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Preventing the Next Pandemic: Why Veterinary Pathology Holds the Key to Global Health Security

Neetu Nehra[1]*, Sushma[1] and Sarthak[2]
1Department of Veterinary Pathology and
2Department of Veterinary Physiology and Biochemistry,
COVS, LUVAS, Hisar
***Corresponding Author:** neetunehra008@gmail.com
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Introduction: Living in the Age of Emerging Zoonoses:

In December 2019, a cluster of unexplained pneumonia cases quietly emerged in Wuhan, China. Within weeks, the world was engulfed in a pandemic that reshaped societies, economies, and healthcare systems. COVID-19 was not entirely unexpected — it reflected the growing collision between humans, animals, and ecosystems in an increasingly interconnected world.

More than 75% of emerging infectious diseases in humans originate from animals, a phenomenon known as *zoonosis* (Sikkema and Koopmans, 2025; Zhang *et al.,* 2025). From Ebola and SARS to avian influenza, Nipah virus, and COVID-19, history repeatedly demonstrates that the next pandemic is more likely to arise from a farm, forest, or wildlife market than from a hospital ward.

Yet, while global health systems largely focus on human medicine, the earliest warning signs of pandemics almost always appear in animals — sick poultry flocks, dying bats, unexplained cattle abortions, or sudden pig mortalities. Detecting, interpreting, and responding to these early signals is the domain of veterinary pathology — a critical yet underrecognized frontline science.

In the post-pandemic era, veterinary pathology is no longer confined to agricultural productivity. It has become a cornerstone of global health security, linking animal health, human medicine, environmental science, and public policy under the One Health framework. As climate change, deforestation, wildlife trade, and intensive farming accelerate disease emergence, understanding zoonotic risks is no longer optional — it is essential for planetary survival.

From Animals to Humans: The Science of Zoonotic Spillover

Zoonotic spillover — the transmission of pathogens from animals to humans — is not random. It is a biologically structured, ecologically driven, and socially amplified process (Bhatia *et al.,* 2024; Sikkema and Koopmans, 2025).

At its core, spillover requires three conditions:

1. A pathogen reservoir — typically wildlife or livestock
2. A transmission interface — close human–animal contact
3. A susceptible human population

Many dangerous pathogens originate in wildlife, making surveillance at the human–wildlife interface a crucial component of pandemic prevention. Scientists monitor viruses circulating in bats, rodents, birds, and other reservoir species known to harbor a vast diversity of pathogens. Migratory bird surveillance helps detect emerging strains of avian influenza, while bat monitoring programs search for novel coronaviruses and paramyxoviruses.

In recent years, researchers have also launched large-scale programs to identify unknown viruses aimed at cataloguing previously unknown viruses in wildlife populations and evaluating their potential to infect humans. By mapping viral diversity across ecosystems and identifying potential zoonotic threats early, these efforts aim to detect emerging pathogens long before they spill over into livestock or human populations.

Such efforts represent a proactive strategy for understanding the hidden virosphere that surrounds human society.

Major Spillover Pathways:

- Wildlife trade & wet markets → SARS, COVID-19
- Intensive poultry farming → Avian influenza
- Pig farming near bat habitats → Nipah virus
- Deforestation & mining → Ebola outbreaks
- Close livestock–human contact → Brucellosis, bovine tuberculosis

Spillover occurs when a pathogen successfully crosses the species barrier from its natural reservoir into a new host species. For this process to occur, three conditions must generally be met: the pathogen must be shed by the reservoir host, the new host must be exposed to the pathogen, and the pathogen must possess the biological ability to infect and replicate in the new host. Understanding how pathogens spill over is only part of the puzzle. Detecting them early requires scientists who can interpret the biological evidence left behind in diseased animals.

Disease Detectives: The Investigative Role of Veterinary Pathologists

Long before laboratory scientists begin their investigations, the earliest signals of disease are often noticed by farmers and local veterinarians. Unusual behavior in animals, sudden declines in milk production, unexplained abortions, or unexpected mortality may indicate the presence of an emerging disease.

Field veterinarians play a vital role in reporting these early warning signs to diagnostic laboratories. In many cases, rapid communication between farmers, veterinarians, and pathologists allows outbreaks to be contained before they spread widely.

Behind every unexplained animal death lies a biological mystery waiting to be solved. Veterinary pathologists function much like scientific detectives, reconstructing the sequence of events that led to

disease outbreaks. Their investigation begins in the field when veterinarians report unusual illness or mortality among animals. Tissue samples collected during necropsy are then examined to uncover the microscopic signatures of disease.

Gross examination of organs may reveal hemorrhages, necrosis, or abnormal enlargements that provide the first clues. For example, vascular damage and hemorrhagic lesions in tissues may suggest infections such as Ebola Virus, while severe pulmonary pathology and diffuse alveolar damage have been associated with infections caused by SARS-CoV-2. Careful interpretation of such lesions allows veterinary pathologists to narrow down potential etiological agents even before molecular confirmation. Histopathology then allows scientists to observe the cellular damage caused by pathogens. Histopathological examination remains one of the most powerful tools for identifying emerging diseases, as specific cellular alterations such as necrosis, inflammatory infiltrates, and inclusion bodies can reveal the underlying pathogen long before complete epidemiological data become available. Molecular diagnostics such as PCR and genome sequencing confirm the identity of the culprit organism. Finally, epidemiological analysis traces how the pathogen entered the population and how it spreads.

This step-by-step investigation transforms scattered observations into actionable knowledge. In many outbreaks, veterinary pathologists identify the pathogen in animals days or even weeks before human infections are recognized, making them a crucial early warning system in the fight against emerging diseases.

Recognizing and strengthening this frontline surveillance network is essential for effective disease control.

When Animals Warn Us First:

- Avian influenza → Detected first in poultry flocks
- Nipah virus → Pig mortality preceded human encephalitis
- Rabies → Animal bite surveillance remains the primary alert system
- Anthrax → Sudden livestock deaths signal soil-borne outbreaks

In many outbreaks, human disease represents only the visible tip of a much larger animal epidemic iceberg.

Despite this critical role, veterinary pathology remains chronically underfunded, particularly in low- and middle-income nations. Limited diagnostic infrastructure, shortage of trained personnel, and fragmented surveillance allow zoonotic pathogens to circulate silently — until humans become collateral damage.

COVID-19: A Global Wake-Up Call

COVID-19 exposed profound weaknesses in global disease surveillance and preparedness. Although experts repeatedly warned that zoonotic pandemics were inevitable, early animal signals were missed, delayed, or ignored.

By the time SARS-CoV-2 was genomically identified, widespread community transmission had

already occurred. Retrospective analyses suggest that animal-to-human spillover likely preceded detection by weeks — a critical window during which containment might have been possible.

What Went Wrong?

- Weak wildlife and livestock disease surveillance
- Fragmented veterinary–medical data systems
- Slow deployment of diagnostics
- Policy inertia

COVID-19 revealed a central truth: pandemic preparedness begins in animals, not hospitals

Major Zoonotic Threats in the Post-Pandemic Era

Experts warn that COVID-19 was not a once-in-a-century anomaly. The next pandemic is already incubating somewhere in the animal world. Several zoonotic pathogens already circulating in animal populations illustrate the diversity of pandemic risks facing humanity. Mapping the occurrence of these pathogens highlights regions where ecological, animal, and human interfaces create conditions favourable for disease emergence (Figure 1).

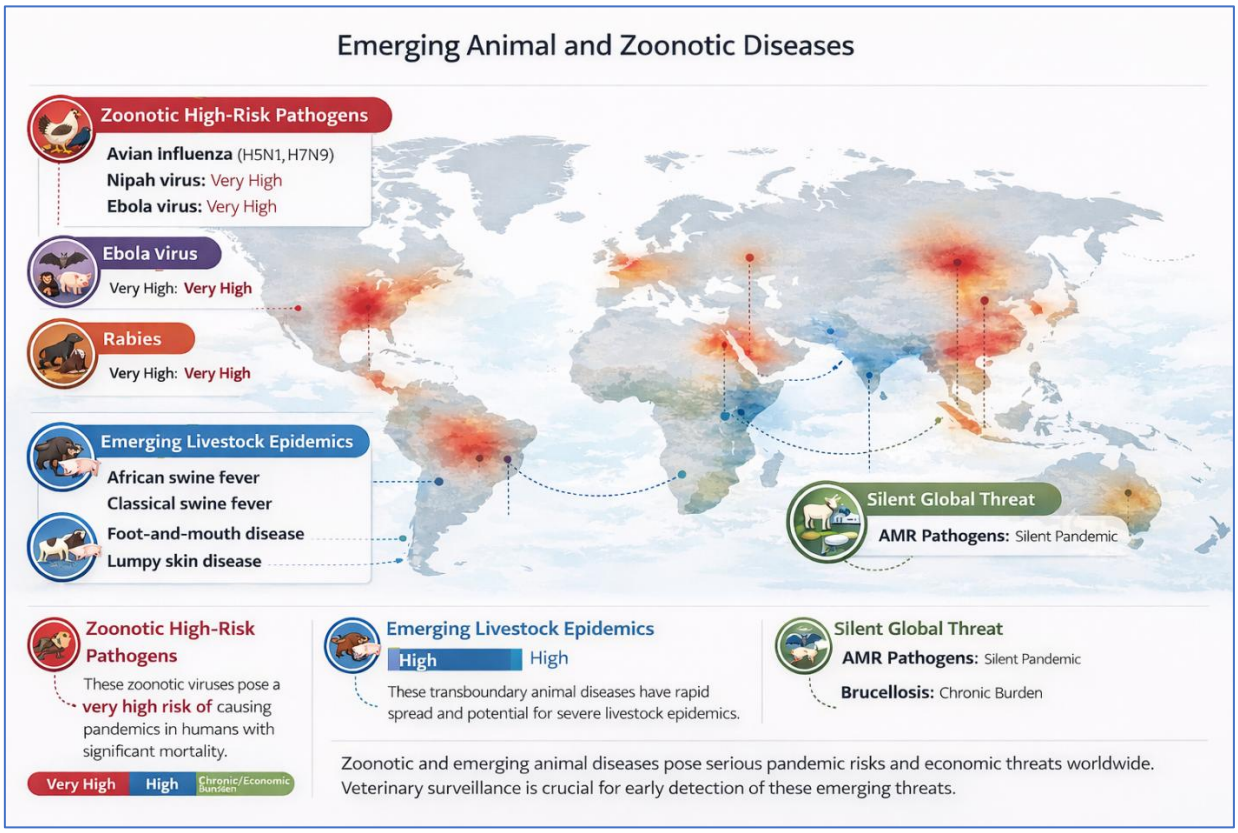

Figure 1. Global Landscape of Emerging Zoonotic and Transboundary Livestock Diseases

The Silent Pandemic: Antimicrobial Resistance (AMR)

AMR represents one of the gravest zoonotic threats of the 21st century. Resistant bacteria emerging in livestock due to use of excessive antibiotics can spread to humans through food products, direct animal contact, contaminated water, and environmental pathways (Zhang *et al.,* 2025). Once established in human

populations, these pathogens become increasingly difficult to treat, turning routine infections into serious medical threats.

- By 2050, AMR could cause 10 million deaths annually
- Livestock systems account for nearly 70% of global antibiotic consumption

Climate Change, Urbanization and Wildlife Trade: The Perfect Storm

Environmental change is intensifying the ecological conditions that drive zoonotic spillover, particularly through climate change, urban expansion, and wildlife trade. Deforestation, rapid urbanization, agricultural expansion, and climate change are bringing humans, livestock, and wildlife into closer contact than ever before. As natural habitats shrink and ecological boundaries blur, pathogens that once circulated quietly in wildlife populations gain new opportunities to cross species barriers and infect domestic animals and humans.

- **Climate Change:**

  Rising temperatures expand vector habitats, driving the spread of:

  - Rift Valley fever
  - Japanese encephalitis
  - West Nile virus
  - Lyme disease

- **Urbanization:**

  By 2050, nearly 70% of humanity will live in cities, often adjacent to peri-urban livestock farms — creating novel disease interfaces.

- **Wildlife Trade:**

  Millions of live animals move through global wildlife markets annually, forming direct channel for pathogen spillover.

One Health: Reuniting Human, Animal and Environmental Medicine

The pandemic transformed One Health from academic theory into global policy necessity. One Health recognizes that human, animal, and environmental health are inseparably linked (Shaheen *et al.,* 2022).

Core Pillars of One Health:

- Integrated disease surveillance
- Shared diagnostic platforms
- Cross-sector data sharing
- Joint outbreak response
- Unified policy frameworks

Countries adopting One Health systems report:

- 60–70% faster outbreak detection
- 40–50% reduction in response time

Modern Diagnostics and Digital Pathology: A Technological Revolution

Today's outbreak defense is increasingly fought in laboratories where molecular biology meets artificial intelligence. Modern diagnostic technologies such as PCR/qPCR, next-generation sequencing, digital pathology, AI-assisted microscopy, and mobile diagnostic laboratories are transforming veterinary disease surveillance by enabling rapid detection, genomic monitoring, and field-level outbreak investigation (Figure 2).

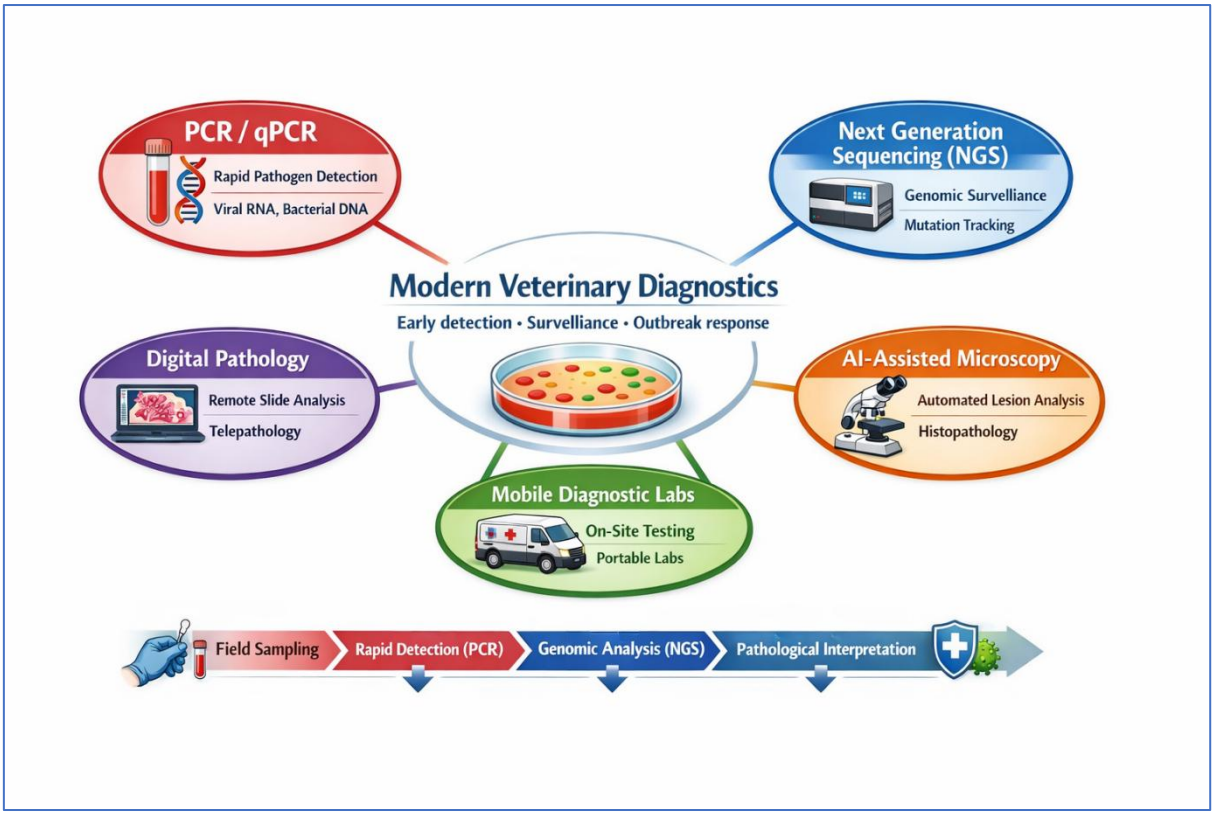

Figure 2. Modern Diagnostic Technologies in Veterinary Disease Surveillance

Faster Diagnostics in the Modern Era:

Traditional diagnostics required 5–14 days. Modern molecular tools deliver results in under 6 hours, sometimes within 60 minutes in field settings. Digital pathology platforms now enable real-time global collaboration — democratizing expert diagnostics, especially for low-resource regions.

India's Zoonotic Landscape: Risks and Opportunities

India stands at a critical crossroads of vulnerability and leadership.

Why India Is Highly Vulnerable?

- World's largest livestock population
- High rural human–animal contact
- Rich wildlife biodiversity
- Rapid urban expansion
- Heavy antibiotic usage

India is endemic for rabies, brucellosis, leptospirosis, tuberculosis, scrub typhus, and avian influenza, while facing emerging threats like Nipah virus and Kyasanur Forest Disease.

Yet, India also possesses powerful institutional capacity:

ICAR • ICMR • IVRI • NIV • NIHSAD • National One Health Mission

With strategic investment, India could become a global hub for zoonotic early-warning systems.

Policy, Surveillance and Global Cooperation:

Pandemics are not merely biological events — they are policy failures amplified by biology.

- COVID-19 caused > $13 trillion global losses
- Annual pandemic prevention costs: $20–30 billion

Every $1 invested in prevention saves nearly $500 in outbreak response.

The Road Ahead: Predictive, Preventive and Precision Veterinary Medicine:

The future lies in anticipation, not reaction.

Predictive Disease Intelligence:

- Predictive pathology using AI + climate + genomics
- Smart farms with biosensors and automated alerts
- Precision livestock medicine minimizing antibiotic usage

Together, these form One Health 2.0 — a digital immune system for the planet.

Genomic Epidemiology:

Advances in genomic technologies have revolutionized the way infectious diseases are investigated. Sequencing the genetic material of pathogens allows scientists to reconstruct the evolutionary history of an outbreak and track how a disease spreads across regions and species.

Genomic epidemiology played a crucial role during the COVID-19 pandemic, when thousands of viral genomes were sequenced worldwide to monitor the emergence of new variants. Similar approaches are now widely used in veterinary medicine to track outbreaks of avian influenza, African swine fever, and other transboundary diseases.

By comparing pathogen genomes collected from animals and humans, researchers can determine whether infections originated from wildlife, livestock, or human-to-human transmission. This integration of molecular biology and epidemiology has become an essential tool for modern outbreak investigation.

Sentinel Surveillance:

Traditional disease surveillance focuses on responding to outbreaks after they occur. However, scientists are increasingly exploring whether future pandemics can be predicted before they emerge. Veterinary diagnostic laboratories and pathology networks function as critical surveillance nodes where unusual lesions detected during routine necropsy examinations may signal the emergence of new infectious threats in animal populations.

Surveillance systems increasingly integrate ecological monitoring, wildlife disease reporting, and international data sharing to identify emerging threats early. Artificial intelligence systems are also being

developed to analyse vast datasets of animal disease reports and environmental variables. Although prediction remains imperfect, such approaches represent an important shift from reactive to proactive pandemic preparedness.

Animals often act as sentinels, providing early indications of environmental or infectious threats that may later affect humans. Monitoring diseases in livestock, wildlife, and companion animals therefore plays an important role in global health security.

International organizations and surveillance networks increasingly collaborate to share disease information across borders. These systems allow scientists and policymakers to detect unusual disease patterns rapidly and coordinate responses before outbreaks escalate into global emergencies.

Strengthening such early warning networks will be essential for preventing future pandemics.

Conclusion:

COVID-19 revealed a sobering reality: by the time hospitals fill with patients, the opportunity for prevention has already passed.

The earliest warnings of emerging pandemics often appear far from intensive care units—in poultry farms, livestock markets, forest edges, and veterinary diagnostic laboratories. There, veterinary pathologists examine tissues, detect unusual lesions, and identify pathogens that may one day threaten human populations

Whether it becomes a global catastrophe will depend on how early we recognize the warning signs and how effectively human and veterinary health systems work together to respond.

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