Viruses*. 2024;16(11):1728. Available from: <https://www.mdpi.com/1999-4915/16/11/1728>
 - 29 Khan SA, Imtiaz MA, Islam MM, Tanzin AZ, Islam A, Hassan MM. Major bat-borne zoonotic viral epidemics in Asia and Africa: a systematic review and meta-analysis. *Vet Med Sci*. 2022;8(4):1787–801. Available from: <https://onlinelibrary.wiley.com/doi/full/10.1002/vms3.835>
 - 30 Nii-Trebi NI, Mughogho TS, Abdulai A, Tetteh F, Ofosu PM, Osei MM, et al. Dynamics of viral disease outbreaks: a hundred years (1918/19–2019/20) in retrospect—losses, lessons and emerging issues. *Rev Med Virol*. 2023;33(6):e2475. Available from: <https://onlinelibrary.wiley.com/doi/abs/10.1002/rmv.2475>
 - 31 Sparrer MN, Hodges NF, Sherman T, VandeWoude S, Bosco-Lauth AM, Mayo CE. Role of spillover and spillback in SARS-CoV-2 transmission and the importance of one health in understanding the dynamics of the COVID-19 pandemic. *J Clin Microbiol*. 2023;61(7):e01610–22. Available from: <https://journals.asm.org/doi/abs/10.1128/jcm.01610-22>
 - 32 Banerjee A, Doxey AC, Mossman K, Irving AT. Unraveling the zoonotic origin and transmission of SARS-CoV-2. *Trends Ecol Evol*. 2021;36(3):180–4. Available from: [https://www.cell.com/trends/ecology-evolution/fulltext/S0169-5347\(20\)30348-7?s=09](https://www.cell.com/trends/ecology-evolution/fulltext/S0169-5347(20)30348-7?s=09)
 - 33 Erkyihun GA, Alemayehu MB. One Health approach for the control of zoonotic diseases. *Zoonoses*. 2022;2(1):963. Available from: <https://www.scienceopen.com/hosted-document?doi=10.15212%2FZOOLOSES-2022-0037&s=08>
 - 34 Ahmed MM, Okesanya OJ, Othman ZK, Ibrahim AM, Adigun OA, Ukoaka BM, et al. Holistic approaches to zoonoses: integrating public health, policy, and one health in a dynamic global context. *Zoonotic Dis*. 2025;5(1):5. Available from: <https://www.mdpi.com/2813-0227/5/1/5>
 - 35 Wang X, Rainey JJ, Goryoka GW, Liang Z, Wu S, Wen L, et al. Using a one health approach to prioritize zoonotic diseases in China, 2019. *PLoS One*. 2021;16(11):e0259706. Available from: <https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0259706>
 - 36 Sharan M, Vijay D, Yadav JP, Bedi JS, Dhaka P. Surveillance and response strategies for zoonotic diseases: a comprehensive review. *Sci One Health*. 2023;2:100050. Available from: <https://www.sciencedirect.com/science/article/pii/S2949704323000446>
 - 37 Daniels RS, McCauley JW. The health of influenza surveillance and pandemic preparedness in the wake of the COVID-19 pandemic. *J General Virol*. 2023;104(2):001822. Available from: <https://www.microbiologyresearch.org/content/journal/jgv/10.1099/jgv.0.001822>
 - 38 Haq Z, Nazir J, Manzoor T, Saleem A, Hamadani H, Khan AA, et al. Zoonotic spillover and viral mutations from low and middle-income countries: improving prevention strategies and bridging policy gaps. *PeerJ*. 2024;12:e17394. Available from: <https://peerj.com/articles/17394/>
 - 39 Naguib MM, Li R, Ling J, Grace D, Nguyen-Viet H, Lindahl JF. Live and wet markets: food access versus the risk of disease emergence. *Trends Microbiol*. 2021;29(7):573–81. Available from: [https://www.cell.com/trends/microbiology/fulltext/S0966-842X\(21\)00043-3?dgcid=raven_jbs_aip_email](https://www.cell.com/trends/microbiology/fulltext/S0966-842X(21)00043-3?dgcid=raven_jbs_aip_email)
 - 40 Sanya S, Fischer C. Implications of a wildlife trade ban. *Emerg Infect Dis*. 2021;2(2):77–84. Available from: https://www.researchgate.net/profile/Cecilia-Fischer-2/publication/354820640_Implications_of_a_Wildlife_Trade_Ban/links/614e1262522ef665b5a778b/Implications-of-a-Wildlife-Trade-Ban.pdf
 - 41 Rush ER, Dale E, Aguirre AA. Illegal wildlife trade and emerging infectious diseases: pervasive impacts to species, ecosystems and human health. *Animals*. 2021;11(6):1821. Available from: <https://www.mdpi.com/2076-2615/11/6/1821>
 - 42 Butala C, Fyfe J, Welburn SC. The contribution of community health education to sustainable control of the neglected zoonotic diseases. *Front Public Health*. 2021;9:729973. Available from: <https://www.frontiersin.org/articles/10.3389/fpubh.2021.729973/full>
 - 43 Nasir MF, Naz G, Rasheed M, Rafiq H, Rafique A, Javed U, Hassan Z, Khalid N. From awareness to action promoting behavior change for zoonotic disease prevention through public health education. In: *Zoonosis*. Vol. 1. Faisalabad, Pakistan: Unique Scientific Publishers; 2023. p. 304–15. Available from: <https://uniquescientificpublishers.com/wp-content/uploads/2023/zon-v1/304-315.pdf>
 - 44 Dente MG, Riccardio F, Declich S, Milano A, Robbiati C, Agrimi U, et al. Strengthening preparedness against global health threats: a paradigm shift based on One Health approaches. *One Health*. 2022;14:100396. Available from: <https://www.sciencedirect.com/science/article/pii/S2352771422000283>
 - 45 Noguera ZLP, Charypkhan D, Hartnack S, Torgerson PR, Ruegg SR. The dual burden of animal and human zoonoses: a systematic review. *PLoS Negl Trop Dis*. 2022;16(10):e0010540. Available from: <https://journals.plos.org/plosntds/article?id=10.1371/journal.pntd.0010540>
 - 46 Carroll D, Daszak P, Wolfe ND, Gao GF, Morel CM, Morzaria S, et al. The global virome project. *Science*. 2018;359(6378):872–4. Available from: <https://www.science.org/doi/abs/10.1126/science.aap7463>