

Global Epidemiology and Emerging Trends of Hantavirus Infection: A One Health Perspective

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ABSTRACT

Hantaviruses are rodent-borne zoonotic pathogens responsible for Hemorrhagic Fever with Renal Syndrome (HFRS) and Hantavirus Cardiopulmonary Syndrome (HCPS). Their epidemiology is strongly influenced by interactions among reservoir hosts, environmental conditions, climatic variability, and human activities. Increasing evidence indicates that climate change, urbanization, deforestation, agricultural expansion, and biodiversity alterations are reshaping hantavirus transmission dynamics worldwide. To review the global epidemiology of hantavirus infections and examine the roles of rodent reservoirs, transmission ecology, climate change, environmental drivers, and One Health approaches in disease emergence, surveillance, and prevention. A narrative review was conducted using literature retrieved from PubMed/MEDLINE, Embase, Scopus, and Web of Science. Peer-reviewed studies published between 2000 and 2025 were screened using predefined inclusion and exclusion criteria. Epidemiological studies, surveillance reports, ecological investigations, outbreak analyses, and One Health-related publications were included. Findings were synthesized according to major thematic areas, including global epidemiology, reservoir ecology, environmental determinants, surveillance strategies, and prevention approaches. Approximately 150,000–200,000 HFRS cases are estimated to occur annually worldwide, with China accounting for the majority of reported infections. Europe experiences recurrent outbreaks of Puumala virus-associated nephropathia epidemica, while HCPS remains a significant concern in North and South America because of case-fatality rates ranging from 30% to 40%. Climatic factors such as temperature, precipitation, and extreme weather events influence rodent population dynamics and disease transmission. Environmental changes, including deforestation, habitat fragmentation, and urbanization, further increase opportunities for human exposure. Integrated surveillance systems combining ecological, environmental, and epidemiological data have improved outbreak prediction and preparedness. Hantavirus epidemiology is shaped by complex interactions among humans, rodents, and environmental systems. Climate change and environmental modification are expected to influence future disease emergence. Strengthening One Health surveillance, expanding ecological monitoring, improving diagnostic capacity, and promoting interdisciplinary collaboration are essential for reducing disease burden and enhancing preparedness for future outbreaks.

Keywords

Hantavirus;
Hemorrhagic Fever
with Renal
Syndrome;
Hantavirus
Cardiopulmonary
Syndrome; One
Health; Climate
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Reservoirs;
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Introduction

Hantaviruses are globally distributed zoonotic pathogens belonging to the family Hantaviridae and represent a significant public health concern due to their capacity to cause severe and potentially fatal disease in humans. These enveloped, negative-sense single-stranded RNA viruses are maintained in nature through persistent infections in rodent reservoirs and are transmitted primarily through inhalation of aerosolized excreta from infected animals. Human infection can result in two major clinical syndromes: Hemorrhagic Fever with Renal Syndrome (HFRS), which predominates in Asia and Europe, and Hantavirus Cardiopulmonary Syndrome (HCPS), which occurs mainly in North and South America (1).

Since the identification of Hantaan virus during investigations of Korean hemorrhagic fever, the global significance of hantavirus infections has become increasingly apparent. Current estimates suggest that approximately 150, 000–200, 000 HFRS cases occur annually worldwide, with China accounting for the majority of reported infections (1). In contrast, HCPS occurs less frequently but is associated with considerably higher mortality rates, often exceeding 30–40% despite advances in intensive care management (2). The geographical distribution of hantavirus infections closely mirrors the ecological distribution of their rodent reservoirs, emphasizing the critical role of environmental and ecological factors in disease transmission (1, 3).

The emergence and re-emergence of hantavirus infections are strongly influenced by dynamic interactions among hosts, pathogens, and environmental conditions. Numerous studies have demonstrated associations between climatic variability and hantavirus outbreaks. Changes in temperature, precipitation patterns, and extreme weather events can directly influence rodent population density, breeding patterns, food availability, and habitat suitability, thereby affecting viral transmission dynamics (4, 5). One of the most widely cited examples is the 1993 HCPS outbreak in the Four Corners region of the United States, where increased precipitation associated with the El Niño Southern Oscillation resulted in enhanced vegetation growth, increased rodent abundance, and subsequent amplification of human exposure risk (1, 6).

In addition to climatic influences, anthropogenic environmental changes have emerged as important

determinants of hantavirus epidemiology. Deforestation, agricultural expansion, urbanization, mining activities, and habitat fragmentation alter natural ecosystems and increase opportunities for contact between humans and infected wildlife reservoirs (7). Such environmental disturbances may promote rodent migration into peri-domestic environments, facilitate spillover transmission, and contribute to the emergence of disease in previously unaffected regions. Furthermore, globalization and changing patterns of land use have intensified interactions between humans, animals, and ecosystems, increasing the potential for zoonotic disease emergence (8).

Recent advances in ecological surveillance, geographic information systems (GIS), remote sensing technologies, molecular epidemiology, and predictive modeling have substantially improved understanding of hantavirus transmission dynamics. These tools have facilitated identification of environmental risk factors, prediction of outbreak-prone regions, and monitoring of reservoir populations (9). However, despite these technological advances, significant challenges remain in predicting disease emergence and implementing effective prevention strategies.

The complexity of hantavirus transmission has led to increasing recognition of the importance of the One Health framework. One Health is an integrated and collaborative approach that recognizes the interconnectedness of human health, animal health, and environmental health. This framework emphasizes interdisciplinary collaboration among clinicians, veterinarians, ecologists, epidemiologists, environmental scientists, and public health professionals to address emerging infectious diseases comprehensively (10). Given that hantavirus transmission occurs at the interface of wildlife, humans, and the environment, the disease serves as an ideal model for applying One Health principles.

Although several reviews have examined specific aspects of hantavirus biology, ecology, and clinical manifestations, there remains a need for a comprehensive synthesis of recent evidence regarding global epidemiological trends, environmental drivers, reservoir ecology, and emerging surveillance approaches from a One Health perspective. Therefore, this narrative review aims to summarize current knowledge regarding the global epidemiology of hantavirus infections, examine the role of rodent reservoirs and ecological determinants

in disease emergence, explore the influence of climate change and environmental modifications on transmission dynamics, and discuss current and future strategies for surveillance and prevention within a One Health framework.

Materials and Methods

Review Design

A narrative review methodology was adopted to synthesize current evidence regarding the epidemiology, ecology, environmental determinants, and One Health aspects of hantavirus infection. Narrative reviews are particularly suitable for integrating evidence from diverse study designs, including epidemiological investigations, ecological studies, surveillance reports, outbreak analyses, and environmental research (11).

Search Strategy

A comprehensive literature search was conducted using four major electronic databases: PubMed/MEDLINE, Embase, Scopus, and Web of Science. The search included studies published from January 2000 to March 2025. Additional relevant articles were identified through manual screening of reference lists from key publications. The following keywords and Medical Subject Headings (MeSH) were used in various combinations: "Hantavirus, " "Orthohantavirus, " "Hemorrhagic Fever with Renal Syndrome, " "Hantavirus Cardiopulmonary Syndrome, " "epidemiology, " "surveillance, " "rodent reservoir, " "climate change, " "environmental factors, " "zoonotic disease, " "ecology, " "outbreak, " and "One Health." A representative PubMed search strategy was: ("Hantavirus" OR "Orthohantavirus") AND ("epidemiology" OR "surveillance") AND ("climate change" OR "environmental factors") AND ("rodent reservoir") AND ("One Health")

Eligibility Criteria

Studies were included if they:

- Reported epidemiological, ecological, environmental, or surveillance-related findings on hantavirus infections.
- Examined reservoir host ecology or transmission dynamics.

- Investigated climate-related or environmental determinants of disease occurrence.
- Addressed One Health approaches relevant to hantavirus surveillance or prevention.
- Were published in peer-reviewed journals.
- Were available in English.

Studies were excluded if they:

- Were conference abstracts without full-text availability.
- Focused exclusively on laboratory-based virology without epidemiological relevance.
- Were duplicate publications.
- Were non-English articles without accessible translations.

Study Selection

Titles and abstracts retrieved from database searches were independently screened for relevance. Full-text articles meeting the eligibility criteria were subsequently reviewed.

Relevant review articles were examined to identify additional studies not captured during the initial database search.

Preference was given to large epidemiological studies, national surveillance reports, systematic reviews, and landmark ecological investigations. (Figure -1)

Data Extraction and Synthesis

Data extracted from eligible studies included geographical location, study design, hantavirus species, reservoir hosts, epidemiological findings, climatic variables, environmental determinants, surveillance approaches, and One Health components. Findings were synthesized narratively and organized into thematic categories, including global epidemiology, reservoir ecology, climate change, environmental drivers, surveillance strategies, and future research priorities.

To enhance methodological transparency and reporting quality, the review was informed by the Checklist for One Health Epidemiological Reporting of Evidence (COHERE), which emphasizes integration of human, animal, and environmental health domains in epidemiological research (10).

Global Epidemiology of Hantavirus Infection

Global Burden and Distribution

Hantaviruses are among the most widely distributed zoonotic pathogens worldwide, with documented circulation across Asia, Europe, Africa, and the Americas. The epidemiology of hantavirus infections is strongly influenced by the geographic distribution of their reservoir hosts, environmental conditions, climatic factors, and human activities that facilitate contact with infected rodents. Although human infections have been reported from more than 70 countries, the burden of disease varies considerably across regions owing to differences in surveillance systems, ecological conditions, and dominant hantavirus species (1, 2).

Globally, an estimated 150,000–200,000 cases of Hemorrhagic Fever with Renal Syndrome (HFRS) occur annually, with the majority reported from Asia, particularly China (1).

In contrast, Hantavirus Cardiopulmonary Syndrome (HCPS), primarily reported in the Americas, occurs less frequently but is associated with substantially higher mortality rates, ranging from 30% to 40% (3). The distribution of human disease closely reflects the ecological niches occupied by specific rodent hosts, emphasizing the importance of reservoir ecology in determining regional disease patterns.

Long-term epidemiological surveillance indicates that hantavirus infections exhibit cyclical fluctuations associated with rodent population dynamics, climatic variability, and environmental changes. Seasonal peaks are commonly observed during periods of increased rodent activity and human exposure. Increasing evidence also suggests that climate change and anthropogenic land-use modifications are contributing to the emergence of hantavirus infections in previously unaffected regions (4).

Epidemiology in Asia

Asia bears the greatest burden of hantavirus disease globally. China alone accounts for approximately 70–90% of all reported HFRS cases worldwide and remains the most affected country despite substantial reductions in incidence achieved through vaccination programs and rodent control measures (1, 5).

Historically, more than 1.6 million HFRS cases and over 46,000 deaths have been reported in China since national surveillance began in the 1950s (6). The predominant causative agents are Hantaan virus (HTNV) and Seoul virus (SEOV), which are maintained by the striped field mouse (*Apodemus agrarius*) and Norway rat (*Rattus norvegicus*), respectively (1). High-incidence provinces include Heilongjiang, Jilin, Liaoning, Shandong, Shaanxi, Hunan, and Zhejiang (7). China has experienced significant epidemiological shifts over the past three decades. Following the introduction of nationwide vaccination programs and improved surveillance, annual incidence rates have declined substantially. However, localized outbreaks continue to occur, particularly in rural agricultural communities where occupational exposure remains common (8).

South Korea remains another important endemic region. HFRS was first recognized among United Nations troops during the Korean War and continues to be reported annually. Cases are typically associated with military training activities, farming, and outdoor occupational exposures (9). Hantaan virus remains the dominant pathogen, with seasonal peaks occurring during autumn and early winter when rodent populations increase.

In Russia, hantavirus infections are widely distributed across both European and Asian territories. Puumala virus and Hantaan-like viruses contribute substantially to disease burden. Several thousand HFRS cases are reported annually, particularly in western regions bordering Europe (10).

Other Asian countries reporting hantavirus infections include Japan, India, Vietnam, Thailand, and Indonesia. Although incidence rates are generally lower than those observed in China and Korea, serological studies suggest that hantavirus circulation may be underrecognized due to limited diagnostic capacity and surveillance infrastructure (11).

Epidemiology in Europe

Europe represents the second major endemic region for hantavirus infections, with Puumala virus (PUUV) accounting for most reported cases. Unlike HFRS caused by Hantaan virus, Puumala virus infection typically manifests as nephropathia epidemica (NE), a milder form of HFRS characterized by fever, renal dysfunction, and thrombocytopenia (12).

The bank vole (*Myodes glareolus*) serves as the principal reservoir host for Puumala virus. Disease incidence is strongly associated with cyclic fluctuations in bank vole populations, which are influenced by forest ecology, food availability, and climatic conditions (13).

Finland reports some of the highest incidence rates of hantavirus infection worldwide, frequently exceeding 30–40 cases per 100,000 population during epidemic years (14). Cyclical outbreaks occur every three to four years and are associated with increased vole abundance following mast years of forest trees.

Sweden, Norway, Belgium, Germany, Slovenia, Croatia, and France also report substantial numbers of cases annually (15). Germany has experienced periodic outbreaks involving several thousand confirmed infections, particularly in southern regions characterized by extensive forest ecosystems (16).

The Dobrava-Belgrade virus (DOBV) is predominantly distributed in the Balkan Peninsula and is associated with more severe clinical disease than Puumala virus infection. Reservoir hosts include the yellow-necked mouse (*Apodemus flavicollis*) and related rodent species (17).

Recent surveillance data indicate increasing geographic expansion of hantavirus activity in Europe. Climate-driven changes in rodent habitats and altered ecological conditions have been implicated in this expansion, raising concerns regarding future disease emergence (18).

Epidemiology in the Americas

The epidemiology of hantavirus infection in the Americas differs significantly from that observed in Europe and Asia. Here, hantaviruses primarily cause Hantavirus Cardiopulmonary Syndrome (HCPS), a severe respiratory disease characterized by pulmonary edema, cardiogenic shock, and high mortality (3).

The first recognized HCPS outbreak occurred in 1993 in the Four Corners region of the southwestern United States. Investigation identified Sin Nombre virus (SNV) as the causative agent and the deer mouse (*Peromyscus maniculatus*) as its primary reservoir (19). Since then, more than 850 HCPS cases have been reported in the United States, with an overall case-fatality rate of approximately 35% (20).

Canada reports sporadic HCPS cases, primarily in western provinces where deer mouse populations are abundant. Disease incidence remains relatively low but demonstrates strong associations with environmental conditions affecting rodent abundance (21).

South America exhibits greater hantavirus diversity than North America. Multiple hantavirus species have been identified in Argentina, Chile, Brazil, Paraguay, Uruguay, and Bolivia (22). Andes virus is particularly important because it is one of the few hantaviruses capable of documented human-to-human transmission (23).

Argentina and Chile experience recurrent outbreaks of Andes virus-associated HCPS. Mortality rates range from 25% to 40%, although improvements in intensive care management have contributed to better survival outcomes in recent years (24).

Brazil reports the largest number of HCPS cases in South America. Since surveillance began in the early 1990s, thousands of cases have been documented, particularly in agricultural regions undergoing environmental transformation and deforestation (25). Studies have demonstrated strong associations between agricultural expansion, landscape fragmentation, and increased HCPS risk (26).

Hantavirus Epidemiology in Africa

Compared with Asia, Europe, and the Americas, hantavirus epidemiology in Africa remains poorly understood. Historically, the continent was not considered an important region for hantavirus transmission. However, advances in molecular diagnostics and wildlife surveillance have identified several hantavirus-like viruses among African rodents, shrews, and bats (27).

Serological evidence of human exposure has been reported from several African countries, including Côte d'Ivoire, Guinea, Nigeria, Senegal, and the Democratic Republic of Congo (28). Nevertheless, laboratory-confirmed human disease remains uncommon, likely reflecting substantial underdiagnosis and limited surveillance capacity.

Recent ecological studies suggest that hantavirus diversity in Africa may be considerably greater than previously recognized. Novel hantavirus species have

been detected in rodent populations across West, Central, and East Africa, indicating the presence of complex wildlife reservoirs (29).

The public health significance of these viruses remains uncertain, and further research is required to determine their pathogenic potential and contribution to human disease. Strengthening zoonotic surveillance systems and enhancing laboratory diagnostic capabilities are essential priorities for improving understanding of hantavirus epidemiology in Africa (30).

Emerging Global Trends

Several important trends are shaping the contemporary epidemiology of hantavirus infections worldwide. First, climate change is increasingly recognized as a major driver of disease emergence through its effects on rodent population dynamics, habitat suitability, and viral transmission (4). Rising temperatures and altered precipitation patterns influence food availability and reservoir abundance, thereby affecting human exposure risk.

Second, urbanization and environmental modification are altering traditional transmission patterns. Seoul virus infections associated with Norway rats have increasingly been reported from urban environments, highlighting the growing importance of peri-domestic transmission (31).

Third, improved molecular surveillance has facilitated the discovery of numerous novel hantaviruses in rodents, shrews, moles, and bats, expanding understanding of hantavirus diversity and evolution (32). Finally, advances in geographic information systems, remote sensing technologies, and predictive ecological modeling are enabling more sophisticated surveillance and outbreak forecasting strategies (33). Collectively, these developments underscore the importance of integrated One Health approaches that address human, animal, and environmental determinants of hantavirus transmission.

Rodent Reservoirs, Transmission Ecology, Climate Change, and Environmental Drivers

Rodent Reservoirs and Hantavirus Maintenance in Nature

The epidemiology of hantavirus infections is fundamentally linked to the ecology of their reservoir

hosts. Unlike many zoonotic pathogens that circulate among multiple host species, most hantaviruses exhibit a high degree of host specificity and have evolved long-term associations with particular rodent species. This co-evolutionary relationship allows the virus to establish persistent infections in reservoir hosts without causing significant disease, thereby facilitating continuous viral maintenance and transmission within natural ecosystems (34, 35).

Rodents belonging to the families Muridae, Cricetidae, and Sigmodontinae constitute the primary reservoirs of hantaviruses worldwide. Each pathogenic hantavirus is generally associated with a specific rodent host. For example, Hantaan virus is maintained by the striped field mouse (*Apodemus agrarius*), Seoul virus by the Norway rat (*Rattus norvegicus*), Puumala virus by the bank vole (*Myodes glareolus*), Sin Nombre virus by the deer mouse (*Peromyscus maniculatus*), and Andes virus by the long-tailed pygmy rice rat (*Oligoryzomys longicaudatus*) (1, 13).

Reservoir hosts typically develop chronic asymptomatic infections and shed the virus through saliva, urine, and feces for extended periods. Viral persistence is facilitated by complex host immune responses that allow infection without causing severe pathological damage. This phenomenon contrasts sharply with human infections, where immune-mediated vascular dysfunction contributes significantly to disease severity (3, 35).

Rodent population density is a critical determinant of hantavirus transmission dynamics. Increased host abundance enhances opportunities for intraspecies transmission through aggressive encounters, territorial behavior, mating activities, and environmental contamination.

Consequently, fluctuations in rodent populations directly influence infection prevalence and subsequent human exposure risk (36).

Numerous studies have demonstrated that male rodents exhibit higher infection rates than females because of increased territorial aggression and contact frequencies. Age-related differences have also been observed, with adult rodents typically showing higher seroprevalence than juveniles due to cumulative exposure over time (37). Understanding these ecological patterns is essential for predicting periods of increased transmission risk.

Transmission Ecology and Human Exposure Pathways

Human infection occurs primarily through indirect exposure to contaminated environments rather than direct contact with infected animals. Aerosolization of virus-containing particles from rodent urine, feces, or saliva represents the principal route of transmission. Activities such as sweeping enclosed spaces, cleaning rodent-infested buildings, handling contaminated materials, and agricultural work may generate infectious aerosols that are subsequently inhaled by humans (1, 38).

Occupational exposure remains a major risk factor worldwide. Farmers, forestry workers, military personnel, construction workers, wildlife researchers, and agricultural laborers experience elevated risks due to frequent contact with rodent habitats (39). In rural communities, storage of food products, poor housing conditions, and inadequate waste management practices further increase opportunities for rodent-human interactions.

The epidemiology of hantavirus infections often exhibits marked seasonal variation. In temperate regions, human cases frequently peak during spring and autumn when rodent activity and human outdoor activities increase. Seasonal agricultural activities, harvesting periods, and changes in rodent behavior contribute to these temporal patterns (13).

Although person-to-person transmission is generally absent for most hantaviruses, Andes virus represents a notable exception. Several outbreaks in Argentina and Chile have demonstrated limited human-to-human transmission, particularly among household contacts and healthcare settings.

Molecular epidemiological investigations have confirmed transmission chains in specific outbreaks, making Andes virus unique among known hantaviruses (40).

Environmental contamination plays a significant role in maintaining transmission cycles. Rodent infestations in homes, storage facilities, barns, and agricultural settings create opportunities for persistent environmental contamination. Consequently, public health interventions emphasizing rodent control, environmental sanitation, and safe cleaning practices remain central components of disease prevention (41).

Climate Change and Hantavirus Emergence

Climate change has emerged as one of the most important drivers of zoonotic disease emergence globally. Increasing evidence suggests that climatic variability significantly influences hantavirus epidemiology by affecting reservoir host populations, habitat suitability, food availability, and transmission dynamics (4, 18).

Temperature, precipitation, humidity, and extreme weather events interact to shape ecological conditions favorable for rodent population growth. Increased rainfall often enhances primary productivity through increased vegetation growth, providing abundant food resources for rodent populations. Subsequent increases in rodent abundance may amplify viral circulation and elevate the probability of human exposure (42).

One of the most extensively studied examples occurred during the 1993 outbreak of Hantavirus Cardiopulmonary Syndrome in the Four Corners region of the southwestern United States. Climatic analyses demonstrated that unusually heavy rainfall associated with the El Niño Southern Oscillation resulted in substantial increases in vegetation cover. This ecological response enhanced food availability for deer mice (*Peromyscus maniculatus*), leading to rapid population expansion and increased opportunities for viral transmission (6). Human exposure subsequently increased as infected rodents entered residential and occupational environments.

Similar climate-disease relationships have been documented in Europe. In Finland, Sweden, and other Nordic countries, periodic outbreaks of Puumala virus infection are associated with fluctuations in bank vole populations driven by climatic conditions and forest productivity cycles. Mild winters and increased food availability have been linked to elevated vole abundance and increased disease incidence (14, 43).

In China, numerous studies have demonstrated associations between meteorological variables and HFRS incidence. Temperature, precipitation, relative humidity, and vegetation indices have all been identified as important predictors of disease occurrence.

Climate-driven ecological changes influence both rodent abundance and human exposure patterns, contributing to regional differences in disease risk (5, 44).

Climate change may also alter the geographic distribution of reservoir hosts. Rising temperatures can expand suitable habitats into previously inhospitable regions, potentially facilitating the emergence of hantavirus infections in new geographic areas. Predictive ecological models suggest that continued warming may shift the distribution of several rodent species toward higher latitudes and elevations, creating novel opportunities for pathogen transmission (45).

Land-Use Change and Environmental Drivers

Beyond climate change, anthropogenic environmental modifications have become increasingly important determinants of hantavirus emergence. Rapid population growth, urbanization, agricultural expansion, deforestation, mining, infrastructure development, and habitat fragmentation have transformed ecosystems worldwide, altering interactions among humans, wildlife, and pathogens (8).

Deforestation is particularly significant because it disrupts natural habitats and forces wildlife species into closer proximity with human populations. Forest clearing for agriculture and development may increase encounters between humans and infected rodents by reducing habitat availability and altering species composition (46). In several regions of South America, deforestation has been associated with increased HCPS incidence through its effects on rodent community structure and abundance.

Agricultural expansion represents another important environmental driver. Conversion of natural landscapes into agricultural land often creates favorable habitats for rodent populations by providing abundant food resources and shelter. Agricultural workers frequently experience increased exposure due to occupational activities involving grain storage, harvesting, and fieldwork (47).

Urbanization has introduced new epidemiological challenges, particularly concerning Seoul virus transmission. The Norway rat (*Rattus norvegicus*), the principal reservoir of Seoul virus, thrives in densely populated urban environments characterized by poor sanitation and abundant food resources. Increasing reports of Seoul virus infections in urban settings highlight the growing importance of peri-domestic transmission and urban rodent surveillance (48).

Habitat fragmentation may also influence disease dynamics through effects on biodiversity. Changes in

species composition can alter host-pathogen interactions, potentially increasing reservoir abundance and transmission efficiency. Several studies have suggested that reduced biodiversity may increase zoonotic disease risk by favoring competent reservoir hosts, although the specific mechanisms vary among ecosystems (49).

Ecological Surveillance and Predictive Modeling

Understanding the ecological determinants of hantavirus transmission has led to the development of increasingly sophisticated surveillance systems. Modern ecological surveillance integrates wildlife monitoring, environmental assessment, climate forecasting, geographic information systems (GIS), remote sensing technologies, and molecular epidemiology to identify regions at elevated risk of disease emergence (33).

Rodent surveillance remains a cornerstone of outbreak prediction. Monitoring reservoir abundance, infection prevalence, and geographic distribution can provide early warning signals before human cases occur. Longitudinal studies have demonstrated that increases in rodent populations frequently precede outbreaks by several months, creating opportunities for preventive interventions (50).

Remote sensing technologies offer valuable tools for monitoring environmental conditions associated with disease emergence. Satellite-derived vegetation indices, land surface temperature measurements, and precipitation data have been incorporated into predictive models capable of identifying ecological conditions favorable for transmission (51). Such approaches are particularly useful in resource-limited settings where extensive field surveillance may be impractical.

Recent advances in machine learning and spatial epidemiology have further improved predictive capabilities. Integrating climatic, ecological, demographic, and epidemiological data allows development of risk maps that identify vulnerable regions and guide targeted public health interventions (52). These approaches align closely with One Health principles by combining information from multiple disciplines to support disease prevention.

One Health Implications

The complex interactions among rodents, humans, and environmental systems underscore the importance of a

One Health approach to hantavirus prevention and control. Human disease cannot be understood solely through clinical surveillance; effective prevention requires simultaneous consideration of wildlife ecology, environmental change, and socio-economic determinants of exposure (10).

One Health strategies emphasize interdisciplinary collaboration among physicians, veterinarians, wildlife biologists, ecologists, climatologists, and public health professionals. Integrated surveillance systems that combine human case detection with rodent monitoring and environmental assessment provide more comprehensive understanding of transmission dynamics and improve outbreak preparedness (53).

As climate change and environmental transformation continue to reshape ecosystems worldwide, the application of One Health principles will become increasingly important for anticipating and mitigating future hantavirus outbreaks. Strengthening ecological surveillance, improving predictive modeling, and enhancing collaboration across sectors are essential components of sustainable disease prevention strategies.

One Health Surveillance, Prevention Strategies, Future Directions, and Conclusion

One Health Surveillance Approaches

The increasing recognition of hantavirus infection as a complex zoonotic disease has highlighted the necessity of adopting comprehensive surveillance systems that extend beyond traditional human disease monitoring. Since hantavirus transmission is influenced by intricate interactions among reservoir hosts, environmental conditions, climatic factors, and human behaviors, effective surveillance requires integration of data from human, animal, and environmental health sectors. This interdisciplinary approach forms the foundation of the One Health framework, which has become increasingly important in addressing emerging infectious diseases worldwide (10, 53).

Conventional surveillance systems primarily focus on detecting and reporting human cases. While such systems are essential for identifying outbreaks and monitoring disease trends, they often fail to provide sufficient early warning before transmission occurs. In contrast, One Health surveillance incorporates monitoring of reservoir

populations, environmental changes, climatic variables, and ecological indicators that may predict increased transmission risk (54).

Rodent surveillance constitutes a critical component of hantavirus prevention. Monitoring rodent abundance, species distribution, infection prevalence, and habitat characteristics can provide valuable information regarding potential disease emergence. Studies have demonstrated that increases in rodent population density frequently precede human outbreaks by several months, creating opportunities for proactive public health interventions (50). Regular trapping programs, serological testing, and molecular surveillance of rodent populations can help identify emerging hotspots and guide targeted prevention strategies.

Environmental surveillance is equally important. Remote sensing technologies, satellite imagery, and geographic information systems (GIS) enable continuous monitoring of environmental variables associated with hantavirus transmission, including vegetation indices, land-use changes, precipitation patterns, and temperature fluctuations (51). These tools facilitate identification of ecological conditions favorable for rodent population expansion and may support the development of early warning systems.

Recent advances in molecular epidemiology have further strengthened surveillance capabilities. Whole-genome sequencing and phylogenetic analyses enable identification of novel hantavirus strains, monitoring of viral evolution, and tracking of transmission pathways (55). Integration of genomic data with ecological and epidemiological information enhances understanding of disease emergence and supports evidence-based public health decision-making.

Several countries have successfully implemented integrated surveillance systems incorporating human, animal, and environmental data. Such systems exemplify the practical application of One Health principles and demonstrate the potential benefits of interdisciplinary collaboration in zoonotic disease prevention (56).

Prevention and Control Strategies

Currently, no universally effective antiviral treatment exists for most hantavirus infections, and clinical management remains largely supportive.

Figure.1 PRISMA Flow Diagram for Literature search process

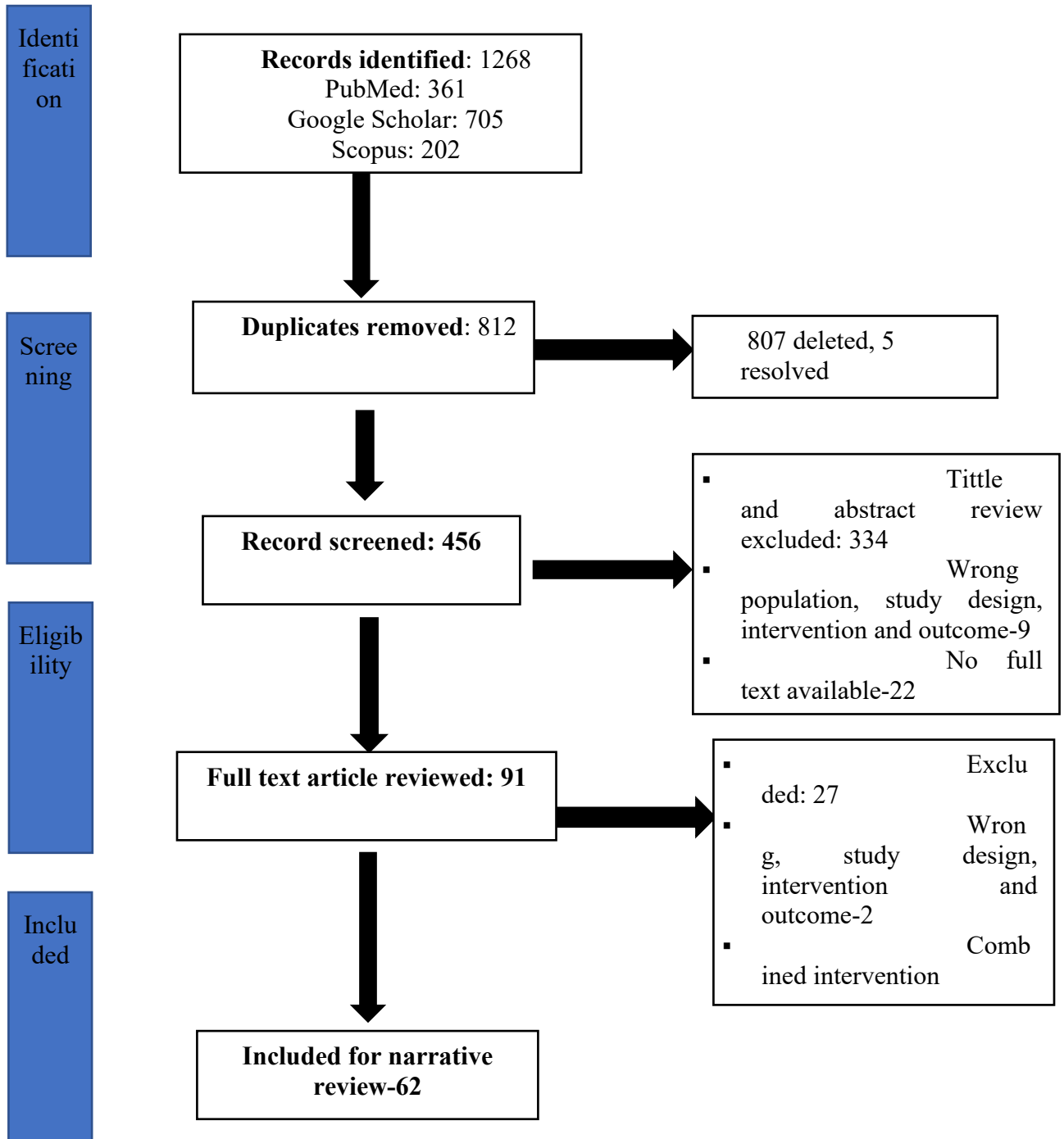


Table.1 Major Hantaviruses, Reservoir Hosts, and Geographic Distribution

Virus	Reservoir Host	Geographic Distribution	Clinical Syndrome
Hantaan virus	<i>Apodemus agrarius</i>	China, Korea, Russia	HFRS
Seoul virus	<i>Rattus norvegicus</i>	Worldwide urban areas	HFRS
Puumala virus	<i>Myodes glareolus</i>	Northern and Central Europe	Nephropathia epidemica
Dobrava-Belgrade virus	<i>Apodemus flavicollis</i>	Balkans, Eastern Europe	Severe HFRS
Sin Nombre virus	<i>Peromyscus maniculatus</i>	USA, Canada	HCPS
Andes virus	<i>Oligoryzomys longicaudatus</i>	Argentina, Chile	HCPS
Araraquara virus	Wild sigmodontine rodents	Brazil	HCPS

Table.2 Continental Distribution and Epidemiological Characteristics of Hantavirus Infection

Continent	Major Viruses	Estimated Disease Burden	Predominant Syndrome
Asia	Hantaan, Seoul	>100, 000 cases annually	HFRS
Europe	Puumala, Dobrava	Thousands annually	HFRS/NE
North America	Sin Nombre	Sporadic cases	HCPS
South America	Andes, Araraquara	Hundreds annually	HCPS
Africa	Novel hantaviruses	Unknown	Under investigation

Table.3 Climatic and Environmental Drivers Associated with Hantavirus Emergence and Transmission

Driver	Mechanism	Impact on Rodent Ecology	Impact on Human Disease Risk
Increased precipitation	Enhanced vegetation growth	Increased food availability and rodent abundance	Increased exposure and outbreak risk
Elevated temperature	Extended breeding seasons	Expansion of rodent populations and habitats	Increased transmission potential
Mild winters	Improved rodent survival	Higher overwintering populations	Greater seasonal disease incidence
El Niño events	Altered rainfall and productivity	Rodent population booms	Documented outbreaks (e.g., Four Corners, USA)
Deforestation	Habitat disruption	Rodent migration toward human settlements	Increased spillover opportunities
Agricultural expansion	Increased food resources	Higher rodent density in agricultural areas	Elevated occupational exposure
Urbanization	Growth of peri-domestic rodent populations	Expansion of Norway rat habitats	Increased Seoul virus transmission
Habitat fragmentation	Changes in biodiversity	Altered reservoir-host interactions	Enhanced disease emergence risk
Climate change	Long-term environmental alteration	Shifts in geographic distribution of hosts	Expansion into new endemic regions
Extreme weather events	Ecological disturbance	Altered population dynamics and dispersal	Increased outbreak unpredictability

Table.4 One Health Interventions for Hantavirus Prevention and Control

One Health Domain	Intervention	Expected Outcome
Human Health	Early diagnosis and case reporting	Reduced morbidity and mortality
Human Health	Public health education	Improved awareness and prevention
Human Health	Occupational safety programs	Reduced exposure among high-risk groups
Animal Health	Rodent surveillance	Early detection of transmission risk
Animal Health	Reservoir mapping	Identification of emerging hotspots
Animal Health	Wildlife monitoring	Improved understanding of viral circulation
Environmental Health	Habitat management	Reduced rodent-human contact
Environmental Health	Waste management	Decreased rodent infestation
Environmental Health	Land-use planning	Reduced ecological disruption
Integrated One Health	Climate-informed surveillance	Early outbreak prediction
Integrated One Health	GIS and remote sensing	Risk mapping and targeted interventions
Integrated One Health	Intersectoral collaboration	Improved preparedness and response
Integrated One Health	Genomic surveillance	Detection of emerging strains
Integrated One Health	Research and policy integration	Sustainable disease control strategies

Consequently, prevention represents the most effective strategy for reducing disease burden (1, 3). Given the ecological nature of hantavirus transmission, prevention efforts must address multiple levels of risk, including individual behaviors, environmental management, rodent control, and community-based interventions.

Rodent Control Measures

Rodent control remains one of the most effective approaches for preventing human infection. Strategies include elimination of food sources, proper waste management, structural modifications to prevent rodent entry into buildings, and reduction of nesting sites around residential and occupational environments (57).

Integrated pest management programs combining environmental sanitation, trapping, and community education have demonstrated effectiveness in reducing rodent populations and minimizing human exposure.

Particular attention should be directed toward agricultural settings, food storage facilities, military camps, and rural communities where exposure risk is elevated (39).

Environmental Management

Environmental modifications can substantially reduce opportunities for rodent-human contact. Maintaining clean surroundings, controlling vegetation around homes, securing food supplies, and improving housing infrastructure are essential preventive measures. Community-level interventions aimed at reducing environmental conditions favorable to rodents have shown positive impacts in endemic regions (58).

Urban environments require special consideration due to the growing importance of Seoul virus transmission through Norway rat populations. Improving sanitation, waste disposal systems, and housing conditions in urban areas may significantly reduce disease risk (48).

Occupational Protection

Certain occupational groups face increased exposure risks, including farmers, forestry workers, military personnel, wildlife researchers, and construction workers. Appropriate preventive measures include use of personal protective equipment (PPE), adherence to safe cleaning procedures, avoidance of direct rodent contact,

and implementation of workplace education programs (38).

Public health agencies recommend wet-cleaning methods using disinfectants rather than dry sweeping of rodent-contaminated areas, as sweeping can generate infectious aerosols. Occupational health programs should incorporate hantavirus awareness and prevention training in high-risk regions (57).

Vaccination Efforts

Vaccination represents a potentially valuable preventive strategy, particularly in highly endemic regions. Inactivated vaccines have been developed and utilized in China and South Korea with varying levels of success (59). These vaccination programs have contributed to reductions in HFRS incidence in some populations.

However, currently available vaccines provide limited global coverage and are primarily effective against specific hantavirus species. Continued research is needed to develop broadly protective vaccines capable of addressing diverse hantavirus strains. Advances in molecular vaccine technologies, including mRNA and viral-vector platforms, may offer promising opportunities for future vaccine development (60).

Future Directions

Despite significant advances in understanding hantavirus epidemiology, several important knowledge gaps remain. Addressing these challenges will require continued interdisciplinary collaboration and investment in research, surveillance, and public health infrastructure.

Climate-Informed Predictive Modeling

Climate change is expected to remain a major driver of zoonotic disease emergence during the coming decades. Future research should focus on developing climate-informed predictive models capable of forecasting periods and regions of elevated transmission risk. Integration of meteorological data, vegetation indices, rodent surveillance information, and epidemiological records may improve outbreak prediction and facilitate timely interventions (4, 18). Machine learning approaches and artificial intelligence applications offer promising opportunities for enhancing predictive

accuracy. Such tools may enable public health authorities to allocate resources more effectively and implement preventive measures before outbreaks occur (52).

Expanded Wildlife Surveillance

The discovery of numerous novel hantaviruses in rodents, shrews, moles, and bats has expanded understanding of hantavirus diversity and evolution (32). However, the pathogenic potential of many newly identified viruses remains unknown. Expanded wildlife surveillance programs are needed to characterize reservoir populations, identify emerging pathogens, and assess spillover risks.

Long-term ecological studies examining host-pathogen interactions under changing environmental conditions will be essential for understanding future disease emergence patterns. Such investigations should be conducted within a One Health framework that integrates wildlife ecology, environmental science, and human health perspectives (61).

Strengthening Global Surveillance Networks

Many regions, particularly in Africa, Southeast Asia, and parts of Latin America, lack comprehensive hantavirus surveillance systems. Underdiagnosis and limited laboratory capacity likely contribute to substantial underestimation of disease burden. Strengthening surveillance infrastructure, expanding diagnostic capabilities, and promoting international data sharing are essential priorities (30).

The COVID-19 pandemic highlighted the importance of global preparedness for emerging zoonotic diseases. Lessons learned from pandemic surveillance systems may inform future approaches to hantavirus monitoring and outbreak response (62).

Advancing One Health Implementation

While the One Health concept has gained widespread acceptance, implementation challenges remain. Future efforts should focus on establishing sustainable mechanisms for interdisciplinary collaboration, data integration, and joint decision-making among human health, veterinary, environmental, and wildlife sectors (53).

Development of standardized One Health surveillance frameworks, harmonized reporting systems, and collaborative research networks may enhance the effectiveness of disease prevention programs. Policymakers should prioritize investments in integrated surveillance systems that address the upstream ecological drivers of zoonotic disease emergence (10).

In conclusion, Hantavirus infections remain a significant global public health challenge characterized by complex interactions among reservoir hosts, environmental conditions, and human populations. The epidemiology of these infections varies considerably across regions, reflecting differences in reservoir ecology, climatic conditions, land-use patterns, and surveillance capacity. Asia continues to account for the majority of reported HFRS cases, while HCPS remains a major concern in the Americas because of its high case-fatality rate.

Growing evidence indicates that climate change, environmental degradation, urbanization, agricultural expansion, and biodiversity loss are reshaping hantavirus transmission dynamics worldwide. These factors influence rodent population abundance, habitat distribution, and opportunities for human exposure, increasing the risk of disease emergence in both endemic and previously unaffected regions.

The One Health framework provides a comprehensive approach for understanding and addressing the multifactorial determinants of hantavirus transmission. Integration of human disease surveillance, wildlife monitoring, environmental assessment, climate forecasting, and molecular epidemiology can substantially improve outbreak prediction and prevention. Strengthening interdisciplinary collaboration among public health professionals, veterinarians, ecologists, environmental scientists, and policymakers is essential for reducing disease burden and enhancing preparedness for future outbreaks.

Future strategies should prioritize climate-informed surveillance, expanded wildlife monitoring, improved diagnostic capacity, vaccine development, and implementation of integrated One Health programs. By addressing the interconnected drivers of disease emergence, a One Health approach offers the most sustainable pathway toward reducing the global impact of hantavirus infections and improving resilience against future zoonotic threats.

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Data Availability

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethical Approval Not applicable.

Consent to Participate Not applicable.

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