



REVIEW ARTICLE

Major Livestock-associated Zoonoses in Mongolia: An Overview

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Abstract

Mongolia's unique socio-economic and geographical characteristics, including its vast grasslands and reliance on traditional livestock herding, pose substantial risks regarding the emergence and transmission of novel zoonotic pathogens. In Mongolia, which has a livestock population exceeding 64 million, close interactions between humans and animals are integral to the livelihoods of rural communities but heighten the risk of zoonotic pathogen transmission. Major livestock-associated zoonoses in Mongolia, such as brucellosis, tuberculosis, anthrax, and rabies, have serious impacts on humans, livestock, and the economy. These risks are exacerbated by traditional practices, such as the consumption of raw or unpasteurized animal products, and challenges such as climate change, limited access to veterinary services, and nomadic herding. Collaborative zoonotic pathogen control strategies involving health and veterinary sectors have been implemented, including surveillance programs and vaccination efforts. However, gaps remain in disease management, surveillance, and public education. Strengthening infrastructure and adopting a One Health approach is critical to mitigating zoonotic pathogen risks for both humans and animals.

Key words: Livestock zoonoses, public health, Mongolia, zoonoses, epidemiology, review

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Received: January 29 2025

Revised: April 23 2025

Accepted: May 26 2025

Published Online: July 1 2025

INTRODUCTION

Mongolia is a sparsely populated, land-locked country in East Asia. Although Mongolia is geographically the 18th largest country, its human population is less than 4 million people, and its extensive grasslands are particularly suitable for raising livestock. Mongolia's rich tradition of livestock herding plays crucial roles in its economy and culture. According to the 2023 census [1], Mongolia reported a total livestock population of 64.7 million animals. Of this total population, sheep comprised 45.5%, goats comprised 38.1%, cattle comprised

8.3%, horses comprised 7.5%, and camels comprised 0.7%. The largest livestock populations were recorded in Khuvsgul (5.7 million) and Tuv (4.9 million), which were closely followed by Arkhangai (4.8 million), Uvurkhangai (4.7 million), and Khentii (4.4 million) aimags (provinces) [1]. Livestock herding remains an essential aspect of rural life and contributes to Mongolia's economy in the forms of meat, wool, cashmere, and other animal products. In 2023, the primary source of livelihood in 189,300 herder households in Mongolia was managing livestock year-round [1].

Mongolia's healthcare system, inherited from the Semashko model [2], features a tiered structure: primary healthcare providers are distributed across administrative units nationwide. Secondary healthcare facilities are located in the centers of each aimag and in districts of the capital, Ulaanbaatar, whereas tertiary care services are concentrated in the capital.

Zoonotic diseases are diseases transmitted between animals and humans. According to the National Center for Zoonotic Diseases (NCZD), five of Mongolia's most common zoonotic diseases are tick-borne rickettsiosis, anthrax, rabies, tick-borne encephalitis, and brucellosis [3].

Herein, we summarize the major zoonotic diseases associated with livestock in Mongolia. We examine the factors contributing to zoonotic disease transmission, and discuss the strategies and interventions currently being implemented to address the challenges posed by these diseases.

METHODS

This narrative review was conducted to explore major livestock-associated zoonoses in Mongolia. We reviewed national laws, regulations, government reports, policy documents, and peer-reviewed literature. Relevant documents were retrieved from publicly accessible databases from Mongolia's NCZD and General Authority of Veterinary Services (GAVS), and international organizations including the World Health Organization (WHO) and the World Organisation for Animal Health (WOAH/OIE). Additionally, a literature search was conducted in the PubMed, Web of Science, Scopus, and Google Scholar databases. The search used combinations of keywords and Boolean operators to identify relevant studies. The search terms included the following: ("zoonoses" OR "zoonotic diseases") AND ("Mongolia") AND ("livestock" OR "herding" OR "pastoralism" OR "sheep" OR "goats" OR "cattle" OR "camels" OR "horses"). Eligible sources included materials published in English or Mongolian, describing research conducted in, or applicable to, Mongolia.

LIVESTOCK-ASSOCIATED ZONOTIC DISEASES

Bacterial zoonoses

Brucellosis

Brucellosis is caused by *Brucella* species (*Brucella* spp.), which are facultative intracellular, gram-negative coccobacilli. The primary species that lead to human infections include *Brucella abortus* (*B. abortus*), *Brucella melitensis* (*B. melitensis*), *Brucella suis* (*B. suis*), and *Brucella canis* (*B. canis*) [4]. These bacteria reside primarily in the reproductive organs of host animals, and can lead to abortions and sterility. They can be shed through urine, milk, amniotic fluid, and other animal secretions. Transmission to humans occurs through consumption of unpasteurized milk and dairy products, undercooked meat, skin contact with infected animals, inhalation of contaminated aerosols, conjunctival exposure, blood transfusions, and transplacentally from mother

to fetus. Human-to-human transmission is rare. The incubation period for brucellosis ranges from 3 days to several weeks [5]. Many *Brucella* species have been identified, four of which have moderate-to-high human pathogenicity: *B. melitensis* (from sheep), *B. suis* (from pigs), *B. abortus* (from cattle), and *B. canis* (from dogs). Whereas *B. melitensis* and *B. suis* have the highest pathogenicity, *B. abortus* and *B. canis* have moderate pathogenicity [5,6].

Brucellosis is more prevalent in male than female humans, primarily because of occupational exposure to animals [7]. The disease is also more common in younger individuals: approximately 60% of cases occur in people 13–40 years of age [4]. In developing countries, children are particularly vulnerable because of the lack of milk pasteurization [5].

Brucellosis vaccines are available for livestock but not humans. The vaccines frequently used in animals are a live-attenuated *B. abortus* strain 19 (S19) vaccine and live-attenuated *B. melitensis* strain Rev.1 [8], which are available and used preventively in Mongolia [9].

In Mongolia, animal brucellosis was first documented in 1935, and human brucellosis was officially recognized in 1949. The national livestock survey results from the 1950s indicated apparent brucellosis seroprevalence rates of 17% in cattle, 3.5% in sheep, and 2% in goats. Since 1960, with support from the WHO, a national survey reported seroprevalence rates of 1.7% in urban and 4.4% in rural populations [10].

Subsequently, a test-and-slaughter strategy was implemented between 1965 and 1968, and a mass vaccination campaign was performed between 1975 and 1985. The campaign used the Rev.1 vaccine for small ruminants and S19 vaccine for cattle and yaks [10]. Consequently, the annual incidence of human brucellosis decreased from 25 cases per 100,000 in 1975 to 0.23 per 100,000 in 1986 [11].

After Mongolia's transition to a market economy in 1990, limited resources led to weakening of both healthcare and veterinary services. Consequently, government-operated disease surveillance and control activities were markedly disrupted. Subsequently, the annual incidence of human brucellosis increased from 4.9 cases per 100,000 in 1990 to 67 per 100,000 in 1999 [11].

The public health effects of brucellosis in Mongolia, particularly in relation to ovine and bovine cases, remain important [12]. Mongolia has among the highest rates of human brucellosis infections worldwide [4].

A 2010 study conducted in Zavkhan and Sukhbaatar aimags, analyzing 8,054 livestock and dog serum samples and 574 human serum samples, has revealed variations in seroprevalence across species. The apparent seroprevalence of brucellosis was 27.3% in humans, 6.2% in sheep, 5.2% in goats, 16.0% in cattle, 2.5% in camels, 8.3% in horses, and 36.4% in dogs [13].

The overall seroprevalence of *Brucella* spp. was 11.1% in 2010–2012, on the basis of a sample of 2,856 randomly selected rural residents 4–90 years of age, with rates ranging from 2.3% to 22.6% across the eight aimags:

Sukhbaatar, Zavkhan, Arkhangai, Khuvsgul, Selenge, Uvs, Umnugovi, and Govi-Altai. Adults 45 years of age or older have been found to have elevated risk, particularly veterinarians, because of their frequent and close contact with animals [4]. A seroprevalence study conducted at the Blood Center in Mongolia between August 2004 and February 2005 indicated a 3.3% prevalence of brucellosis among blood donors [14].

Another study on human brucellosis, conducted in 2015 in Dundgovi and Uvurkhangai aimags, indicated seropositivity rates of 10% (26/254) in Dundgovi and 3.8% (9/252) in Uvurkhangai. Among animals tested in the same regions, the seropositivity rates were 44% in cattle, 92% in yaks, 70% in goats, and 65% in sheep; however, the exact number of animals tested was not specified [15].

According to a Center for Health Development of Mongolia annual report, 5 and 57 human brucellosis cases were confirmed in 2021 and 2022, respectively, and the incidence rates were 0.1 and 0.2 per 10,000 population. The highest incidence rates, observed in Dornod aimags, were 3.5 per 10,000 population in 2021 and 5.6 per 10,000 population in 2022 [16].

Although Mongolia's GAVS collects many specimens for brucellosis testing, identification of animal reservoirs has been limited, and surveillance must be expanded [4,17,18]. As part of the National Animal Health Program, in 2021, a total of 283,200 animal samples were studied from among 353,000 breeding animals. Nationwide, 702 samples tested positive or were diseased, thus resulting in an infection prevalence estimate of 0.25%. Additionally, in 2021, a total of 13.66 million female animals were included in the immunization program for brucellosis prevention, and the completion rate was 94.0% [19]. Recent findings have indicated notable seroprevalence in Mongolian camels, particularly in eastern aimags, and have shown that camel infections are closely associated with contact with cattle [20].

An overview of prevalence, transmission routes, and host species for major zoonoses in Mongolia, including brucellosis and others, is provided in Table 1.

Zoonotic tuberculosis

Bovine tuberculosis (bTB), a zoonotic disease affecting primarily cattle, is caused by *Mycobacterium bovis* (*M. bovis*), which is closely related to *Mycobacterium tuberculosis* (*M. tuberculosis*), the cause of tuberculosis (TB) in humans [38,39]. bTB can be transmitted directly by contact with infected domestic and wild animals or indirectly by ingestion of contaminated material. The usual route of infection within cattle herds is inhalation of aerosols and respiratory droplets from infected animals, which are expelled from the lungs [40]. Humans can become infected through the same routes as animals, including inhalation, ingestion, direct contact with mucous membranes, or breaks in the skin [41].

Mammalian TB can be subacute or chronic, and variable rates of progression are observed in animals. Typical clinical signs include weakness, loss of appetite and weight, fever, dyspnea, coughing, swollen lymph nodes,

and decreased milk production. In humans, the symptoms are similar to those of human TB, and include cough, fever, weight loss, and night sweats. Hence, infections caused by *M. tuberculosis* cannot be clinically differentiated from those caused by *M. bovis*. Diagnosis may be further complicated by the tendency of *M. bovis* infections to be located in tissues other than the lungs. In addition, *M. bovis* is naturally resistant to pyrazinamide, an antimicrobial agent commonly used to treat human TB [41].

Prevention and control measures for bTB include post-mortem meat inspection, intensive surveillance including on-farm visits, pasteurization of milk, adequate local legislation, and public education. Vaccination is practiced in humans but has rarely been used to date for controlling the disease in animals, because vaccination can induce a cellular immune response that makes differentiating between infected and vaccinated animals difficult [42].

In 2019, 140,000 global cases of zoonotic TB occurred in humans, primarily in Africa (50%) and South-East Asia (31%) [43]. Mongolia has a high TB burden: in 2022, a total of 2,355 TB cases occurred, and the incidence rate was approximately 7 cases per 10,000 population [16]. TB remains the most prevalent communicable disease in the country, thereby posing major public health challenges. However, the lack of data on zoonotic TB in people indicates a need for zoonotic TB surveillance systems and incorporation of mycobacterium species differentiation into routine clinical protocols.

Q fever

Q fever, caused by *Coxiella burnetii* (*C. burnetii*), is a global concern affecting both humans and animals. This zoonotic disease typically is acute, febrile, and self-limiting, but it can also lead to chronic manifestations such as endocarditis or vasculitis [44]. In humans, because the symptoms of Q fever are similar to those of many other diseases, diagnosis is often difficult. Common symptoms include fever, fatigue, and muscle pain. In animals, *C. burnetii* resides primarily in the reproductive system, particularly in the uterus and mammary glands, and can potentially lead to abortion or infertility [45]. The main reservoirs of *C. burnetii* are cattle, sheep, and goats [46].

The most common infection route is inhalation of dust or mist contaminated with *C. burnetii*, as often found in environments near livestock, particularly during calving or lambing. In addition, bacteria can be transmitted through direct contact with infected animals, or consumption of raw milk or dairy products. In a less common route, ticks can carry and transmit *C. burnetii* to humans.

People with certain jobs, including veterinarians, meat processing plant workers, dairy workers, livestock ranchers, and researchers at facilities housing sheep and goats, have elevated risk of exposure to *C. burnetii* [44]. Case-control studies have demonstrated that occupational exposure to animals or animal products is associated with significantly higher odds of seroconversion compared to the general population [47]. Therefore, receiving proper

TABLE 1 | Prevalence/incidence of major livestock zoonoses in Mongolia.

Disease or disease agent	Type of pathogen	Major animal-human transmission route	Wild animal host	Domestic animal host	Prevalence/incidence of human infection	Prevalence/incidence in livestock animals and products	References
Bacterial zoonoses							
Brucellosis	<i>Brucella</i>	Direct contact Indirect contact	Bison, deer, wild boar, and other marine mammals	Sheep, goats, cattle, swine, and domestic dogs	Seroprevalence: 27.3% (n=574 human sera, Sukhbaatar and Zavkhan aimags, 2010); 11.1% (n=2,856 rural individuals, 8 aimags, 2011–2012); 10% (26/254, Dundgovi) and 3.8% (9/252, Uvurkhangai aimag, 2011–2014)	Seroprevalence: 6.2% in sheep, 5.2% in goats, 16.0% in cattle, 2.5% in camels, 8.3% in horses, and 36.4% in dogs (n=8,054, Sukhbaatar and Zavkhan aimags, 2010); 44% in cattle, 92% in yaks, 70% in goats, and 65% in sheep (Dundgovi and Uvurkhangai aimags, 2011–2014)	[4,13,15]
Zoonotic tuberculosis	<i>Mycobacterium bovis</i>	Indirect contact (foodborne)	Cloven-hooved mammals and non-human primates	Cattle	N/A	N/A	
Q fever	<i>Coxiella burnetii</i>	Direct contact Indirect contact (rare)	Rodents, birds, hares, other mammals, and arthropods	Cattle, sheep, goats, cats, and dogs	No confirmed cases (2017–2022)	N/A	[21]
Enterohemorrhagic <i>Escherichia coli</i> infection	<i>Escherichia coli</i> O157:H7	Direct contact Indirect contact (foodborne)	Deer, bison, wild ruminants, and wild boar	Cattle, sheep, goats, and deer	N/A	Prevalence in rectal swabs of cattle: 12.9% (n=350, near Ulaanbaatar, 2024)	
Plague	<i>Yersinia pestis</i>	Direct contact Indirect contact (vectorborne)	Marmots, rodents, wild carnivores, and wild cloven-hoofed mammals	Rodents (marmots, rats)	Prevalence: 0.1 cases per 10,000 population (2022)	N/A	[21]
Yersiniosis	<i>Yersinia enterocolitica</i>	Foodborne Direct contact	Rodents, hares, birds, reptiles, and aquatic animals	Swine, dogs, cats, and sheep	N/A	N/A	
Salmonellosis	<i>Salmonella</i>	Indirect contact (foodborne) Direct contact	Wild mammals, birds, reptiles, and amphibians	Poultry, swine, cattle, and pets including cats and dogs	Prevalence: 15.7% in rectal swabs of NCCD patients (n=187, 2018–2020)	N/A	[22]
Campylobacteriosis	<i>Campylobacter</i>	Indirect contact (foodborne, waterborne)	Wild birds, wild mammals, and carnivores	Poultry, cattle, sheep, and goats	N/A	N/A	
Listeriosis	<i>Listeria monocytogenes</i>	Indirect contact (foodborne) Direct contact	Wide range of mammals, birds, and aquatic animals	Poultry and domestic ruminants	Prevalence in nasal and cervical swabs of high-risk individuals: 1.06% (n=188, Khuvsgul aimag, 2017)	90 sheep and goats infected during 10 outbreaks in 8 soums across 5 aimags (2022)	[23,24]
Glanders	<i>Burkholderia mallei</i>	Direct contact Indirect contact (rare)	Wild equids, camels, wild carnivores, and rodents	Horses, mules, and donkeys	N/A	Seroprevalence in horses: 7.7% (26/337) by RBT and 8.3% (28/337) by CFT (central and eastern Mongolia, 2018–2019)	[25]

TABLE 1 | (Continued)

Disease or disease agent	Type of pathogen	Major animal-human transmission route	Wild animal host	Domestic animal host	Prevalence/incidence of human infection	Prevalence/incidence in livestock animals and products	References
LA-MRSA	LA-MRSA	Direct contact Indirect contact (foodborne)	Wild birds, wild boars, and rodents	Pigs, cattle, chicken, horses, dogs, and cats	N/A	N/A	
Leptospirosis	<i>Leptospira</i>	Direct contact Indirect contact (waterborne)	Rodents	Rodents, swine, cattle, and dogs	N/A	Seropositivity in cattle: 80.4% (86/107) in Dornod, 28.9% (13/45) in Arkhangai, and 23.5% (12/51) in Khuvsgul aimags (2013)	[26]
Tick-borne rickettsiosis	<i>Rickettsia</i>	Indirect contact (vectorborne)	Rodents, rabbits, and foxes	Cattle and sheep	Prevalence: 0.65, 1.16, and 0.64 cases per 10,000 population (2016, 2017, and 2018); 21.8% in participants with a history of suspected tick bites (n=4,724, 2016–2020)	Prevalence in livestock whole blood samples: 57.6% <i>Anaplasma</i> , 12.8% <i>Bartonella</i> , and 0.4% <i>Ehrlichia</i> (n=243, Dornogovi, Selenge, Tuv aimags, 2014–2015)	[27–29]
Anthrax	<i>Bacillus anthracis</i>	Direct contact Indirect contact (foodborne)	Herbivorous mammals (primary) and birds	Cattle, sheep, horses, and swine	N/A	Prevalence: 2,014 cases (78.3% cattle, 17% sheep and goats, 4.3% horses, 0.25% camels, 0.15% dogs, 0.1% pigs; 1996–2005)	[30]
Parasitic zoonoses							
Trichinellosis	Trichinella	Indirect contact (foodborne)	Wild carnivores and rodents	Swine and domestic dogs	N/A	N/A	
Viral zoonoses							
H5N1 influenza	Influenza A subtype H5N1	Direct contact Indirect contact	Bar-headed geese, swans, and other migratory or non-migratory birds of the Anatidae	Poultry	Prevalence: 1,279–2,798 influenza-like illnesses and 81–666 severe acute respiratory illnesses per 100,000 population (winter seasons 2013–2014 to 2017–2018)	N/A	[31]
Rabies	Rabies virus	Direct contact	Bats, and Carnivora particularly wolves, jackals, foxes, and badgers	Domestic dogs	Prevalence: 0.4 cases per million inhabitants (11 cases, 1994–2004)	Prevalence: 2,359 cases (861 cattle, 268 goats, 251 sheep, 221 dogs; 2012–2018)	[32,33]
Hepatitis E	Hepatitis E virus	Direct contact Indirect contact (foodborne, waterborne)	Wild boars (primary), deer, rabbits, and mongooses	Swine (primary)	Prevalence: 4% (n=302 patients with acute hepatitis, 2012–2013); 20.8% (n=154 patients with acute hepatitis, 2014–2015); 13.3% (n=309 Bactrian camel herds, Bayankhongor aimag, 2023–2024)	Prevalence: 2% (4/200) in sheep and 15% (30/200) in pigs (Tuv aimag, 2020–2022)	[34–37]
Tick-borne encephalitis	Tick-borne encephalitis virus	Indirect contact (vectorborne)	Rodents, hares, and birds	Dogs, cats, cattle, sheep, and horses	Prevalence: 0.17, 0.20, and 0.10 cases per 10,000 inhabitants (2016, 2017, and 2018)	N/A	[28]

N/A = not available; LA-MRSA = livestock-associated methicillin resistant *Staphylococcus aureus*; CFT = complement fixation test; RBT = Rose Bengal plate agglutination test.

public health education, avoiding contact with contaminated animals, using personal protective equipment, pasteurizing milk and dairy products, and controlling infections in livestock populations are crucial in decreasing the number of Q fever cases. Even though a vaccine (Q-Vax[®]) is commercially available, its licensed use is limited to Australia [48].

Research on human infections is limited in Mongolia. According to the NCZD annual report, no confirmed cases of Q fever were registered in 2017–2022 in humans [21]. For animal infections, a total of 8072 tick species were tested for *C. burnetii*, 18.54% of which were positive [21]. However, no information is available regarding the geographical distribution of *C. burnetii* positive ticks. In addition, *C. burnetii* was detected in snow leopards (25%) from 2008 to 2015, and in various tick populations throughout the Umnugovi aimag [49].

Enterohemorrhagic *Escherichia coli* infection

Enterohemorrhagic *Escherichia coli* (EHEC) infection is caused by Shiga toxin producing *E. coli* (STEC), most notably serotype O157:H7, an important food and waterborne pathogen that causes diarrhea, hemorrhagic colitis, and hemolytic uremic syndrome (HUS) in humans. Cattle are natural carriers of STEC and typically do not exhibit pathological symptoms [50,51]. Zoonotic transmission of *E. coli* O157:H7 occurs after consumption of undercooked meat or poorly pasteurized dairy products, or contact with contaminated fomites. Additional transmission routes include exposure to contaminated water from potable drinking sources, swimming pools, or lakes; consumption of contaminated food, such as undercooked meats, improperly washed leafy greens or fruits, or unpasteurized beverages; and direct contact with infected animals. Additionally, equipment such as knives, saws, and tables used in beef processing can spread STEC among carcasses and cuts of meat [52].

Although EHEC is a major cause of morbidity as well as the condition known as HUS, which is associated with Shiga toxin production, no licensed vaccines have been approved for human and animal use [53]. Research is ongoing, and some vaccine candidates have shown potential in various models [54].

A study on the isolation of STEC from cattle in Mongolia has indicated that major *E. coli* types frequently found in human patients, such as O26:H11 and O157:H7, are also present in cattle. The researchers concluded that STEC infections have increased in the past two decades and might previously have been overlooked or misdiagnosed because of inadequacies in the diagnostic systems of the human health sector [55].

Plague

Yersinia pestis (*Y. pestis*), a gram-negative bacterium, is the pathogen responsible for plague, a zoonotic disease that has caused numerous historical pandemics, most notably the Black Death in the 14th century [56]. *Y. pestis* is maintained in nature primarily in rodent populations,

particularly in areas where it remains endemic, such as the western United States, parts of Asia, and Africa [57]. Fleas serve as vectors for transmitting the bacteria between rodents and occasionally humans or other animals, including livestock.

The bacterium infects its host through flea bites or direct contact with infected tissues or fluids [58]. Once inside the host, *Y. pestis* can manifest in three clinical forms—bubonic, septicemic, and pneumonic plague—depending on the route of infection and progression of the disease. Bubonic plague, the most common form, is characterized by swollen lymph nodes (buboes), whereas pneumonic plague is the most lethal and can spread between humans via respiratory droplets [59].

Although *Y. pestis* affects primarily rodents, cases of infection in livestock have been documented, particularly during outbreaks in areas where the disease is endemic [57]. Domestic animals, including dogs and cats, can serve as hosts and occasionally transmit the bacteria to humans. However, infections in cattle and other large livestock are rare, because of these animals' natural resistance to the pathogen [60]. Livestock infections typically occur when animals are close to infected rodent populations.

Plague prevention measures include public health surveillance, health education, vaccination for high-risk groups, and prompt treatment. Although the WHO does not recommend the use of old-generation plague vaccines, immunization efforts continue to be implemented in Mongolia. According to the most recent data from 2022, a total of 24,600 vaccine doses were distributed across 13 aimags and Ulaanbaatar, the capital city [21].

Mongolia has vast grasslands and arid environments, which are conducive to certain rodent species, such as marmots (*Marmota sibirica*), which serve as natural reservoirs for *Y. pestis* [61]. These animals, particularly in the Altai Mountains and other high-altitude regions, harbor the bacterium, and fleas (*Oropsylla silantiewi* and *Neopsylla setosa*) act as vectors. Fleas often carry the bacteria and cause transmission to humans [62]. In Mongolia, marmots have long been hunted for their fur and meat, thereby posing a considerable risk of zoonotic transmission of *Y. pestis*. Traditional Mongolian hunting practices often involve close contact with potentially infected animals, thereby increasing the chance of flea bites or direct contact with contaminated tissue [63].

Mongolia has several active plague foci, particularly in regions where the bacterium persists in wild animal populations, particularly marmots. Since the first human cases were recorded in 1897, periodic outbreaks have continued in fluctuating numbers, depending on environmental conditions, human behavior, and wildlife population dynamics [64]. Epidemiological studies have revealed that *Yersinia* strains from Mongolia are genetically diverse [64]. Molecular analysis techniques, such as multilocus variable-number tandem repeat analysis (MLVA) and single nucleotide polymorphism (SNP) typing, have been used to categorize more than 100 strains from Mongolia,

and demonstrated significant variation underscoring the country's status as a plague diversity hotspot.

Mongolia experiences occasional cases of plague, most notably in the rural western and southwestern aimags, where marmot hunting is common. Between 2000 and 2020, Mongolia recorded several plague outbreaks, with fluctuating case numbers depending on predisposing factors such as marmot population density, flea prevalence, and climatic conditions [65]. The transmission of *Y. pestis* in Mongolia is primarily sylvatic, circulating between wild rodents and fleas, and humans and livestock become accidental hosts. Human cases are typically bubonic, septicemic, or pneumonic, among which the pneumonic form is particularly dangerous, because of its potential for human-to-human transmission [66].

According to the NCZD, a total of 216 cases of plague were reported in Mongolia between 1970 and 2022, and the mortality rate was 39.3%. In 2022, two confirmed cases were recorded, corresponding to a prevalence rate of 0.1 per 10,000 population [21].

Riehm and colleagues have analyzed 100 *Y. pestis* strains from 37 locations in Mongolia with clustered regularly interspaced short palindromic repeats and MLVA, and identified six main genetic clusters, including the *microtus* biovars Ulegeica, Altaica, and Xilingolensis [64]. The largest cluster consisted of 78 isolates unique to Mongolia, whereas 89 strains were categorized under the *Y. pestis Antiqua* biovar. Three clusters corresponded to previously known SNP branches, and 11 isolates were classified into various *microtus* subspecies. That study revealed that Mongolia hosts a recent *microtus* clade, Ulegeica, and was likely to have been recolonized by new plague strains from China in the past 600 years, thereby underscoring Mongolia's critical role in the evolutionary history of *Y. pestis* [64].

Yersiniosis

Yersiniosis is a disease caused by the bacterium *Yersinia enterocolitica* (*Y. enterocolitica*), a gram-negative pathogen that thrives in low-oxygen environments. These bacteria are catalase-positive, non-spore producers that are specifically adapted to cold conditions and consequently are psychrophilic. *Y. enterocolitica* is particularly resilient, because it can survive in a viable but non-culturable state and thrive in cold environments (4–8°C), where it can produce a stable toxin. This adaptability poses major food safety challenges, particularly during storage and refrigeration [67]. These bacteria can thrive in environments with pH below 9. However, acidic conditions, particularly the presence of organic acids such as acetic, lactic, and citric acids, can hinder their growth [68].

Among livestock species, pigs are considered the principal reservoir of *Y. enterocolitica*, particularly serotypes O:3, O:5,27, and O:9, which have also been implicated in human infections [69]. The organism commonly colonizes the tonsils and intestines in swine without necessarily causing clinical signs, thereby contributing to

subclinical carriage and environmental contamination [69,70].

The primary modes of transmission among livestock are the fecal-oral route, direct contact between animals, and indirect contact through contaminated equipment or fomites. Human infection occurs through consumption of undercooked pork, or contact with infected animals or contaminated environments [71]. Other potential sources include fresh or pasteurized milk, dairy products, infected plants, seafood, and drinking water [72]. Although they may thrive at temperatures of 0–45°C, these bacteria grow best at 25–32°C [73].

Good hygiene and food safety practices, such as cooking foods properly, avoiding consumption of raw or undercooked meat, and performing milk pasteurization, can decrease the risk of yersiniosis. Although no licensed vaccine is available for all forms of yersiniosis, ongoing research is aimed at developing effective vaccines [74,75].

Limited information is available on yersiniosis in Mongolia. Therefore, further research will be essential to better understand its prevalence, transmission dynamics, and public health effects.

Salmonellosis

Salmonella bacteria are part of the *Enterobacteriaceae* family. These pathogens are identified primarily according to their ability to use citrate as a primary carbon source and lysine as a nitrogen source, and to generate hydrogen sulfide [76]. These bacteria are gram-negative, anaerobic, non-spore-forming, straight rods [77]. They are intracellular facultative pathogens, between 2 and 3 µm in length. The rod shape is supported by a bacterial cytoskeleton composed of an actin-like protein [78].

These bacteria pose a serious risk to the food industry, because of their ability to adapt to environmental conditions that differ greatly from their typical growth range. Some strains can thrive at temperatures as high as 54°C, whereas others can grow at temperatures as low as 2–4°C [79]. *Salmonella* species (*Salmonella* spp.) have been estimated to be responsible for more than 90 million cases of diarrhea-related illnesses globally each year, 85% of which are food-borne [80].

Salmonella infection can occur through direct contact with infected animals or indirectly through their surroundings. Additionally, eating contaminated products or food prepared in contaminated settings can lead to food poisoning [81]. The primary source of pathogenic *Salmonella* responsible for food poisoning in humans is contaminated eggs and egg products [82]. Meat is frequently contaminated with *Salmonella* spp. during production, because bacteria prevalent in animal intestines can transfer to the meat because of negligent processing or poor hygiene practices [83].

Currently, no approved vaccine for use in humans or animals exists against non-typhoidal *Salmonella*, which causes most foodborne salmonellosis [84].

Poultry and eggs have been found to be common sources of *Salmonella* in Mongolia. A 2021 study by Zhanabayeva et al. conducted polymerase chain reaction (PCR) analysis on imported poultry meat in Mongolia, and detected *Salmonella enteritidis* in chicken from Tyson (USA), Xilingol (China), and a Mongolian producer. Therefore, contamination probably occurred before importation, because some samples exceeded microbial safety standards and carried antibiotic resistance genes [85]. Multiplex PCR analysis of 187 rectal swab and stool samples from patients admitted to the National Center for Communicable Diseases (NCCD) has detected *Salmonella* spp. in 15.7% (20) of samples [22].

Campylobacteriosis

Campylobacter subspecies are a common cause of foodborne gastrointestinal illnesses in humans globally. The incidence of campylobacteriosis, caused primarily by *Campylobacter jejuni* (*C. jejuni*), has risen in recent decades in both developed and developing nations [86]. *Campylobacter* species are small, non-spore-forming, spiral-shaped, gram-negative rods measuring 0.2–0.9 μm in width and 0.2–5.0 μm in length. Their movement, reminiscent of a corkscrew's, is enabled by a single polar flagellum located at one or both ends of the cell [86,87].

Campylobacteriosis is associated primarily with the consumption of contaminated poultry, beef, or pork. Approximately 30% of infections result from poultry consumption; 50–80% of *Campylobacter* strains are traced back to chicken, 20–30% are associated with cattle, and a smaller percentage of cases are caused by pathogens from other sources, such as game [88,89]. *Campylobacter* strains do not multiply outside the digestive tract in warm-blooded animals but can survive for weeks in food, particularly under storage at low temperatures [90,91]. Beyond animals and animal-derived food products, vegetables are a common source of campylobacteriosis. Contamination can occur through direct or indirect contact with livestock feces. *Campylobacter* species can survive on fruit and vegetable surfaces for 1–8 days [91]. Infections rarely occur directly through fertilization with manure or using contaminated water in the field but commonly occur later, in kitchens, homes, or restaurants. Maintaining proper hygiene and washing vegetables thoroughly can prevent infection with this bacterium [90,91]. Additionally, infection with *C. jejuni* is considered a possible trigger for conditions such as irritable bowel syndrome, celiac disease, and even inflammatory bowel diseases, which can be long-lasting [86,92].

Although vaccines for humans against *C. jejuni* have been explored, no licensed vaccine is available for humans. The complexity of *Campylobacter* surface antigens and the lack of long-lasting natural immunity in infected people have made vaccine development challenging [93]. However, a vaccine is available for livestock, particularly sheep, and is currently used in New Zealand [94].

Evidence has suggested a global increase in campylobacteriosis over the past decade, including rising incidence

in North America, Europe, and Australia. Although data from Africa, Asia, and the Middle East remain incomplete, available information indicates that *Campylobacter* infection is widespread in these areas. The incidence and reported case numbers vary among countries or within different regions of the same country [95,96]. In developing countries where *Campylobacter* is widespread, infections are seen primarily in children, and the illness-to-infection ratio decreases with increasing age. Therefore, early exposure might help build protective immunity [97], thereby potentially explaining why asymptomatic *Campylobacter* infections are frequent in developing countries, and might potentially contribute to bacterial spread through individuals who shed the pathogen without showing illness [98].

In developing regions such as Mongolia, limited food safety infrastructure and surveillance systems often lead to underreporting of campylobacteriosis cases [99]. Studies in neighboring regions have shown a growing prevalence of *Campylobacter* infections from consumption of undercooked meat and unpasteurized dairy, which are dietary staples in Mongolia [100]. Given the importance of herding and traditional diets, concerns have been raised that the endemic presence of *Campylobacter* might pose ongoing risks to public health, particularly in rural areas, where sanitation and hygiene practices are challenging to enforce. Research from other developing countries has suggested that early childhood exposure to *Campylobacter* might result in the development of immunity, thus contributing to the high prevalence of asymptomatic infections observed in these populations [101]. This pattern might similarly be reflected in Mongolia, where rural children might frequently be exposed to the bacteria through contaminated food or water. Despite the limited epidemiological data from Mongolia, the potential for widespread asymptomatic carriage could increase transmission and complicate public health interventions [86].

Listeriosis

Listeriosis is a bacterial infection caused by *Listeria monocytogenes* (*L. monocytogenes*), a gram-positive, moderately anaerobic, oxidase-negative, and catalase-positive bacteria that appears as small motile rods (0.4–0.5 $\times$ 1–2 μm) that do not form spores [102]. These bacteria can thrive in harsh conditions, including high salt concentrations, low temperatures (e.g., -0.4°C), high temperatures (up to 45°C), a wide pH range (4.4–9.4), and environments with low water activity (0.9) [103,104]. At least 13 serotypes of *L. monocytogenes* have been identified. Among these, the most frequently isolated serotypes from infected individuals are 1/2a, 1/2b, 1/2c, and 4b [105].

L. monocytogenes is an intracellular pathogen that invades a range of host cells, including the intestines, spleen, liver, brain, heart, and placenta, and subsequently establishes infection [106,107]. Listeriosis tends to affect older individuals, pregnant women, and people with weakened immune systems. Infections caused by *L. monocytogenes* are marked by prolonged incubation periods, typically 1–70 days, with

an average of 8 days. In pregnant people, this period can be even longer, between 17 and 67 days. Incubation times differ depending on the symptoms: bacteremia (1–10 days, average 2 days), febrile gastroenteritis (6 hours to 10 days, average 24 hours), and listeriosis affecting the nervous system (1–14 days, average 9 days) [108,109]. The precise infectious dose of *L. monocytogenes* is not established, and varies according to host susceptibility and the virulence of the specific bacterial strain. Symptoms of listeriosis can develop within 24 hours, and in otherwise healthy adults may include joint pain, headache, abdominal pain, diarrhea, nausea, vomiting, loss of appetite, fatigue, and drowsiness. These symptoms typically resolve within 1–3 days [104].

Pathogenic strains of *L. monocytogenes* can also infect domesticated animals such as cattle, sheep, goats, horses, and poultry, as well as wildlife such as birds, fish, and shellfish [110]. Ruminants can carry *L. monocytogenes* without showing symptoms but can also develop infections caused by the bacteria. In both scenarios, animals release the bacteria into the environment through their feces. Under favorable conditions, the bacteria can persist in the environment for extended periods and potentially infect other animals in the same herd or in other herds grazing on the same pasture [82,111].

According to GAVS reports on animal listeriosis, ten outbreaks were recorded in eight soums across five aimags, and 90 sheep and goats were reported to be infected [23]. In a 2017 study conducted in Khuvsgul aimag on *L. monocytogenes* among high-risk individuals, including those admitted for spontaneous miscarriage, *L. monocytogenes* was detected in 1.06% (2 of 188) of collected specimens, including nasal and cervical swabs [24].

Glanders

Glanders, an infectious disease caused by the bacterium *Burkholderia mallei* (*B. mallei*), affects primarily horses, donkeys, and mules, which are the only known natural reservoirs [112]. Susceptibility to glanders has also been observed in camels, cattle, goats, and sheep [113,114]. The bacteria enter through the eyes, nose, mouth, or wounds in the skin. Risk factors for infection include poor sanitation and overcrowded stables. Zoonotic transmission is uncommon, and cases occur primarily among veterinarians, individuals working closely with horses, and laboratory personnel. Human-to-human transmission is rare [115].

Both acute and chronic forms of the disease have been documented, with an incubation period of 1–14 days for the acute form and as many as 12 weeks for the chronic form [115]. Acute cases are most common in donkeys and mules, which show high fever and respiratory symptoms. In horses, glanders typically shows chronic progression, and affected animals may survive for several years. Typical symptoms in horses include nasal discharge, ulcerations of the nasal mucosa, and multiple skin nodules, particularly on the hindlimbs and abdomen [116].

Currently, no veterinary treatments are available to cure glanders, and no vaccine is available to prevent its

spread. Effective disease control relies on early detection and diagnostic testing of suspected cases, screening of apparently healthy equids, and elimination of infected animals. Glanders has been eradicated in North America, Australia, and Europe. However, sporadic cases of the disease are being reported across Asia, Africa, the Middle East, and South America [117].

Recent studies have indicated that glanders continues to be enzootic in Mongolia, and the seroprevalence rates in horses were 7.7% (26/337) by Rose Bengal plate agglutination test (RBT) and 8.3% (28/337) by complement fixation test (CFT) in central and eastern Mongolia during 2018–2019 [25]. Interestingly, native Mongolian horses exhibited lower seropositivity for *B. mallei* than crossbred horses (5.1% vs 26.6%, $P < 0.01$) and thoroughbred horses (5.1% vs 17.1%, $P < 0.05$) [25]. Molecular characterization of *B. mallei* strains isolated from horses in Mongolia has revealed a unique sub-branch within the L3B1 cluster, thereby indicating evolutionary divergence specific to the Far East region [118].

Livestock-associated methicillin-resistant *Staphylococcus aureus*

Livestock-associated methicillin-resistant *Staphylococcus aureus* (LA-MRSA) is a specific type of bacteria that has developed resistance to certain antibiotics and has been identified in livestock across various countries. LA-MRSA evolved independently from common hospital-acquired or community-associated MRSA typically found in humans, and belongs primarily to *Staphylococcus aureus* (*S. aureus*) clonal complex CC398. Although its main reservoirs are pigs, poultry, or cattle, LA-MRSA CC398 has no pronounced host specificity and can colonize or infect other animals, such as horses, dogs, and humans [119]. In animal production farms, the primary goal is to raise healthy animals for human consumption. However, the use of antibiotics in food animals for disease treatment, prevention, and growth promotion is frequently associated with the global rise of antimicrobial resistance [120–122].

Antimicrobial-resistant bacteria can be transmitted to humans through direct contact with infected animals, indirectly via the food chain, or through exposure to environments with high antimicrobial pollution. High prevalence of antimicrobial resistance has been observed among farm workers, veterinarians, and slaughterhouse employees in close contact with food-producing animals [123,124].

Several studies on the epidemiology of MRSA in Mongolia have focused on either hospital-acquired or community-associated cases [125,126]. A study of *S. aureus* in livestock products reported that 35% (100 samples) of raw beef from markets in Ulaanbaatar, Mongolia, contained *S. aureus*, and 17.1% (6 out of 35 isolates) were identified as MRSA [127].

Leptospirosis

Leptospirosis, a zoonotic disease caused by the bacterial agent *Leptospira* species (*Leptospira* spp.), is distributed

worldwide and has no effective vaccine currently available [128,129]. Although many wild and domestic animals can serve as reservoir hosts, the brown rat (*Rattus norvegicus*) is the primary source of human infections [128]. Transmission occurs predominantly through direct or indirect contact with the urine of infected animals, including exposure to contaminated water or soil. The bacteria can enter the body through mucous membranes or damaged skin [130].

Nearly all mammals can serve as carriers for leptospirosis. After an initial leptospiraemic phase, the bacteria can colonize various organs, particularly the kidneys, thus resulting in intermittent shedding in the urine, and the genital tract, where they may be found in semen or vaginal discharge [128]. Clinical illness in humans can range from mild self-limiting acute febrile illness to a severe life-threatening condition with multiple organ dysfunction [128,130].

In cattle, leptospirosis is a common disease that often leads to reproductive failures such as abortion and infertility. Individuals living in urban environments characterized by inadequate sanitation and poor housing have high risk of exposure to rats and consequently leptospirosis [128].

In 2005, the seroprevalence of *Leptospira interrogans* serovar Hardjo in Mongolian cattle varied significantly by region, and accounted for 80.4% (86 cases) in Dornod aimag, 28.9% (13 cases) in Arkhangai aimag, and 23.5% (12 cases) in Khuvsgul aimag [26]. Subsequent research in 2009–2010 by Iu V Anan'ina et al. across seven aimags in eastern, central, and southern Mongolia highlighted the epizootic significance of the Tarassovi serogroup of leptospirae in cattle, as well as the Sejroe serogroup (probably including the Hardjo serovar) in goats, sheep, and camels [131]. Additionally, an analysis of Mongolia's wildlife has suggested potential circulation of leptospirae in natural foci [131]. In a study on health and zoonotic infections in snow leopards (*Panthera unica*) in the South Gobi Desert of Mongolia, serum antibodies against *Leptospira* spp. were found in 20% (4 of 20) of tested blood samples.

Tick-borne rickettsiosis

Tick-borne rickettsiosis is a group of diseases caused by bacteria of the genus *Rickettsia*, which are transmitted to humans through tick bites. Hard ticks transmit most *Rickettsia* species (*Rickettsia* spp.), but rickettsiae in soft ticks (Argasidae) are continually being identified [132]. Although livestock are not the primary *Rickettsia* reservoirs, they can harbor infected ticks, thereby contributing to the overall tick population and serving as a source of infection for humans [27].

Transmission in North America often occurs through various tick species including *Dermacentor variabilis* (American dog tick), *Amblyomma americanum* (lone star tick), and *Rhipicephalus sanguineus* sensu lato (brown dog tick). Common symptoms of tick-borne rickettsiosis include fever, headache, rash, muscle pain, and fatigue.

The rash often begins as small spots and may progress extensively. In severe cases, complications such as organ failure or death may occur in the absence of treatment [133,134]. Rickettsial diseases have varied signs, symptoms, and severity, and therefore are often difficult to distinguish from other infections [135].

Rickettsiosis is among Mongolia's most prevalent zoonotic diseases [3]. The reported rates of rickettsiosis in 2016, 2017, and 2018 were 0.65, 1.16, and 0.64 per 10,000 inhabitants, respectively, whereas the mortality rates for those years were 0%, 0.56%, and 0.49%, respectively [28]. Among voluntary participants with a history of suspected tick bites, the seroprevalence of *Rickettsia* was 21.8% (1,032 of 4,724), and herders exhibited a notably higher rate of 40.6% [29]. In a study of 4,022 *Hyalomma asiaticum* ticks collected from southern aimags, 64% tested positive for various rickettsial species. Melt curve analyses identified four distinct *Rickettsia* spp. present in these tick populations. Amplicon sequencing of the *ompA* gene revealed *Rickettsia* spp. closely resembling *R. raoultii* and *R. sibirica* [136]. Metagenomic analysis of whole blood samples from livestock—including cattle, camels, goats, horses, and sheep across three aimags of Mongolia—revealed *Anaplasma*, *Bartonella*, and *Ehrlichia* prevalence rates of 57.6%, 12.8%, and 0.4%, respectively [27]. These findings indicate a notable prevalence of tick-borne pathogens within the livestock population.

Anthrax

Anthrax, a severe infectious disease caused by the bacterium *Bacillus anthracis* (*B. anthracis*), affects primarily livestock but can also infect humans through contact with infected animals or contaminated animal products. Soil is the natural reservoir of the *B. anthracis* spores and the primary source of animal infection. Soil conditions, such as high moisture, rich calcium, high organic content, and neutral to alkaline pH, correlate with the onset of outbreaks [137]. The main transmission routes are cutaneous, inhalation, gastrointestinal, and injection [138]. Symptoms vary and include fever, chills, fatigue, weakness, sore throat, cough, and abdominal pain. Vaccination is available for high-risk individuals [138].

Mongolia has reported cases of anthrax for many years, and outbreaks are typically associated with livestock, particularly during periods of heavy rainfall or flooding that facilitate the spread of spores. Anthrax has seasonal features and occurs primarily in the summer, when animals graze on pastures. The disease is found primarily in domestic animals such as cattle, sheep, and goats, which are integral to the livelihoods of many herders [30].

Annex to Order No. A/03 of 2019 of the Director of the GAVS "Guidelines for Preventing and Combating Animal Anthrax in Mongolia" requires reporting of all suspected cases of anthrax. Animals or animal carcasses with symptoms suggestive of anthrax (e.g., high fever, breathing difficulty, sudden death, or a carcass without rigor mortis) are considered suspicious cases, whereas those with

positive standard bacteriology and molecular laboratory tests are defined as confirmed cases. Vaccination is available for animals in endemic regions of Mongolia and for high-risk populations [9,30].

The prevalence of anthrax in Mongolia has markedly decreased since the 1950s, owing to the use of anthrax antiserum and vaccines. Before the 1990s, domestic animals were state property, and all preventive and disease control services for animals were provided by the State Veterinary Services. However, since the 1990s, with adoption of a market economy system, the privatization of the animal husbandry sector and changes in the structures of the veterinary and medical delivery systems in Mongolia over the past decade have led to challenges in disease control [30]. Between 1996 and 2005, 108 human anthrax cases, including seven fatal cases, were reported. During that period, anthrax outbreaks were reported in 16 of the country's 21 aimags, in 2,014 cases of infected animals. A total of 78.3% of anthrax cases occurred in cattle, 17% in sheep and goats, 4.3% in horses, 0.25% in camels, 0.15% in dogs, and 0.1% in pigs [30]. Analysis of data from 1986 to 2015 on the disposal sites of livestock carcasses in Khuvsgul aimag revealed a localized source of exposure and a new hotspot in the northern part of the aimag, which emerged in the past 30 years of the study period [139].

Parasitic zoonoses

Trichinellosis

Trichinellosis is a disease caused by nematodes of the genus *Trichinella*. The primary sources of human infection are pigs, horses, reptiles, and birds. The species *Trichinella spiralis*, *Trichinella britovi*, and *Trichinella murrelli* are found in horses, and are most prevalent. The life cycle of *Trichinella* involves two generations in a single host. Larvae from undercooked meat mature in the intestines, reproduce, and then migrate to, and encyst in, muscle tissues, thus affecting primarily humans among a broad range of host species, including mammals, birds, and reptiles [140]. Trichinellosis is spread through the consumption of infected meat or meat products. This bacterium is typically transmitted among wild animals through predation and scavenging. In pigs, infection usually occurs through the ingestion of raw meat waste or consumption of infected rodents. Humans are most often infected through consuming undercooked meat or meat products from infected animals [38]. Currently, no licensed vaccines are available for trichinellosis in humans or animals [141].

Data on human and animal trichinellosis in Mongolia are lacking. This gap in knowledge hinders effective surveillance, risk assessment, and implementation of control strategies.

Viral zoonoses

Influenza

Influenza, a short-term respiratory disease known since the 16th century, spreads quickly through communities

during outbreaks [142]. In temperate climate areas, outbreaks occur every year, following a regular seasonal pattern, whereas in tropical regions, outbreaks can occur throughout the year with irregular surges [143]. Influenza epidemics spread quickly, with an average reproductive number of 1.28 and an attack rate of 10–20%, which varies by age group [144,145]. Influenza outbreaks are frequently first detected in children displaying fever. As the epidemic advances, a rise in hospitalizations and deaths, associated with respiratory or circulatory issues, is observed. A typical influenza epidemic peaks within 2–3 weeks after it starts and persists for 5–6 weeks thereafter [142]. Each year, seasonal influenza causes thousands of deaths and hospitalizations in Europe and the USA, and takes an even larger toll in developing nations [146–148].

Frequent sporadic infections of humans by animal influenza viruses present an ongoing public health threat. Influenza viruses are zoonotic and are categorized into two groups according to the frequency of animal-to-human transmission. Influenza viruses are classified into four main types: A, B, C, and D. Influenza A virus is the most prevalent; is responsible for seasonal epidemics and pandemics; and can infect both humans and animals, including birds and pigs.

Influenza B virus affects primarily humans and is associated with seasonal outbreaks, although it typically causes less severe illness than type A. Influenza C virus is relatively less common and generally causes mild illness, mainly in children, and shows limited human-to-human transmission. Influenza D virus (IDV) infects many animals but does not currently pose a serious risk to humans. Influenza viruses stemming from cattle, horses, dogs, and bats are considered to pose a low zoonotic risk to humans, whereas those from birds and pigs carry a higher zoonotic risk [149].

IDV was first identified in pigs in the USA in 2011; however, cattle have been shown to serve as the main reservoir for this virus [150]. IDV has additionally been found in Europe, Asia, Africa, and South America. IDV has a wide host range that is now recognized to include small ruminants such as sheep and goats, as well as horses and camelids; however, experimentally, it has also been found to infect mice, ferrets, and guinea pigs [151].

Human infection with swine influenza A virus typically occurs through close interaction between pigs and humans, particularly in pig farms or slaughterhouses. Notably, whereas pig-to-human transmission of influenza A virus has been consistently documented, the number of human cases is lower than that of avian influenza virus (AIV) transmission [149].

AIV infects a wide variety of mammal species [152]. Numerous AIV strains have successfully crossed species barriers and caused serious infections in humans. The infections vary from asymptomatic to mild cases or even death. Most infections occur through direct contact with sick birds or contaminated environments. Primary sources of infection

include live bird markets, backyard birds, slaughterhouses, and the culling of farmed poultry [153,154]. Since the first case of human infection in Hong Kong in 1997, H5N1 AIV has attracted substantial attention as a highly pathogenic strain. Highly pathogenic avian influenza (HPAI) 2.3.4.4b H5N1 viruses have shown wide transmission worldwide since 2021, and affect many species [155]. In 2024, spillover of the HPAI H5N1 virus to dairy cattle across several states in the USA was reported. Epidemiological and genomic data have revealed efficient cow-to-cow transmission after apparently healthy cows from an affected farm were transported to a premise in a different state [156]. The farms that first reported and confirmed the HPAI H5N1 viral infection in cattle are all along the Central North American migratory bird flyway, thus providing many opportunities for livestock animals to make direct or indirect contact with migratory birds [155]. The HPAI H5N1 virus has also been detected in a variety of animals beyond cattle, including goats, pigs, and cats [157,158].

Influenza zoonosis—the transmission of influenza viruses from animals to humans or vice versa—is a significant public health challenge worldwide, particularly in Mongolia. The nomadic pastoralism and close human-animal interactions in Mongolia create an environment conducive to zoonotic transmission of various influenza strains, particularly AIVs [159]. In Mongolia, the risk of avian influenza transmission is heightened by the country's location along major migratory bird flyways. Migratory birds act as natural reservoirs for AIVs and can introduce these viruses into domestic bird populations, which come into close contact with humans [160]. Vaccination of poultry against avian H5N1 is available in Mongolia [161].

A recent report has suggested that AIVs might be infecting Mongolia's horses [86]. Between July 2021 and October 2023, Damdinjav and colleagues collected serum samples from ten horses across 24 herds three times per year. Of 997 nucleoprotein-positive samples tested for H5 antibodies, 9 were positive, 8 were doubtful, and 980 were negative; virus neutralization assays confirmed H5 antibodies in two working horses, whereas EIV cross-reactivity was ruled out [162]. In recent years, outbreaks of HPAI in wild and domestic birds in Mongolia have raised concerns regarding the potential for human infections [163]. NCZD conducted surveillance for AIV among wild birds in 10 aimags in 2022 [21]. Close monitoring of wild bird populations and poultry farming practices is critical in decreasing the zoonotic risk of AIVs [164].

Rabies

Rabies is a vaccine-preventable, zoonotic viral disease caused by the rabies virus, which is known for its high neurotropism [165,166]. Although all mammals are believed to be susceptible to rabies, the primary reservoirs are terrestrial mesocarnivores and bats. Other potential carriers include ferrets, horses, and livestock [167–169].

Domestic animals often become exposed through contact with infected wildlife.

The virus spreads through contact with the saliva or neural tissue of an infected animal, typically via bites, scratches, or open wounds. Transmission from dogs is the most common cause of rabies in humans [165]. The incubation period of rabies typically ranges from 1 to 2 months; the shortest reported period was 7 days, whereas the longest was 6 years [166,170]. Varying clinical signs can make early detection challenging. Symptoms may include anorexia, pruritus, ataxia, lameness, tenesmus, hypersalivation, and aggression [165]. Rabies vaccines are used to prevent rabies infection in humans and animals [171].

Between 1970 and 2005, Mongolia reported 21,302 cases of rabies in domestic animals, and an additional 2,359 cases were recorded from 2012 to 2018. Cattle accounted for the highest number of cases (861), and were followed by goats (268), sheep (251), and dogs (221). Among wildlife, red foxes were the primary carriers (317 reported cases) and were followed by wolves (151 cases) [32]. Between 1994 and 2004, Mongolia reported 11 human rabies cases, equating to 0.4 cases per million inhabitants, and dogs were identified as the most common source of human infection [33]. In 2010, molecular analysis of the rabies virus, on the basis of the viral N gene, indicated that the endemic Mongolian rabies virus can be classified into two distinct groups. These groups are closely related to the Steppe-type and Arctic-like viruses found in Russia [172]. Nucleotide sequencing of the glycoprotein and nucleoprotein genes has revealed multiple lineages of the rabies virus in the central region of Mongolia [173]. A recent case of rabies exposure involved a 6-year-old boy who was bitten by a horse on both the head and leg, thus underscoring the urgent need for routine vaccination of domestic animals in Mongolia [174].

Hepatitis E

Hepatitis E virus (HEV), an important foodborne pathogen with zoonotic potential, belongs to the *Hepeviridae* family [175]. Among several genotypes of HEV, increasing human infections have been linked to zoonotic transmission of genotypes 3 and 4, primarily through consumption of contaminated, undercooked, or raw pork [176]. Pigs and wild boars are the primary HEV reservoir, but other animals, including cattle, sheep, goats, and rabbits, can also transmit the virus to humans [177,178].

Infection is often asymptomatic, although mild to moderate liver and lymph node changes can occur in infected animals and humans. Infected pigs have viremia lasting 1–2 weeks and shed viruses in the feces for approximately 3–7 weeks [176]. Most acute HEV infections in humans do not require special treatment; however, HEV-1 infection in pregnant people (particularly in the third trimester) is associated with high maternal morbidity and mortality [179]. Individuals who work with livestock, such as farmers and veterinarians, are prone to HEV infection [179]. Currently, one vaccine has received approval in China and

Pakistan for use among high-risk human populations, and is recommended by the WHO during outbreaks [180].

A study in patients with acute hepatitis in Mongolia from 2012 to 2013 identified 12 patients (4%) testing positive for HEV. Molecular analysis revealed high nucleotide identity with Chinese isolates of genotype 4 [34]. In a screening of 154 patients diagnosed with acute hepatitis in Ulaanbaatar, Mongolia, between 2014 and 2015, 20.8% (32 patients) were infected with acute hepatitis E caused by HEV-1 [35].

The prevalence of HEV infection among Bactrian camel herds in Bayankhongor aimag, Mongolia, was 13.3% (41 cases). HEV seropositivity was associated with water supply sources, consumption of khoormog (a camel milk drink), and co-infection with Hepatitis B virus and Hepatitis C virus [36]. Recently, HEV-4 has been confirmed in sheep (2%) and pigs (15%) in Tuv aimag, Mongolia [37].

Tick-borne encephalitis

Tick-borne encephalitis (TBE) is a viral infection that affects the central nervous system and is transmitted through the bites of infected ticks. The TBE virus, particularly within the family *Flaviviridae* and genus *Flavivirus*, has several subtypes including European, Siberian, and Far Eastern strains [181]. The main reservoir hosts of TBE are small mammals such as rodents and insectivores. Although it is transmitted primarily by ticks, TBE can also spread through consumption of unpasteurized dairy products from infected animals [182].

Symptoms usually emerge 7–14 days after infection, and initially manifest as fever, headache, muscle pain, and fatigue, resembling flu-like symptoms. A second phase may occur in some cases, thus leading to severe complications such as meningitis, encephalitis, or meningoencephalitis [183].

TBE has been reported in Mongolia since the 1980s and is among the most prevalent zoonotic diseases in the country [3]. The primary vector for TBE is the tick species *Ixodes persulcatus* [184]. Analyses of isolates from tick homogenates have indicated that they belong to the Siberian subtype of TBE [185]. The recorded incidence of TBE in 2016, 2017, and 2018 was 0.17, 0.20, and 0.10 cases per 10,000 inhabitants, respectively, and the corresponding mortality rates were 3.86%, 8.06%, and 0% [28]. In 2022, eight confirmed cases were reported, primarily in Selenge (75%), Darkhan-Uul (12.5%), and Ulaanbaatar city (12.5%). Vaccination is available for individuals traveling or living in areas where the virus is prevalent. A total of 5,145 people were vaccinated in 2022 in Mongolia [21].

FACTORS CONTRIBUTING TO LIVESTOCK ZOOSES IN MONGOLIA

Mongolia's reliance on livestock for sustenance and income heightens the risk of zoonotic diseases, because of the close interactions between humans and animals

[186]. Traditional practices, such as animal slaughter and the consumption of undercooked animal products, further exacerbate this risk. The prevalent method of scattered individual herding, combined with the lack of meat inspection in remote areas, often leads herders to slaughter animals for personal consumption and sale. Consumption of unpasteurized milk from infected animals can facilitate the transmission of diseases including brucellosis, tuberculosis, and zoonotic enteric parasitic diseases [187,188].

In Mongolia, where more than 200,000 households engage in production of livestock including sheep, goats, horses, and cattle, the close coexistence of different species may create micro-environments that facilitate interspecies transmission of pathogens, particularly from animals to humans [189].

The mobility of nomadic herding can facilitate the spread of pathogens across regions. As herders migrate with their animals, they may carry zoonotic diseases to new areas, thereby potentially exposing local populations to previously unencountered pathogens [186]. Nomadic herding often involves grazing in diverse ecosystems, which can alter wildlife populations and habitats. These changes create new interfaces between wildlife and livestock, and consequently increase the likelihood of zoonotic spillover. This likelihood is further exacerbated by the effects of climate change, which affect migration patterns and the availability of grazing lands, thus prompting herders to move into new areas [190].

Additionally, many nomadic communities have limited access to veterinary and healthcare services, given their remote locations. This lack of resources can result in inadequate disease management and vaccination, and consequently allow zoonotic diseases to proliferate within animal populations [191].

CONTROL STRATEGIES AND MEASURES FOR LIVESTOCK ZOOSES

Responsibilities for health issues affecting humans and domestic animals in Mongolia are distributed among various ministries and government levels. Key national entities include the Ministry of Health (MoH); the Ministry of Food, Agriculture, and Light Industry (MoFALI); the GAVS; the NCZD; and the NCCD. At the local level, health departments, veterinary offices, and zoonotic disease centers operate across 21 aimags. These organizations implement laws and regulations associated with animal and public health, including the Law on Veterinary Medicine and the Law on Animal Health, which are aimed at preventing, controlling, and managing zoonotic diseases effectively. Surveillance, vaccination, and control strategies for major zoonoses in Mongolia are summarized in Table 2.

GAVS was established in 1923 as an Animal Health and Breeding Division. Currently, it operates a comprehensive network of veterinary services dedicated to monitoring animal health, conducting disease surveillance,

TABLE 2 | Major livestock zoonoses monitoring and management in Mongolia.

Disease	Pathogen	OIE-listed diseases* [192]	Surveillance and monitoring in Mongolia [9,16,21,161]	Vaccination of people in Mongolia [21,193,194]
Bacterial zoonoses				
Brucellosis	<i>Brucella</i>	Yes	Yes	
Zoonotic tuberculosis	<i>Mycobacterium bovis</i>	Yes	Yes	Available
Q fever	<i>Coxiella burnetii</i>	Yes	Yes	
Enterohemorrhagic <i>Escherichia coli</i> infection	<i>Escherichia coli</i> O157:H7			
Plague	<i>Yersinia pestis</i>		Yes	Available
Yersiniosis	<i>Yersinia enterocolitica</i>			
Salmonellosis	<i>Salmonella</i>			
Campylobacteriosis	<i>Campylobacter</i>	Yes		
Listeriosis	<i>Listeria monocytogenes</i>		Yes	
Glanders	<i>Burkholderia mallei</i>	Yes	Yes	
LA-MRSA	LA-MRSA			
Leptospirosis	<i>Leptospira</i>			
Tick-borne rickettsiosis	<i>Rickettsia</i>		Yes	
Anthrax	<i>Bacillus anthracis</i>	Yes	Yes	Available
Parasitic zoonoses				
Trichinellosis	Trichinella	Yes		
Viral zoonoses				
H5N1 influenza	Influenza A subtype (H5N1)	Yes	Yes	
Rabies	Rabies virus	Yes	Yes	Available
Hepatitis E	Hepatitis E virus			
Tick-borne encephalitis	Tick-borne encephalitis virus		Yes	Available

*OIE-listed diseases are those identified by the World Organisation for Animal Health (WOAH) as being of international concern, because of their potential effects on animal and human health, as well as international trade. LA-MRSA = livestock-associated methicillin resistant *Staphylococcus aureus*.

and implementing vaccination programs for livestock to decrease the risk of zoonotic diseases. Its subnational veterinary laboratories, located in all 21 aimags, are equipped with PCR machines and essential reagents [195].

The General Agency for Specialized Inspection (GASI) oversees and ensures compliance with regulations and standards in specialized sectors, such as health, safety, environmental protection, and quality control, at the national level. Its activities also encompass the inspection of livestock and animal products at market locations and during transportation. However, in 2022, GASI functions were transferred to the relevant ministries, and the responsibilities of the provincial and district inspection departments were shifted to the corresponding Office of the District or aimag governor [196].

Mongolia has implemented several strategic control programs for transboundary animal diseases and zoonoses over the years, thereby reflecting the country's dependence on livestock and public health concerns. One key program

is the Foot-and-Mouth Disease Control Program, which has been in place for many years, because of its effects on livestock trade and livelihoods. The program includes vaccination campaigns, surveillance, and control measures, such as zoning and compartmentalization for disease-free zones, alongside improved border biosecurity to prevent transboundary spread [197].

Another notable program is the Brucellosis Control Program, which began decades ago in response to the zoonotic nature of the disease affecting both humans and livestock. National brucellosis surveillance was initiated in the 1950s, and a test-and-slaughter policy was introduced in 1960. The government also launched a vaccination program between 1973 and 1983. These measures led to a decline in animal brucellosis prevalence from 10% to 0.5%. Efforts have since focused on large-scale vaccination campaigns, testing, culling infected animals, and raising public awareness regarding safe livestock handling and consumption practices [195,198].

The Anthrax Control Program was implemented to address anthrax outbreaks in livestock, which pose a public health risk. This program includes annual vaccination of livestock in endemic areas, disposal and decontamination of carcasses in outbreak sites, and public education to prevent exposure [199]. Similarly, the Rabies Control Program has been ongoing for many years, because of the threat of rabies spreading through dogs and wildlife. It includes the vaccination of domestic animals, surveillance of wildlife reservoirs, and community education on prevention and post-exposure treatment [200].

Mongolia has also focused on zoonotic TB control, particularly given the transmission of *M. bovis* from livestock to humans. The program involves testing and removal of infected animals, awareness campaigns for herders and healthcare workers, and collaboration between veterinary and human health sectors [201]. The HPAI Control Program was set up to manage the risks posed by migratory birds and domestic poultry. Surveillance of migratory bird populations, contingency planning, and biosecurity measures in poultry farms are key components of this program [202].

Finally, the Zoonotic Plague Control Program has been in place in response to the endemic nature of plague in some regions of Mongolia. This program involves surveillance of rodent populations, flea control, and public education regarding avoiding exposure to the disease [201]. Mongolia's efforts are supported by international collaborations with organizations including the WOAHO/OIE, the Food and Agriculture Organization, and the WHO. National frameworks such as the One Health Approach have played important roles in integrating human, animal, and environmental health for the control of zoonotic diseases.

Many collaborative activities against zoonoses have been undertaken in Mongolia since 2006. The joint serological survey by MoH and MoFALI, conducted in 2007–2009, helped define the distribution of some zoonoses in Mongolia. Subsequently, the Intersectoral Coordination Committee on Zoonoses was officially established in Mongolia in February of 2010, including chairs and representatives from MoH, MoFALI, the National Emergency Management Agency, the Ministry of Nature and Environment, GASI, and the WHO, to foster robust human and animal health sectors, along with emergency response and national inspection agencies, working collaboratively to achieve a healthier community [198]. The work of the Coordination Committee has led to the implementation of joint risk assessments and outbreak investigations, improved collaboration between veterinary and human health laboratories, and enhanced risk communication strategies.

On the basis of the Joint External Evaluations conducted in 2017 and 2023, which assessed Mongolia's health security capacity—the Pandemic Fund project was initiated to enhance public health and emergency response systems

through a One Health approach. This project will prioritize improving surveillance, bolstering laboratory capacity, and strengthening human resources for public health and emergencies [203].

CONCLUSION

Although Mongolia has made progress in implementing control strategies for zoonoses, ongoing challenges require attention. Strengthening surveillance systems, enhancing public health education, improving veterinary services, and fostering intersectoral collaboration will be crucial for better control of zoonotic diseases in the country.

ACKNOWLEDGEMENTS

We thank Dr. Judith Oguzie and Jessica Rodriguez at the University of Texas Medical Branch and Dr. Batsukh Zayat at the Institute of Veterinary Medicine, Mongolian University of Life Sciences, for their helpful review of the manuscript. We also express our sincere appreciation to U01 principal investigator, Dr. Davaalkham Dambadarjaa, and the entire Mongolian GEOHealth Center study team for their strong support and for providing us the opportunity to be part of this important research initiative. Research reported in this publication was supported by the Fogarty International Center of the National Institutes of Health under award numbers 5U01TW012229-03 and U2RTW012239 and by USDA-ARS Agreement 58-3022-4-048. The content is solely the responsibility of the authors and does not necessarily represent the official views of the National Institutes of Health.

CONFLICTS OF INTEREST

The authors declare that there are no conflicts of interest.

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