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Hantavirus Surveillance and One Health Preparedness in The Philippines: A Systematic Review of Human, Animal, and Environmental Evidence

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Abstract

Hantavirus infection is an emerging zoonotic disease transmitted primarily through contact with infected rodents and contaminated environments. Occupational exposure, environmental disruption, and ecological change have increasingly contributed to hantavirus transmission worldwide. Despite favorable ecological conditions for rodent-borne disease transmission, hantavirus surveillance and diagnostic capacity remain limited in the Philippines and many tropical developing countries. This systematic review and meta-analysis aimed to synthesize available evidence regarding hantavirus exposure at the human–rodent interface, with emphasis on occupational risk factors, reservoir ecology, environmental determinants, epidemiological patterns, and public health implications relevant to the Philippines. This systematic review and meta-analysis was conducted in accordance with PRISMA 2020 guidelines and registered in PROSPERO under registration number: CRD420261395675. Literature searches were performed using PubMed, Scopus, Web of Science, Google Scholar, and grey literature sources including WHO, CDC, ECDC, and public health surveillance reports. Eligible studies included seroprevalence investigations, ecological surveillance studies, outbreak reports, occupational exposure studies, and molecular investigations involving hantavirus transmission and reservoirs. Random-effects meta-analysis was performed for studies reporting extractable prevalence data. A total of 86 studies and surveillance reports were included in the qualitative synthesis, while 29 studies were included in the meta-analysis. Occupational groups at elevated risk included forestry workers, agricultural laborers, military personnel, wildlife handlers, sanitation workers, and rodent breeders. Environmental factors such as flooding, climate variability, urbanization, deforestation, and agricultural expansion were consistently associated with increased transmission risk. Philippine studies demonstrated measurable hantavirus seropositivity among humans and identification of bat-associated Quezon virus. The pooled human hantavirus seroprevalence was 4.96% (95% CI: 2.80–8.64%), while pooled reservoir positivity was 7.59% (95% CI: 4.79–11.85%), with substantial heterogeneity observed across studies. Hantavirus infection remains an underrecognized global zoonotic threat influenced by occupational exposure, wildlife reservoirs, and environmental change. The findings highlight the need for strengthened One Health surveillance, improved diagnostic capacity, ecological monitoring, and occupational biosafety interventions, particularly in the Philippines and other resource-limited tropical settings.

Keywords: *Hantavirus, occupational exposure, zoonotic disease, rodent reservoirs, One Health, seroprevalence, Philippines.*

INTRODUCTION

Hantaviruses are zoonotic, single-stranded, negative-sense RNA viruses belonging to the genus *Orthohantavirus* within the family *Hantaviridae* [1, 2]. These viruses are primarily maintained in rodent reservoirs and are transmitted to humans through inhalation of aerosolized excreta, including urine, saliva, and feces from infected rodents [3]. Human infection with hantaviruses may result in severe clinical syndromes, mainly Hemorrhagic Fever with Renal Syndrome (HFRS), predominantly reported in Europe and Asia, and Hantavirus Pulmonary Syndrome (HPS), which is more common in the Americas [4, 5].

The disease is characterized by endothelial dysfunction, capillary leakage, thrombocytopenia, and multi-organ involvement, often leading to significant morbidity and mortality [6, 7]. The diversity of hantavirus species, their rodent hosts, and regional epidemiological patterns has made hantavirus infection an important emerging public health concern worldwide [8, 9]. Recent global analyses have demonstrated continued expansion of hantavirus surveillance activities and increasing recognition of hantavirus-associated disease burden in both endemic and previously underrecognized regions [10, 11].

Hantaviruses are classified based on their phylogenetic relationships, geographic distribution, and associated rodent reservoirs [12, 13]. Old World hantaviruses, such as Hantaan virus, Seoul virus, Puumala virus, and Dobrava-Belgrade virus, are commonly associated with HFRS, whereas New World hantaviruses, including Sin Nombre virus and Andes virus, are linked to HPS [14, 15] Each hantavirus species demonstrates host specificity, with transmission dynamics strongly influenced by ecological and environmental conditions affecting rodent populations [16]. Assessment and diagnosis of hantavirus infection involve serological methods such as enzyme-linked immunosorbent assay (ELISA), immunofluorescence assay (IFA), and immunoblotting, as well as molecular techniques including reverse transcription polymerase chain reaction (RT-PCR) for viral RNA detection [18 - 20]. In epidemiological studies, occupational exposure is commonly assessed using seroprevalence surveys, environmental risk assessments, rodent surveillance, and structured exposure questionnaires focusing on contact with rodents or contaminated environments [21].

At the population level, hantavirus infection represents a significant occupational and environmental health threat, particularly among populations with frequent exposure to rodents or rodent-infested environments [1]. Agricultural workers, forestry personnel, military recruits, miners, waste handlers, and laboratory workers are among the groups at elevated risk of infection [22]. Rapid urbanization, deforestation, agricultural expansion, climate variability, and poor sanitation practices have increased human–rodent interactions thereby facilitating zoonotic spillover events [23, 24]. Global outbreaks have demonstrated that hantavirus infections can emerge unexpectedly and may impose considerable healthcare and economic burdens due to high hospitalization rates and case fatality ratios [1]. The increasing convergence of human, animal, and environmental health challenges has reinforced the importance of One Health approaches for surveillance and prevention of rodent-borne zoonotic diseases [25]. Furthermore, climate-driven changes in rodent population dynamics have been associated with increased transmission potential, making hantavirus surveillance increasingly important within the framework of One Health and emerging infectious disease preparedness [11].

In Southeast Asia, hantavirus infections remain underrecognized despite ecological conditions favorable for rodent-borne disease transmission. Similar concerns have been reported throughout Southeast Asia, where rapid urbanization, agricultural intensification, and climate-related environmental change have increased opportunities for rodent-borne zoonotic transmission. [11, 26]. The Philippines, an archipelagic country with extensive agricultural activities, tropical climate conditions, dense urban settlements, and recurrent flooding events, presents multiple environmental and occupational factors that may promote hantavirus circulation [27, 28]. Rodent infestation remains a persistent challenge in urban slums, public markets, agricultural farms, and rural communities across the country [32, 34]. Previous studies in the Philippines have reported evidence of rodent-borne viral pathogens, including hantaviruses and related zoonoses, among both rodent populations and humans exposed to contaminated environments [35, 36]. Occupational groups such as rice farmers, market workers, sanitation personnel, sewer workers, and informal waste collectors may experience repeated exposure to rodent reservoirs without adequate awareness or protective measures [33, 37]. However, routine hantavirus surveillance and diagnostic capacity remain limited in many Philippine healthcare and public health institutions, leading to possible underdiagnosis and underreporting of infections [36, 38, 39].

Although several international studies have examined hantavirus epidemiology, transmission dynamics, and occupational risk factors, important gaps remain in the literature [31]. Existing studies are highly heterogeneous with respect to geographic coverage, exposure definitions, diagnostic methods, and occupational categories assessed [31, 39]. Few systematic reviews have specifically synthesized evidence regarding occupational exposure at the human–rodent interface, particularly within low- and middle-income countries where surveillance systems are limited [35]. There is insufficient integration of findings relevant to tropical developing nations such as the Philippines, where ecological and socioeconomic conditions differ substantially from those in temperate regions where most hantavirus research has been conducted [11]. The lack of pooled prevalence estimates and comparative evaluation of occupational risk factors limits evidence-based policymaking and targeted prevention strategies for vulnerable populations [40].

Given these surveillance gaps and the increasing importance of occupational and environmental zoonotic exposure, a comprehensive synthesis of hantavirus transmission at the human–rodent interface is necessary to inform future surveillance and public health preparedness, particularly in tropical developing settings such as the Philippines.

Aim of the Study

This study aims to systematically synthesize and critically evaluate all available evidence regarding hantavirus exposure at the human–rodent interface, particularly occupational and environmental exposure pathways, diagnostic approaches, epidemiological patterns, and public health implications, with specific relevance to the Philippines and other resource-limited settings.

Specific Objectives

1. To identify and summarize all available published evidence and reliable sources relating to hantavirus exposure, infection, transmission, and occupational risk factors at the human–rodent interface.
2. To describe the occupational, environmental, and behavioral factors associated with hantavirus exposure and infection among human populations.
3. To examine the diagnostic and surveillance methods used in detecting hantavirus infections across different settings.
4. To summarize reported prevalence, seropositivity, clinical presentations, and epidemiological trends of hantavirus infection where quantitative data are available.
5. To assess the relevance of existing evidence to the Philippine context, particularly regarding zoonotic surveillance, occupational health, rodent exposure, and emerging infectious disease preparedness.
6. To identify gaps in current literature and propose recommendations for future research, surveillance systems, and public health interventions in the Philippines.

METHODOLOGY

Study Design and Review Framework

This study employed a systematic review and meta-analysis design to synthesize evidence regarding hantavirus transmission at the human–rodent interface, with particular emphasis on occupational exposure, environmental determinants, reservoir ecology, and public health implications relevant to the Philippines. The review was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) guidelines [65]. The review protocol was registered in the International Prospective Register of Systematic Reviews (PROSPERO) under registration number: CRD420261395675. A One Health framework guided the review process by integrating evidence across human, animal, and environmental domains, particularly focusing on ecological and occupational interfaces that facilitate hantavirus transmission, including agricultural work, forestry activities, wildlife handling, urban rodent exposure, and environmental disruption associated with flooding, urbanization, and land-use change.

Search Strategy

A comprehensive literature search was conducted using multiple electronic databases, including PubMed, Scopus, Web of Science, and Google Scholar. Additional literature and preprints were identified through manual reference screening, institutional repositories, and supplementary searches of ResearchGate. Grey literature sources included reports from the World Health Organization (WHO), Centers for Disease Control and Prevention (CDC), European Centre for Disease Prevention and Control (ECDC), and national public health agencies. The search strategy combined controlled vocabulary terms and keywords related to hantavirus infection, occupational exposure, zoonotic transmission, rodent reservoirs, environmental risk factors, and human–animal interfaces.

Example search terms included: ("Hantavirus" OR "Orthohantavirus") AND ("occupational exposure" OR "human–rodent interface" OR "zoonotic transmission") AND ("seroprevalence" OR "reservoir surveillance" OR "public health"). The literature search covered studies published from database inception until May, 2026. Searches were limited to English-language studies where translation was unavailable, and reference lists of eligible articles were manually screened to identify additional relevant studies.

Eligibility Criteria

Studies were considered eligible if they reported data related to hantavirus exposure, transmission, seroprevalence, occupational risk, reservoir surveillance, ecological determinants, outbreak investigations, or public health implications. Both human and animal studies were included when they contributed relevant epidemiological or ecological evidence regarding hantavirus circulation at the human–rodent interface. Eligible study designs included cross-sectional studies, cohort studies, case-control studies, outbreak investigations, ecological surveillance studies, molecular surveillance studies, seroprevalence investigations, and systematic reviews providing extractable epidemiological data. Because peer-reviewed evidence regarding hantavirus surveillance in the Philippines and several tropical regions remained limited, selected public health advisories, surveillance bulletins, outbreak reports, and epidemiologically relevant grey literature were also included when they provided contextual or surveillance information not sufficiently represented in the scientific literature. However, non-peer-reviewed sources were used primarily for narrative synthesis and were excluded from quantitative pooling unless extractable primary epidemiological data were available. Studies were excluded if they lacked relevance to hantavirus epidemiology or occupational exposure, contained insufficient methodological or epidemiological data, represented duplicate publications, were editorials or opinion pieces without primary data, or lacked accessible full text.

Study Selection

All identified records were exported into a screening database, and duplicate records were removed prior to screening. Title and abstract screening were conducted independently according to predefined eligibility criteria, and potentially relevant studies subsequently underwent full-text review for final inclusion. A total of 1,344 records were identified through database searching and grey literature retrieval. After removal of 318 duplicate records, 1,026 studies underwent title and abstract screening. Of these, 826 records were excluded because of lack of relevance to hantavirus exposure, occupational risk, or epidemiological outcomes. Full-text assessment was conducted for 200 articles and reports, of which 114 were excluded because of insufficient epidemiological data, lack of relevance to human exposure, duplicate reporting, inaccessible full texts, or inadequate methodological detail.

Ultimately, 86 studies and surveillance reports were included in the qualitative synthesis, while 29 studies with extractable quantitative prevalence data were included in the meta-analysis. The study selection process was summarized using the PRISMA 2020 flow diagram.

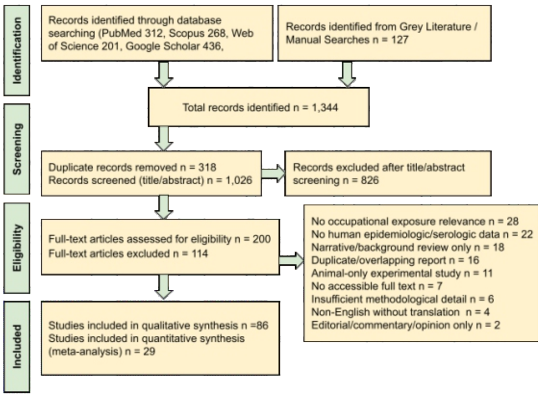

Figure 1: PRISMA 2020 Flow Diagram of Study Selection

Data Extraction

Data extraction was performed using a standardized extraction form developed for this review. Extracted variables included author and publication year, country and geographic setting, study population or reservoir species, occupational exposure category, study design, diagnostic methods, prevalence estimates, environmental or ecological risk factors, clinical manifestations, and key epidemiological findings. For quantitative synthesis, studies reporting extractable numerator and denominator data for hantavirus seroprevalence or reservoir positivity were included in the meta-analysis dataset. Human seroprevalence studies and reservoir surveillance studies were analyzed separately because they represented distinct epidemiological populations and outcomes.

Quality Assessment and Risk of Bias

Methodological quality assessment was conducted using the Joanna Briggs Institute (JBI) Critical Appraisal Tools for prevalence, cross-sectional, and observational studies, while the Newcastle–Ottawa Scale (NOS) was applied to cohort and case-control studies where appropriate. Risk-of-bias assessment focused on sampling methods, diagnostic validity, exposure assessment, reporting completeness, and representativeness of study populations. Rather than excluding studies solely because of methodological limitations, the review adopted a contextual appraisal approach appropriate for emerging zoonotic diseases and surveillance-limited regions. Public health reports and outbreak investigations were interpreted cautiously and were primarily used to support narrative synthesis rather than pooled quantitative estimates.

Statistical Analysis and Meta-analysis

Quantitative synthesis was conducted for studies reporting extractable prevalence data. Random-effects meta-analysis models were used to estimate pooled hantavirus seroprevalence and reservoir positivity with corresponding 95% confidence intervals because substantial heterogeneity across studies was anticipated. Human seroprevalence studies and animal reservoir studies were pooled separately to preserve epidemiological interpretability. Statistical heterogeneity was assessed using the I^2 statistic, and forest plots were generated to visualize prevalence estimates and pooled outcomes. Studies lacking sufficient numerator or denominator data were excluded from quantitative pooling but retained in the narrative synthesis. Quantitative synthesis was conducted using a random-effects inverse variance approach to estimate pooled prevalence and corresponding 95% confidence intervals.

Ethical Considerations

This study involved secondary analysis of previously published literature and publicly available surveillance data, formal ethical approval and informed consent were not required. Nonetheless, principles of responsible scientific reporting, transparency, and accurate citation of original sources were maintained throughout the review process.

RESULTS

Study Selection

A total of 1,344 records were identified through database searching and grey literature retrieval. After removal of 318 duplicate records, 1,026 studies underwent title and abstract screening. Of these, 826 records were excluded because they lacked relevance to hantavirus exposure, occupational risk, or epidemiological outcomes. Full-text assessment was conducted for 200 articles and reports, of which 114 were excluded because of insufficient epidemiological data, lack of relevance to human exposure, duplicate reporting, inaccessible full texts, or inadequate methodological detail. Ultimately, 86 studies and surveillance reports were included in the qualitative synthesis, while 29 studies with extractable quantitative prevalence data were included in the meta-analysis. The study selection process is summarized in the PRISMA 2020 flow diagram.

Study Characteristics and Evidence Sources

The included literature comprised a broad range of evidence sources investigating hantavirus exposure, transmission dynamics, reservoir ecology, occupational risk, environmental determinants, surveillance gaps, and public health implications at the human–rodent interface. Included studies consisted of cross-sectional seroprevalence investigations, ecological and molecular surveillance studies, outbreak investigations, occupational health studies, systematic reviews, meta-analyses, public health surveillance reports, and narrative reviews originating from Asia, Europe, Africa, North America, and South America. Evidence sources included both peer-reviewed scientific publications and surveillance reports from international organizations such as the World Health Organization (WHO), European Centre for Disease Prevention and Control (ECDC), Centers for Disease Control and Prevention

(CDC), Africa Centres for Disease Control and Prevention, and regional public health agencies. Major themes identified across the literature included occupational exposure, rodent and bat reservoir ecology, environmental and climatic determinants of transmission, zoonotic spillover risks, diagnostic approaches, surveillance limitations, and emerging evidence of limited human-to-human transmission associated with Andes virus.

Evidence of Hantavirus Circulation in the Philippines

Available evidence demonstrated that hantavirus exposure and circulation occur in the Philippines despite the absence of extensive national surveillance systems. [39] conducted one of the earliest seroepidemiologic studies in the country and reported a 6.1% hantavirus seropositivity rate among asymptomatic individuals sampled from rural, urban, and urban-poor communities across Luzon, Visayas, Mindanao, Metro Manila, and Metro Cebu. Seropositivity did not significantly differ according to sex, age, or residence type, suggesting widespread but underrecognized exposure within the Philippine population. The authors emphasized that hantavirus infection likely exists in both urban and rural settings and recommended improved rodent surveillance, RT-PCR testing, and validation of diagnostic assays within the country. [36] further highlighted that hantavirus infections remain likely underdiagnosed in the Philippines because clinical manifestations overlap substantially with leptospirosis, dengue fever, and other tropical febrile illnesses. The review additionally referenced historical serologic evidence from San Lazaro Hospital and emphasized limited national diagnostic capacity and surveillance preparedness.

Molecular surveillance studies additionally demonstrated the presence of hantavirus-associated wildlife reservoirs in the Philippines. [31] identified Quezon virus (QZNV), a genetically distinct bat-borne hantavirus, in Geoffroy's rousette bats captured in Quezon Memorial National Park using RT-PCR and phylogenetic analysis. [30] later reviewed expanding evidence of bat-associated hantaviruses globally and emphasized the evolutionary significance of Philippine Quezon virus among bat-borne hantaviruses identified across Asia. These findings suggested that hantavirus reservoirs in the Philippines extend beyond rodents and may involve ecologically diverse wildlife hosts contributing to zoonotic emergence and viral evolution.

Several contemporary Philippine public health reports also documented national surveillance concerns associated with the multinational MV *Hondius* outbreak involving Filipino crew members. Reports from [41 - 44] emphasized that no officially confirmed domestic hantavirus cases had recently been recorded in the Philippines while simultaneously highlighting gaps in surveillance systems, diagnostic preparedness, occupational protection for maritime workers, and public awareness regarding emerging zoonotic infections.

Occupational Exposure at the Human–Rodent Interface

Numerous studies identified occupational exposure as a major determinant of hantavirus transmission risk. Forestry workers, agricultural laborers, military personnel, rodent breeders, sanitation workers, wildlife farmers, environmental consultants, and outdoor laborers consistently demonstrated elevated exposure risk because of frequent contact with rodent-infested environments and contaminated materials. Forestry-related occupational seroprevalence studies conducted in Poland, Hungary, and France demonstrated measurable hantavirus exposure among workers operating in forest ecosystems. [45] reported a 3% seropositivity rate among forestry workers in Poland, while [46] documented regional seroprevalence variations among Hungarian forestry workers associated with environmental rodent exposure. [47] similarly identified significant hantavirus seropositivity among forestry workers in France, particularly in endemic northeastern regions associated with bank vole populations.

Military personnel and field workers also represented important occupationally exposed populations. [48] demonstrated elevated hemorrhagic fever with renal syndrome (HFRS) risk among military trainees operating near the Korean Demilitarized Zone, where high hantavirus seropositivity was observed among rodent reservoirs inhabiting troop maneuver areas and military structures. [49] further documented occupational acquisition of hantavirus pulmonary syndrome (HPS) in a utility company worker in the United States following exposure to infected rodents at a worksite. [50] reported that agricultural workers, ranchers, forestry workers, cleaners, and wildlife handlers represented major occupational risk groups among 662 laboratory-confirmed HPS cases in the United States.

Wildlife farming and rodent breeding environments were also strongly associated with hantavirus exposure. [51] reported hantavirus IgG seroprevalence among wildlife farmers in Vietnam and identified wildlife farming itself as a significant occupational risk factor. [52] similarly identified hantavirus seropositivity among humans and rodents linked to wet market and rodent trade environments in Vietnam. Recurrent occupational Seoul virus infections among feeder rodent breeding farm workers in Taiwan were documented by [53] and the [4], both of which emphasized that contaminated bedding, infected feeder rats, and inadequate biosafety practices contributed to zoonotic transmission. Occupational exposure pathways involving rodent handling, contaminated aerosols, scratches, bites, and environmental contamination were repeatedly highlighted across the literature.

Environmental and Ecological Drivers of Transmission

Recent global assessments have further identified anthropogenic environmental change and biodiversity loss as key drivers of emerging zoonotic disease transmission [54].

Environmental disruption, climate variability, urbanization, agricultural expansion, biodiversity alteration, and flooding were consistently identified as important ecological drivers of hantavirus transmission. Several studies demonstrated that climatic fluctuations directly influence rodent reservoir abundance, viral persistence, and opportunities for human exposure. [55] identified positive associations between increased rainfall, warmer temperatures, and hantavirus outbreaks in Argentina, particularly among rural agricultural workers. [17] demonstrated cyclical Hantaan virus outbreaks in China linked to temperature and rainfall patterns affecting rodent population dynamics over a 54-year period. [16] further emphasized that climate variability, vegetation productivity, biodiversity changes, and agricultural activities collectively shape hantavirus spillover risk through their effects on rodent ecology and human exposure.

Agricultural expansion and habitat modification also contributed substantially to hantavirus emergence. [56] demonstrated that sugarcane expansion and climate change increased projected hantavirus cardiopulmonary syndrome (HCPS) risk in Brazil by promoting rodent reservoir proliferation and increased human–rodent interaction. [57] identified associations between HCPS occurrence and altered landscape configurations involving pastureland and forest fragmentation. [58] similarly reported that land-use modification, agricultural intensification, and biodiversity changes significantly influenced hantavirus reservoir distribution and human vulnerability in Brazil. [59] further emphasized that urbanization, deforestation, environmental stressors, and poor sanitation may increase rodent persistence and zoonotic spillover risk by intensifying human–rodent overlap.

Rodent and Bat Reservoir Surveillance

Rodent surveillance studies consistently demonstrated widespread hantavirus circulation among multiple rodent reservoir species across Asia, Europe, Africa, and the Americas. [60] documented active hantavirus circulation among urban rodents in Singapore, particularly *Rattus norvegicus*. [61] identified hantavirus antibodies and molecular evidence of Seoul virus and Thailand virus circulation among rodents in Cambodia, Lao PDR, and Thailand. [62] demonstrated circulation of multiple hantavirus strains among rodents captured from agricultural and peri-domestic environments in South Korea, while [63] documented hantavirus seropositivity among rodents inhabiting rice fields and domestic areas in Thailand. Similar findings were reported in Indonesia, Venezuela, Argentina, Germany, Egypt, and Canada, where rodent surveillance identified persistent circulation of pathogenic hantaviruses associated with occupational and environmental exposure risk.

Expanding evidence additionally demonstrated that bats may serve as important alternative hantavirus reservoirs. Bat-associated hantaviruses including Quezon virus, Robina virus, Kiwira virus, Brno virus, and Sarawak mobatvirus were identified in studies from the Philippines, Australia, Africa, Europe, and Southeast Asia.

Molecular and phylogenetic investigations by [31, 64, 66 - 69] demonstrated that bat-borne hantaviruses form genetically distinct evolutionary lineages within the family *Hantaviridae*. These studies collectively suggested that bats may represent ancient or alternative hantavirus reservoir hosts with potential zoonotic significance. Despite uncertainty regarding the human pathogenicity of many bat-associated hantaviruses, the findings emphasized the importance of continued ecological surveillance, wildlife monitoring, and One Health investigations in understanding hantavirus evolution and spillover risk.

Human Seroprevalence and Epidemiological Findings

Human seroprevalence studies demonstrated substantial geographic variability in hantavirus exposure across both endemic and non-endemic regions. [10] conducted a global systematic review and meta-analysis involving over 81,000 participants and estimated an overall hantavirus seroprevalence of 2.93%, with the highest regional prevalence observed in Asia (6.84%). Studies from Southeast Asia, Africa, Europe, and South America similarly demonstrated evidence of asymptomatic or underrecognized hantavirus exposure among both general and occupational populations. Seroprevalence estimates included 6.1% in the Philippines [39], 10.0% in Cambodia [70], 8.1% in urban Kenya [71], 1.7% in Venezuela [72], and 12.2% in Egypt [73].

Multiple studies emphasized that hantavirus infections are likely substantially underdiagnosed because many infections present with mild or nonspecific febrile illnesses. [74] reported evidence of asymptomatic exposure among healthy rural and urban populations in Chile, while [75] demonstrated that serological evidence of hantavirus exposure in the Netherlands exceeded the number of clinically recognized cases. Similar concerns regarding underrecognition, diagnostic overlap with leptospirosis or dengue fever, and limited surveillance capacity were repeatedly highlighted across Southeast Asia and other resource-limited settings.

Meta-analysis of Hantavirus Seroprevalence and Reservoir Positivity

A quantitative meta-analysis was conducted for studies reporting extractable prevalence data, including the number of positive samples and total number tested. Eligible quantitative studies were grouped into human seroprevalence studies and reservoir surveillance studies. Human studies included community-based serosurveys, occupational seroprevalence studies, and high-exposure population studies, while reservoir studies included rodent, bat, and small mammal surveillance investigations. Studies without extractable numerator and denominator data, narrative reviews, public health fact sheets, outbreak news reports, and duplicate publications were excluded from quantitative pooling and retained only for narrative synthesis.

Among human studies with available extractable data, reported hantavirus seroprevalence ranged from 0% among occupational workers in the United States to 12.2% among human participants in Egypt. Philippine evidence from [39] demonstrated 28 seropositive individuals among 461 participants, corresponding to a 6.1% seroprevalence rate. Other studies reported measurable exposure in Venezuela, Chile, Kenya, Cambodia, Vietnam, South Africa, Poland, Hungary, France, and the Netherlands, suggesting that hantavirus exposure occurs across diverse ecological and occupational settings despite substantial geographic variability in prevalence estimates and diagnostic approaches.

The pooled human hantavirus seroprevalence estimate derived from confirmed studies was 4.96% (95% CI: 2.80 – 8.64%), with substantial heterogeneity observed across included studies (I^2 = 96.3%). Reservoir surveillance studies demonstrated a pooled positivity estimate of 7.59% (95% CI: 4.79–11.85%), likewise with considerable heterogeneity (I^2 = 95.7%). High heterogeneity likely reflected major differences in ecological settings, occupational exposure profiles, reservoir species, diagnostic methodologies, and study populations across included studies. Consequently, pooled prevalence estimates were interpreted cautiously and considered broad indicators of hantavirus exposure rather than precise epidemiological measurements.

Among reservoir studies, hantavirus positivity was reported across rodents, bats, and other small mammals. Philippine bat surveillance identified Quezon virus in 1 of 376 bats sampled, while studies from South Korea, Singapore, Thailand, Indonesia, Egypt, Argentina, Chile, Malaysia, Zambia, Australia, and Central Europe reported variable positivity among rodents and bats. Reservoir positivity estimates varied widely according to reservoir species, ecological setting, sampling intensity, and diagnostic approach. Human seroprevalence and reservoir positivity were therefore interpreted separately because they represented biologically and epidemiologically distinct outcomes.

Clinical Manifestations and Diagnostic Findings

Clinical manifestations of hantavirus infection ranged from mild febrile illness to severe pulmonary and renal syndromes with high fatality rates. The two principal clinical syndromes consistently described across studies were hantavirus pulmonary syndrome/hantavirus cardiopulmonary syndrome (HPS/HCPS) and hemorrhagic fever with renal syndrome (HFRS). Common manifestations included fever, headache, myalgia, thrombocytopenia, gastrointestinal symptoms, respiratory distress, pulmonary edema, renal dysfunction, hemorrhage, and shock. [76] demonstrated that severe HPS is characterized by diffuse endothelial dysfunction, pulmonary edema, and vascular leakage. [77 - 79] further emphasized that disease severity varies substantially according to viral strain and host immune response.

Diagnostic methods commonly used across studies included enzyme-linked immunosorbent assays (ELISA), indirect immunofluorescence assays (IFA), immunoblotting, reverse transcription polymerase chain reaction (RT-PCR), immunohistochemistry, and viral sequencing. Several studies highlighted diagnostic challenges caused by symptom overlap with leptospirosis, dengue fever, influenza-like illnesses, and acute respiratory infections. [1, 4], and [80] all emphasized that limited laboratory capacity and low clinician awareness contribute substantially to delayed diagnosis and global underreporting.

Human-to-Human Transmission and the MV *Hondius* Outbreak

Substantial attention across the reviewed literature focused on the 2026 multinational MV *Hondius* outbreak associated with Andes hantavirus infection. Reports from [1, 81, 82, 102] and multiple international public health agencies documented confirmed and suspected cases of hantavirus pulmonary syndrome among passengers and crew members aboard the cruise ship following travel in Argentina and surrounding endemic regions. The outbreak resulted in several deaths, intensive care admissions, international medical evacuations, quarantine procedures, and coordinated multinational public health responses.

The outbreak was particularly significant because Andes virus remains the only hantavirus strain with documented limited human-to-human transmission. Several reports suggested that prolonged close contact among passengers sharing confined spaces aboard the vessel may have contributed to secondary transmission following initial rodent-associated exposure in South America. WHO, ECDC, LSHTM, Science Media Centre experts, and UKHSA consistently emphasized that although human-to-human transmission is biologically plausible for Andes virus, sustained community transmission remains unlikely because spread typically requires prolonged close exposure. Nevertheless, the outbreak highlighted major challenges related to international travel, delayed contact tracing, prolonged incubation periods, quarantine logistics, occupational maritime exposure, and outbreak preparedness within confined environments.

Surveillance Gaps and Public Health Implications

Across the reviewed literature, major surveillance and public health gaps were repeatedly identified. Multiple studies emphasized limited diagnostic capacity, insufficient ecological surveillance, underrecognition of asymptomatic infections, inadequate rodent monitoring systems, and lack of clinician awareness, particularly in tropical and resource-limited countries. [13, 80, 98 - 100] all stressed the need for integrated One Health surveillance systems combining human, animal, and environmental monitoring. Occupational protection measures, rodent control programs, environmental sanitation, climate-informed outbreak forecasting, and strengthened laboratory infrastructure were repeatedly recommended as critical strategies for reducing hantavirus transmission risk.

The Philippine context demonstrated particularly important surveillance gaps. Existing evidence suggested probable underdiagnosis despite measurable seroprevalence and documented wildlife reservoirs. Occupational exposure among farmers, market workers, sanitation personnel, maritime workers, and communities exposed to rodent-infested environments may represent an underrecognized public health concern. The reviewed studies collectively emphasized the urgent need for strengthened zoonotic disease surveillance, improved laboratory diagnostics, ecological monitoring, public health education, and preparedness planning within the Philippines and similar tropical developing settings.

DISCUSSION

This systematic review and meta-analysis synthesized global evidence regarding hantavirus transmission at the human–rodent interface, with particular emphasis on occupational exposure and implications for the Philippines. The findings demonstrated that hantavirus infection remains an important but frequently underrecognized zoonotic disease associated with rodent reservoirs, environmental disruption, occupational exposure, and ecological change. Across the reviewed literature, evidence consistently indicated that individuals working in rodent-infested environments, including forestry workers, agricultural laborers, military personnel, wildlife farmers, sanitation workers, and maritime workers, experience elevated risk of hantavirus exposure because of frequent interaction with contaminated environments, rodent excreta, and aerosolized viral particles [40, 45 - 48, 50, 51, 53]. These findings support previous systematic reviews identifying occupational activities as major drivers of hantavirus spillover and highlight the importance of occupational biosafety interventions, environmental sanitation, and rodent control measures in reducing disease transmission risk [40, 101].

The review additionally demonstrated substantial geographic variability in hantavirus exposure, reflecting ecological differences in reservoir host distribution, environmental conditions, occupational practices, and surveillance capacity. Studies from Asia, South America, Africa, and Europe consistently reported measurable seroprevalence among both occupational and community populations, suggesting that asymptomatic or undiagnosed infections may be considerably more common than previously recognized [39, 70 - 74]. The estimated global seroprevalence reported by [10], together with documented serological evidence from the Philippines, Cambodia, Kenya, Egypt, and South America, supports the hypothesis that hantavirus infection remains underdiagnosed in many tropical and resource-limited settings [10]. Clinical overlap with dengue fever, leptospirosis, influenza-like illnesses, and other febrile diseases further complicates accurate diagnosis, particularly in countries with limited molecular diagnostic capacity and fragmented surveillance systems [36, 77, 79]. These findings are especially relevant in the Philippine setting, where zoonotic febrile illnesses remain common and hantavirus testing is not routinely integrated into differential diagnostic protocols.

An important contribution of this review is the identification of evidence supporting possible hantavirus circulation within the Philippines despite the absence of widespread confirmed case reporting. The seroepidemiological findings of [39], demonstrating a 6.1% seropositivity rate among asymptomatic Filipinos, strongly suggest prior exposure within both urban and rural communities. Furthermore, molecular identification of Quezon virus in Philippine bats by [31] expanded the ecological understanding of hantavirus reservoirs in the country and highlighted the potential role of wildlife diversity in viral evolution and zoonotic emergence. These findings align with growing global evidence suggesting that bats may serve as important ancestral or alternative hantavirus reservoirs in addition to rodents [30, 64, 66, 67]. The ecological diversity of the Philippines, combined with dense urbanization, poor waste management, tropical climate variability, and high rodent exposure in agricultural and informal settlements, may create favorable conditions for zoonotic spillover and undetected viral circulation [28, 35, 37].

Environmental and ecological drivers emerged as major determinants of hantavirus transmission dynamics across the reviewed literature. Climate variability, deforestation, agricultural intensification, habitat fragmentation, flooding, and urban expansion were repeatedly associated with increased rodent population density and enhanced human–rodent interaction [16, 17, 24, 55, 56, 57]. Studies from Argentina, Brazil, China, and Southeast Asia demonstrated that rainfall patterns, temperature variability, and land-use changes directly influence reservoir ecology and outbreak occurrence [17, 55, 58]. These findings are particularly concerning in the Philippine context because the country remains highly vulnerable to climate change, typhoons, flooding, and rapid environmental transformation [27, 28]. Recent international assessments have projected that climate change may substantially alter the distribution and abundance of rodent reservoirs, increasing future spillover opportunities in tropical regions [29]. Increased flooding and poor sanitation following natural disasters may facilitate rodent displacement into human settlements and increase opportunities for zoonotic transmission. Consequently, integrating ecological surveillance and climate-informed outbreak preparedness into national public health planning may be critical for future prevention strategies.

Another major finding of this review was the growing recognition of bats as potential hantavirus reservoirs. Historically, hantavirus ecology focused primarily on rodent hosts; however, multiple molecular studies identified genetically divergent hantaviruses among bat populations in the Philippines, Africa, Europe, Australia, and Southeast Asia [31, 64, 66 - 69, 95]. Although the zoonotic potential of many bat-associated hantaviruses remains uncertain, phylogenetic evidence suggests complex evolutionary relationships within the family *Hantaviridae* [30].

The identification of Quezon virus, Robina virus, Kiwira virus, Brno virus, and related mobatviruses supports the hypothesis that hantavirus diversity may be considerably broader than previously understood. These findings reinforce the importance of One Health approaches integrating wildlife ecology, veterinary surveillance, environmental monitoring, and human public health systems in understanding zoonotic disease emergence [96, 97]. The operationalization of One Health surveillance systems has been increasingly advocated by international organizations as a critical strategy for strengthening preparedness against emerging zoonotic diseases [98]

The review additionally highlighted the epidemiological significance of the multinational MV *Hondius* outbreak linked to Andes hantavirus infection in 2026. Reports from WHO, ECDC, UKHSA, and multiple international surveillance agencies documented confirmed and suspected hantavirus cases among passengers and crew members following travel in South America [13, 81, 82, 83]. The outbreak resulted in fatalities, severe respiratory illness, intensive care admissions, quarantine procedures, and multinational public health coordination efforts [84, 85, 86]. Several reports suggested that prolonged close contact aboard the vessel may have facilitated secondary transmission among passengers and crew members after initial rodent-associated exposure in endemic areas [87, 88]. The outbreak was epidemiologically significant because the Andes virus remains the only hantavirus with documented evidence of limited human-to-human transmission [89, 90]. International health agencies consistently emphasized that sustained community transmission remains unlikely because transmission generally requires prolonged close exposure. Nevertheless, the outbreak highlighted important public health concerns involving global travel, maritime occupational exposure, quarantine logistics, international contact tracing, and zoonotic outbreak preparedness within confined environments such as cruise ships.

The findings of this review have important implications for occupational health policy and zoonotic disease preparedness. Occupational exposure studies consistently identified inadequate biosafety practices, poor environmental sanitation, rodent infestation, and limited awareness regarding zoonotic transmission as major contributors to infection risk [49, 91 - 93]. High-risk occupational groups frequently lacked adequate protective equipment, training, and environmental controls. In low- and middle-income countries such as the Philippines, occupational exposure may be further intensified by informal labor conditions, overcrowded housing, insufficient waste management systems, and limited occupational health infrastructure [32, 33]. Strengthening workplace biosafety protocols, implementing rodent control programs, promoting environmental sanitation, and improving public awareness regarding zoonotic disease prevention may therefore represent essential strategies for reducing transmission risk among vulnerable populations.

This review also identified substantial surveillance and diagnostic gaps that likely contribute to underrecognition of hantavirus infections globally. Many studies emphasized insufficient clinician awareness, limited access to molecular diagnostics, inadequate ecological surveillance, and weak integration between veterinary and public health systems [3, 15, 20, 94]. In the Philippines, routine hantavirus testing remains uncommon despite evidence of rodent infestation, climate-related flooding, occupational exposure, and measurable seroprevalence [36, 39]. The absence of confirmed large-scale outbreaks may therefore reflect diagnostic limitations rather than true absence of disease. Expanding laboratory capacity, integrating hantavirus testing into febrile illness investigations, and strengthening national zoonotic disease surveillance systems may improve early detection and outbreak preparedness [13, 98, 99].

Several limitations should be acknowledged in this review. First, heterogeneity among included studies regarding diagnostic methods, serological assays, ecological settings, and study populations may limit direct comparability of prevalence estimates. Second, many included outbreak reports and surveillance documents originated from grey literature and public health agencies, introducing potential variability in methodological rigor and reporting quality. Third, substantial geographic disparities in surveillance infrastructure likely contributed to underrepresentation of data from low-resource countries, including the Philippines. Fourth, some ecological and molecular studies focused primarily on reservoir surveillance rather than direct human epidemiological outcomes. Finally, because hantavirus remains relatively neglected in many tropical settings, publication bias and underreporting of mild or asymptomatic cases remain likely. Despite these limitations, the review provides one of the most comprehensive syntheses to date regarding occupational hantavirus exposure and the human–rodent interface with specific relevance to Philippine public health.

The evidence synthesized in this review demonstrates that hantavirus infection remains an emerging global zoonotic threat shaped by occupational exposure, environmental disruption, climate variability, wildlife ecology, and surveillance limitations. The Philippines appears to possess several ecological and occupational conditions favorable for hantavirus transmission despite limited confirmed case reporting. Strengthening integrated One Health surveillance systems, improving diagnostic capacity, expanding ecological monitoring, and enhancing occupational biosafety programs may therefore be critical for mitigating future zoonotic spillover and improving public health preparedness. Continued interdisciplinary research involving epidemiology, wildlife ecology, environmental science, occupational health, and infectious disease surveillance will be essential for understanding the evolving dynamics of hantavirus transmission in both the Philippines and the broader global context [3, 5, 15].

CONCLUSION

This systematic review and meta-analysis demonstrated that hantavirus infection represents an important emerging zoonotic disease closely associated with occupational exposure, rodent and wildlife reservoirs, environmental disruption, and ecological change. Evidence synthesized across human seroprevalence studies, ecological surveillance investigations, outbreak reports, and occupational exposure studies consistently identified increased risk of hantavirus exposure among individuals working in rodent-infested or environmentally disrupted settings including forestry workers, agricultural laborers, wildlife farmers, military personnel, sanitation workers, and maritime workers experience elevated risks of hantavirus exposure and transmission. The findings further emphasized the significant influence of climate variability, flooding, urbanization, habitat fragmentation, agricultural intensification, and biodiversity alteration, which contribute substantially.

The review additionally identified evidence supporting possible hantavirus circulation within the Philippines despite the absence of extensive confirmed case reporting. Serological evidence among asymptomatic Filipinos, together with molecular identification of Quezon virus in Philippine bats, suggests that hantavirus exposure and ecologically diverse wildlife reservoirs may already exist within the country. These findings are particularly relevant given the Philippines' vulnerability to flooding, rapid urbanization, poor waste management, rodent infestation, and climate-related environmental disruption, all of which may facilitate increased human–rodent interaction and underrecognized zoonotic transmission.

The growing recognition of bats as potential hantavirus reservoirs further expands current understanding of hantavirus ecology and reinforces the importance of integrated One Health approaches combining human, animal, and environmental surveillance. Furthermore, the multinational MV *Hondius* outbreak emphasized the continued global relevance of hantavirus outbreaks, particularly in relation to international travel, confined occupational settings, delayed diagnosis, and limited human-to-human transmission associated with Andes virus.

Despite limitations related to heterogeneity, surveillance variability, and underreporting, the findings of this review collectively demonstrate that hantavirus infection remains a significant emerging public health concern requiring strengthened occupational health protection, ecological surveillance, diagnostic preparedness, and interdisciplinary research. Expanding laboratory capacity, integrating hantavirus testing into febrile illness investigations, improving rodent and wildlife monitoring, and strengthening climate-informed One Health surveillance systems may be essential for reducing future zoonotic spillover risk and improving outbreak preparedness in the Philippines and other vulnerable tropical settings. Continued collaboration among epidemiologists, clinicians, ecologists, veterinarians, occupational health specialists, and public health authorities will remain critical for understanding and mitigating the evolving dynamics of hantavirus transmission globally.

LIMITATIONS

Several limitations should be considered in interpreting the findings of this systematic review and meta-analysis. First, substantial heterogeneity existed among the included studies with respect to study design, diagnostic methods, serological assays, ecological settings, geographic regions, and study populations, which may limit direct comparability of prevalence estimates and pooled quantitative findings. Differences in occupational exposure categories, reservoir species, sampling strategies, and laboratory techniques likely contributed to the high heterogeneity observed across the meta-analysis.

Second, many included outbreak investigations, surveillance reports, and public health documents originated from grey literature and governmental or international health agencies, introducing potential variability in methodological rigor, reporting quality, and completeness of epidemiological data. Nevertheless, inclusion of these sources was considered necessary because peer-reviewed evidence regarding hantavirus surveillance and occupational exposure remains limited in several tropical and resource-constrained settings, including the Philippines.

Third, substantial geographic disparities in surveillance infrastructure and laboratory capacity likely contributed to underrepresentation of data from low- and middle-income countries. In the Philippines and several tropical regions, limited access to molecular diagnostics, weak ecological surveillance systems, and low clinician awareness may contribute to underdiagnosis and underreporting of hantavirus infections. Consequently, the true burden of hantavirus exposure may be underestimated in many endemic or potentially endemic settings.

Fourth, several ecological and molecular investigations focused primarily on reservoir surveillance rather than direct human epidemiological outcomes. Although these studies provided valuable insight into hantavirus diversity and wildlife reservoirs, the zoonotic pathogenicity and transmission dynamics of many newly identified bat-associated hantaviruses remain incompletely understood. Additionally, some prevalence studies lacked extractable numerator and denominator data and therefore could not be included in the quantitative synthesis.

Finally, publication bias and underrecognition of mild or asymptomatic infections remain likely because hantavirus infection may clinically overlap with leptospirosis, dengue fever, influenza-like illnesses, and other tropical febrile diseases. Despite these limitations, this review provides one of the most comprehensive syntheses to date regarding hantavirus transmission at the human–rodent interface, occupational exposure, ecological determinants, and public health implications with particular relevance to the Philippines and other vulnerable tropical settings.

RECOMMENDATIONS

Based on the findings of this systematic review and meta-analysis, several recommendations are proposed to strengthen hantavirus preparedness, surveillance, prevention, and research in the Philippines. Given the evidence of hantavirus seropositivity among Filipinos, the presence of hantavirus-associated wildlife reservoirs, increasing environmental disruption, and the country's vulnerability to rodent exposure and climate-related disasters, proactive public health interventions are warranted despite the absence of large-scale confirmed outbreaks.

The Department of Health (DOH) should strengthen national preparedness for emerging rodent-borne zoonotic diseases by integrating hantavirus into existing infectious disease surveillance and outbreak preparedness programs. Development of a national hantavirus preparedness framework under a One Health approach is recommended to facilitate coordination among human health, veterinary, environmental, and local government sectors. Surveillance systems should incorporate both human and ecological monitoring, particularly in high-risk areas such as flood-prone communities, agricultural regions, public markets, ports, urban poor settlements, and rodent-infested environments.

The DOH, Research Institute for Tropical Medicine (RITM), and regional public health laboratories should expand diagnostic capacity for hantavirus infection through the gradual integration of serologic and molecular testing methods such as ELISA, immunofluorescence assay, and RT-PCR. Because hantavirus infection may clinically resemble leptospirosis, dengue fever, influenza-like illness, and other tropical febrile diseases, clinicians should be encouraged to include hantavirus in differential diagnosis among patients presenting with compatible symptoms and a history of rodent exposure. Continuing medical education programs and clinical advisories may improve physician awareness and reduce possible underdiagnosis.

Strengthening rodent and wildlife surveillance programs is likewise recommended. Ecological monitoring involving rodents, bats, and other small mammals should be conducted in collaboration with universities, veterinary institutions, environmental agencies, and research laboratories. Periodic surveillance studies may help identify potential reservoir species, geographic hotspots, and environmental conditions associated with viral circulation. Because the review identified evidence of bat-associated hantaviruses in the Philippines, continued wildlife surveillance under strict biosafety protocols is strongly encouraged.

Occupational health protection programs should be prioritized for high-risk occupational groups including farmers, market workers, sanitation personnel, sewer workers, waste collectors, military personnel, wildlife handlers, pest-control workers, and maritime workers. Employers and local government units should promote the use of personal protective equipment, safe cleaning procedures, environmental sanitation, rodent-proof storage practices, and workplace health education regarding rodent-borne disease transmission.

Occupational safety policies addressing zoonotic exposure should also be strengthened, particularly in informal labor settings where biosafety measures are often limited.

The Department of the Interior and Local Government (DILG), together with barangay local government units, should strengthen community-based environmental sanitation and rodent-control programs. Regular waste collection, drainage maintenance, elimination of rodent nesting sites, improvement of food storage systems, and intensified pest-control activities should be implemented especially in densely populated urban communities and public markets. Barangay health workers may also be trained to recognize possible risk factors and educate communities regarding prevention measures.

Given the strong association between flooding, environmental disruption, and increased rodent exposure identified across the reviewed literature, hantavirus prevention strategies should also be incorporated into disaster preparedness and post-flood response programs. During typhoons, flooding events, and evacuation operations, public health authorities should implement intensified sanitation campaigns, rodent control activities, and public advisories on safe cleanup practices to minimize exposure to contaminated rodent excreta.

The Department of Education (DepEd), Commission on Higher Education (CHED), and educational institutions should strengthen health education campaigns regarding rodent-borne diseases and environmental sanitation. Schools and universities should maintain proper waste disposal systems, rodent-proof food storage, clean drainage systems, and safe environmental cleaning practices. Educational campaigns promoting hygiene, sanitation, and zoonotic disease awareness may help improve community-level prevention. Regular campus sanitation inspections, vector and pest-control activities and disaster preparedness education related to flooding and rodent exposure may further strengthen institutional preparedness and reduce potential transmission risks.

At the household level, communities should be encouraged to adopt preventive measures such as proper garbage disposal, safe food storage, elimination of rodent harborages, sealing of wall openings, and safe cleaning of rodent-contaminated areas using disinfectants instead of dry sweeping. Public awareness campaigns emphasizing practical household prevention strategies may contribute substantially to reducing human–rodent interaction.

Finally, further Philippine-based research is strongly recommended to address major knowledge gaps identified in this review. Future studies should include nationwide seroprevalence investigations, molecular surveillance of rodents and wildlife reservoirs, ecological risk mapping, occupational exposure studies, climate-linked transmission modeling, and evaluation of diagnostic tools applicable in resource-limited settings. Long-term interdisciplinary collaboration among epidemiologists, clinicians, ecologists, veterinarians, environmental scientists, and public health authorities will be essential for strengthening hantavirus preparedness and improving zoonotic disease prevention in the Philippines.

Table 1: Characteristics of Studies Included in the Systematic Review and Meta-analysis

Author (Year)	Country	Population/ Reservoir	Study Design	Diagnostic Method	Main Findings
Quelapio et al. (2000)	Philippines	General population	Cross-sectional serosurvey	ELISA	6.1% hantavirus seropositivity among asymptomatic individuals
Rivas et al. (2003)	Venezuela	Human population	Seroprevalence study	IFA	Evidence of hantavirus exposure in rural populations
Muñoz-Zanzi et al. (2015)	Chile	Rural/slum communities	Cross-sectional study	ELISA	Asymptomatic hantavirus exposure detected
van der Westhuizen et al. (2023)	South Africa	Farm/veterinary workers	Occupational study	ELISA	Elevated seroprevalence among high-risk workers
Wróblewska-Łuczka et al. (2017)	Poland	Forestry workers	Occupational serosurvey	ELISA	Occupational exposure among forestry workers
Oldal et al. (2014)	Hungary	Forestry workers	Cross-sectional study	ELISA	Regional variation in occupational exposure
Zeitz et al. (1997)	USA	Occupational workers	Occupational surveillance	Serology	No seropositive cases detected
Arai et al. (2016)	Philippines	Bats	Molecular surveillance	RT-PCR	Identification of Quezon virus in bats
Seo et al. (2022)	South Korea	Rodents	Reservoir surveillance	RT-PCR/ELISA	Rodent hantavirus circulation detected
Zana et al. (2019)	Malaysia	Bats	Molecular surveillance	RT-PCR	Detection of bat-associated hantavirus
Krug et al. (2023)	France	Forestry workers	Occupational seroprevalence	ELISA	Significant regional occupational exposure
Ogola et al. (2021)	Kenya	Human participants	Cross-sectional study	ELISA	Detectable seroprevalence among community participants
Guillebaud et al. (2025)	Cambodia	Human participants	Cross-sectional study	ELISA	High seroprevalence in exposed populations
Cuong et al. (2015)	Vietnam	Rodent trade workers	Occupational study	ELISA	Exposure associated with wildlife trade
Nguyen et al. (2025)	Vietnam	Wildlife farmers	Occupational serosurvey	ELISA	Increased exposure among wildlife farmers
Wong et al. (1989)	Singapore	Urban rodents	Reservoir surveillance	Serology	Active hantavirus circulation among rodents
Nitatpattana et al. (2002)	Thailand	Rodents	Reservoir surveillance	Serology	Rodent seropositivity in agricultural settings
Smith et al. (2025)	Australia	Flying foxes	Molecular surveillance	RT-PCR/Sequencing	Identification of Robina virus
Tortosa et al. (2024)	Global	Human populations	Systematic review/meta-analysis	Multiple	Global pooled hantavirus seroprevalence estimate

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