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Ingrained: Rice farming and the risk of zoonotic spillover, examples from Cambodia

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ABSTRACT

Rice cultivation in Southeast Asia is a One Health interface intersecting human, animal, and environmental health. This complexity creates a potential for zoonotic transmission between diverse reservoirs. Bats harbor viruses like Nipah; mosquitoes transmit arboviruses; rodents spread hantaviruses. Domestic animals— including pigs with influenza and dogs with rabies and aquatic animals can also transmit pathogens. Climate change and urbanization may further disrupt rice agro-ecologies. This paper explores animal viral reservoirs, vectors, and historical practices associated with risk in rice farming. Climate and land use changes could enhance spillover. Solutions are proposed, including surveillance of animals, vectors, water, and air to detect threats before major outbreaks, such as improved biosecurity, hygiene, and livestock vaccinations. Ecological viral surveillance and agricultural interventions together can reduce zoonotic transmission from rice farming.

1. Introduction

Every year on the 4th day of the 6th Lunar month's waning moon - generally in early May - Cambodians gather at Veal Preahmein Square across from the Royal Palace, to celebrate Preah Reach Pithi Chroat Preah Nongkoal, also known as the Royal Plowing Ceremony. During this ceremony, two royal oxen bedecked in red and yellow silks are brought in front of offerings displayed in seven golden trays: corn, sesame seeds, beans, grass, wine, water, or rice. By observing how the oxen interact with the trays, Cambodians predict a wide range of events, including rainfall, floods, famine, and, importantly, rice harvest size.

Rice is one of the most important foods in the world. For Asia alone, nearly 70% of all calories consumed derive from rice-related products [1]. While it is widely debated exactly where rice cultivation first started, the importance of rice is ingrained in the culture and history of countless cultures throughout Asia and Africa [2]. Indeed, all over Asia, the phrase "Have you eaten rice?" is a common greeting followed after the standard salutation "How are you" (Fig. 1). The exact origins are largely unknown, but this expression may have originated due to food shortages and famines experienced by these regions, or it merely signifies the emphasis placed on rice as a key to life.

In Cambodia, a least developed country (LDC) in the Greater Mekong Subregion of Southeast Asia, nearly 70% of the population is involved in rice farming, making up nearly 30% of the country's GDP [3]. Cambodia's deep-rooted rice history dates back to as early as the 11th century CE, with manuscripts depicting rice as offerings to Shiva Linga first discovered in the Ek Phnom Temple in Battambang, Cambodia [4]. Cambodian rice farms function as mixed-usage areas with a wide variety of crops as well as animals, both wild and domestic, allowed to roam these areas for food and shelter. In addition, from respiratory infections and zoonotic spillover to mosquito-borne illnesses, Cambodia is a hotspot for endemic and emerging infectious diseases [5]. Therefore, taken together, Cambodia's abundance of farms, high dependence on agriculture, rapid urbanization, and expansive biodiversity represents a potential high-risk area for zoonotic spillovers in rice-rich regions. (Fig. 2).

2. Ricefields and zoonotic pathogens: air, land, and water

2.1. Bats

Bats are among the most diverse mammals, making up nearly 22% of all known mammalian species [6]. Bats also harbor remarkable viral diversity and are unfortunately stigmatized for their viral capacity. Since

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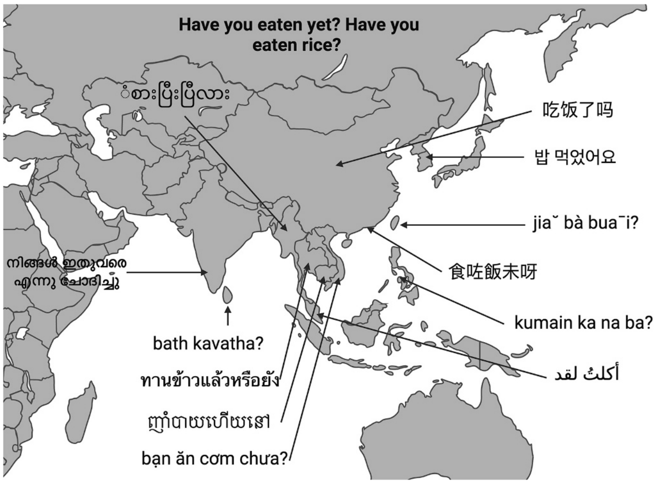

Fig. 1. Common greeting phrases of Southeast Asia involve rice and eating.

their first association with the rabies virus in the 1930s, bats have been associated with a multitude of viruses ranging from respiratory illnesses like SARS-related coronaviruses to hemorrhagic illnesses such as the Marburg virus. Of the large variety of bat species, bats are also associated with many viral families, such as lyssaviruses, filoviruses, coronaviruses, henipaviruses, and rhabdoviruses, many posing as significant threats to humans capable of zoonotic cross-species transmission. With the sizable potential for zoonotic spillover between bats and humans increasing linearly with human-to-bat exposure, there is a significant need for viral discovery and surveillance efforts (Table 1).

In Cambodia, bats are a common sight near rice fields and have a significant impact on the microenvironments in these areas. As most rice farms in Cambodia are mixed farms with a variety of tropical fruit trees, flying foxes (*Pteropus lylei*) can often be observed feeding. The same type of flying foxes is known to be potential carriers of the highly pathogenic Nipah virus [7]. However, Nipah has not been detected in Cambodia since 2003 [7,8]. Similarly, insectivorous and fruit bat species help manage the rice field insect population (see Vector species below) and are important in maintaining ecological balance through pollination and providing essential nutritional sources for the plants and animals on the ground with their nitrogenous guano [9,10]. Importantly, as the overlap between people and bat populations increases, so too does the potential for zoonotic diseases to emerge. The close proximity of bats to humans and the animals inhabiting rice farms, paired with their increasing presence in rice field farms, increases the risk of zoonotic spillover, making it essential to surveil bat populations for emerging infectious diseases.

Table 1
Examples of animals found in ricefields and potential zoonotic pathogens: Air, land, and water.

Animals	Pathogens of concern
Bats	Rabies, SARS-related coronaviruses, Lyssaviruses, Filoviruses, Coronaviruses, Henipaviruses, Rhabdoviruses.
Vector species (Mosquitoes, ticks, flies, fleas)	Mosquitoes (Dengue virus, other arboviruses), Ticks (Rickettsial infections, etc.), Fleas (Flea-borne spotted fever, etc.)
Rodents (Rats, mice, shrews)	Plague, Hantaviruses, Leptospirosis, Toxoplasmosis, Brucellosis, *E. coli*, Swine Influenza, Salmonella, Hepatitis, Tularemia
Household Pets (dogs and cats)	Rabies, Toxoplasma gondii, Hookworms, *Bartonella henselae*, Influenza A, Avian Influenza,
Large and small ruminants (water buffalo, cow, cattle, sheep, goats, camels)	Zoonotic bacteria and protozoa (Brucella, *Dermatophilus congolensis*, *E. coli*, *Leptospira interrogans*, Listeria monocytogens, *Giardia lamblia*, Cyrptosporidium), Foot and mouth disease, Bovine virus diarrhea, Schistosomiasis, Rotaviral infection, Q fever, Orf virus, Mad cow disease, Rift Valley fever
Swine (pigs, hogs, feral swine)	Influenza subtypes, African swine fever, Japanese encephalitis, Nipah virus, Coronaviruses.
Avian species (ducks, chickens, wild birds)	Avian Species Avian tuberculosis, Erysipelas, Ornithosis, Cryptococcosis, Histoplasmosis, Salmonellosis, Escherichiosis, Avian Influenza
Aquaculture (fish, clams, snails)	Enteric pathogens (Norovirus, Sappovirus, Astrovirus, etc.), Hepatitis A virus, Rat lungworm, parasitic diseases (Schistosoma), Fish-borne zoonotic trematodes (FZT)

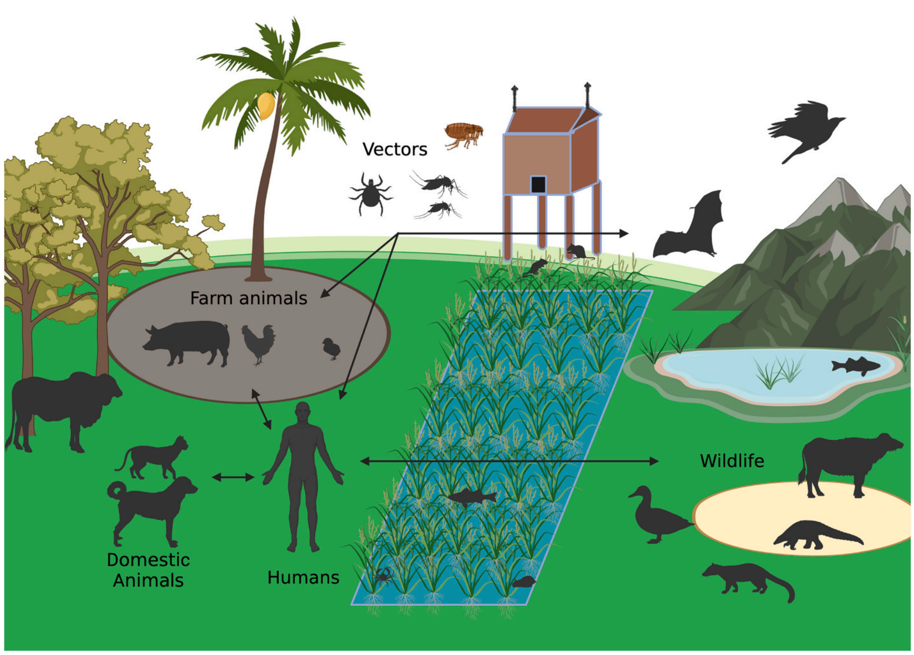

Fig. 2. The characters at play in rice farming ecosystems in Cambodia.

3. Vector species (mosquitoes, ticks, flies, fleas)

Vector-borne diseases cause significant morbidity and mortality in humans and livestock species around the globe. Rice fields are particularly attractive to vector species as there are animal reservoirs, sufficient and consistent moisture, water, and nutrients for extended reproduction [11]. Mosquitoes, despite their diminutive stature, are one of the deadliest creatures throughout history. Currently, known mosquito-borne pathogens include a multitude of arboviruses, e.g. Dengue virus and Japanese Encephalitis (JE), and parasites, e.g. Plasmodium (malaria), that are capable of significant diseases that can result in severe illness with potential permanent neurological damage and even death [11]. Worldwide, these mosquito-borne pathogens infect millions, with nearly 96 million annual symptomatic cases of dengue virus alone, with Cambodia holding one of the highest incidence rates [12,13].

Rice fields are home to nearly 40 mosquito species, many capable of harboring disease [14]. During the rainy season in Southeast Asia, the mosquito population nearly doubles as rainwater and flooding increase the number of potential larval habitats [15]. In addition, large outdoor water barrels, jars, cisterns, pots, and other trash containers capable of holding pools of water suitable for mosquito propagation are often scattered around the fields.

In addition to mosquitoes, rice fields are also home to populations of ticks, fleas, flies, and other vectors capable of disease transmission to humans and animals. In Southeast Asia alone, there are nearly 97 species of ticks, many of them capable of carrying diseases that affect humans and wildlife [16]. Rickettsial infections, caused by bacteria of the *Rickettsia* genera, can be transmitted by ticks, fleas, and mites and results in a broad spectrum of disease in humans and animals. Transmitted via fleas, *R. felis* is harbored in dogs in Cambodia and can cause flea-borne spotted fever in humans [17]. Murine typhus *R. typhi,* which is harbored in rats and transmitted by fleas, is prevalent in young children in Cambodia, as determined through a seroprevalence screening conducted in 2019 [18]. Rickettsial infections only make up a small portion of the vector-borne pathogens detected in Cambodia, with *Anaplasma platys*, *Ehrlichia canis*, *Mycoplasma haemocanis*, and *Babesia vogeli* being a few others that affect a large population of animals and some humans [19]. To date, very little is known about tick-borne viruses in Cambodia, requiring further, active surveillance efforts. Flies can transmit parasitic diseases such as Leishmania in humans and Surra (*Trypanosoma evansi*) in animals [20,21]. Also, for these vectors, little data exists for Cambodia.

Along with the mosquitoes themselves, wild and domestic animals inhabiting Cambodian rice fields (described in more detail below) are capable of acting as lasting pathogen reservoirs of vector-borne disease. Due to increased reliance on irrigation-based agriculture, such as rice fields, breeding habitats for *Culex tritaeniorhynchus* (*Cx. Tritaeniorhynchus*) mosquito vectors have expanded, leading to increased rates of JE in reservoir species such as domestic pigs and possibly spreading to secondary hosts such as domestic dogs [22,23]. Similarly, West Nile virus (WNV), a mosquito-borne zoonotic flavivirus, is known to be harbored and amplified in bird populations plagued by mosquitoes [23,24]. These lasting reservoirs enable viruses to spread within communities and beyond as these animals, along with the mosquitoes themselves, migrate throughout the country [25,26]. While bat-mosquito-human transmission is yet to be proven for any disease, there are known vectors such as *Ae. aegypti, Ae. albopictus,* and *Cx. quinquefasciatus,* which feeds on both humans and bats, increasing the potential for this mode of transmission [23]. These findings demonstrate the potential for vector-borne spillover to be a significant public health concern in the rice field environment.

4. Rodents (rats, mice, shrews)

Rodents such as rice field rats (*Rattus argentiventer* and *Rattus rattus*), mice (*Mus musculus*), and shrews (*Crocidura fuliginosa*) are prevalent in rice fields across Southeast Asia [27]. While there have been significant strides to monitor and control rodent populations, such as maintaining agricultural hygiene in field margins to prevent rodent infestations and community rat hunts, rodents continue to contribute to the biodiversity of rice field microenvironments through manifold mechanisms such as weed management [1,28]. Aside from the devastating impacts they can have on food harvest, rodents can also harbor numerous diseases, from plague to viral hemorrhagic fevers [29].

Rodent-borne diseases pose a significant threat to humans and animals, especially in rodent-dense areas such as rice fields. As rodent habitats are often built on ground level and in vegetation on rice fields during the rainy season in Cambodia, rodent habitats can be disrupted by routine flooding, increasing the risk of leptospirosis spillover. Leptospirosis is a bacterial infection that can be transmitted through indirect contact with water contaminated by infected rodent feces and urine, causing moderate disease in human infections [30,31]. Also carried in rodent feces and urine, hantavirus transmission can occur in humans upon inhalation of the aerosolized virus from rodent droppings and often presents severe disease in humans [32].

As there are many food sources found on rice fields, rodent feces can also potentially contaminate food sources and expose individuals and other animals to multiple pathogens. Hantavirus and hepatitis viruses are well-known rodent pathogens. Human hantavirus infections can be lethal, with severe syndromes occurring in a small proportion of infected humans, such as hemorrhagic fever with renal syndrome (HFRS) and hantaviral cardiopulmonary syndrome [33]. Although there has only been a few clinical cases of hepatitis E virus (HEV—C), HEV-C shares approximately 50–60% of the HEV-A genome, making future human transmission possible [34]. Although hantavirus, hepatitis viruses, arenavirus, and leptospirosis spillover are relatively rare in Cambodia, the abundance of rodents on rice fields increases the risk of future rodent-related pathogen spillover [35,36].

5. Household pets (dogs and cats)

Whether for pest control, security, or general companionship, many rice farmers live in close contact with domestic and stray animals (dogs and cats) on the farm premises. From *Bartonella henselae* to influenza, both dogs and cats are capable of being disease reservoirs for multiple pathogens [37,38]. Although relatively small in human population size, Cambodia has one of the highest incidence rates of rabies in the world, with nearly 375,000 dog bite injuries and 800 cases of human rabies estimated annually [39]. Aside from rabies, 50.5% of dogs sampled in northern Cambodia have tested serologically positive for *Toxoplasma gondii,* the etiological agent for toxoplasmosis, with similarly large rates of hookworms [40]. And to the East of Cambodia, in Vietnam, nearly 70.7% of the dog population were seropositive for flaviviruses acting as sentinels for the impact of flaviviruses in the cities [41]. Outside of Cambodia, domestic cats have been shown to be infected with SARS-CoV-2 and able to transmit to previously uninfected animals that are housed near them [42,43].

Within the last two decades, considerable attention was placed on influenza A infections in dogs and cats. In a cat shelter in New York City in late 2016, a veterinarian treating a cat infected with avian influenza A/H7N2 also became infected with the virus, confirming cat-to-human transmission route [38]. Additionally, dogs have demonstrated susceptibility to pandemic H1N1 influenza (pdmH1N1) and human-canine reassortment H3N2, although these strains have not caused any major zoonotic events [44]. Recently, highly pathogenic A/H5Nx clade 2.3.4.4 viruses have been identified as canine and feline pathogens of concern, as both dogs and cats are readily infected by these viruses [45–47]. Therefore, given the large population of domestic and stray animals living alongside the general population in Cambodian farms and rice fields, there is a significant need for viral surveillance in these populations.

6. Large and small ruminants (water buffalo, cow, cattle, sheep, goats, camels)

Coupling livestock farming with rice production (Fig. 3) is common for many smallholder farmers around Southeast Asia, including in Cambodia [48]. Large (i.e., cattle, camels, domestic water buffalo) and small ruminant animals (goats, sheep) are essential livestock species in rice-growing regions as they are a source of high-quality milk and meat and are also used for plowing rice fields and transporting harvested crops to local markets [48].

Wild and livestock species of small and large ruminants can also serve as pathogen reservoirs for zoonotic emerging infectious diseases [48,49]. Wet conditions in rice fields serve as a medium for the spread of disease-causing bacteria (i.e., *Brucella, Dermatophilus congolensis, E. coli, Leptospira interrogans, and Listeria monocytogens*) and protozoal parasites (i.e., *Giardia lamblia, Cryptosporidium*) that are the causative agents of numerous zoonotic diseases that can be transferred from small domestic ruminants to other ruminants and humans [50,51]. Large ruminants can be susceptible to diseases like foot and mouth disease (FMD), bovine virus diarrhea (BVD), schistosomiasis, fascioliasis, rotaviral infection, leptospirosis, brucellosis, and tuberculosis under particular epidemiological situations (for instance, submerging in muddy water in rice fields and co-mingling with other species) [52]. Schistosomiasis is of particular interest as it is highly prevalent in regions near the Mekong Delta in Cambodia such as Kratie and Stung Treng [53]. Small ruminants are associated with the transmission of various pathogens to humans through direct or indirect contact of feces, urine, milk, or blood from an infected animal, e.g., Q fever (*Coxiella burnetii*), Orf virus (parapoxvirus) infections, mad cow disease (bovine spongiform encephalopathy), and Rift Valley fever [50]. Changes in human behavior in animal handling and consumption of food influence and contribute to future risks of zoonosis in large and small ruminants. While spillover events are rare in humans, continuous monitoring, prevention, and biosecurity measures become vital in limiting the spread of disease and the effective containment of future outbreaks.

7. Swine (pigs, hogs, feral swine)

Traditionally, pig farming in Southeast Asia has been concentrated in major rice-production areas, as farmers relied on rice production to feed the pigs and pig manure to fertilize the soil [54]. Urbanization and economic development bring changes in demand for agricultural products, including pork production, both from growth in population size and shifts in diet demands [55].

The expansion and intensification of pig husbandry can increase the risk of a number of zoonotic viruses, including the emergence and spread of novel influenza subtypes, African swine fever, Japanese encephalitis, Nipah, and coronaviruses [56]. Intensification of pig farming and increased demand for pork are also linked with the zoonotic risk of swine influenza A virus (swIAV) and the transmission and circulation of multiple classical swine influenzas [57]. At the same time, wild hogs exist in rice fields as destructive pests, carrying diseases that spread to other livestock and damaging crops. There are at least thirty different harmful pathogens carried by feral swine that can infect humans, including diseases such as toxoplasmosis, brucellosis, *E. coli*, swine influenza, salmonella, hepatitis, and tularemia [56]. These livestock living in close contact with other wild animals, vectors, and humans create an interface for disease emergence and spillover events with future pandemic potential [56]. As pig-rearing operations globally continue to expand and intensify, routine and sustained surveillance methods, like metagenomic surveillance of air and wastewater sampling, become critical on large farms and slaughterhouses for effective human and animal pathogen control.

8. Avian species (ducks, chickens, wild birds)

Rice production has many forms but traditionally occurs under flooded conditions and, if managed aptly, can provide habitats for many avian species, including both wild and domestic birds. Waterfowl, wading birds, shorebirds, and free- and semi-free-ranging domestic poultry use rice fields as food resources for nesting, breeding, rest, and refueling during migration [58]. Alongside species traditionally

Fig. 3. *(A)* Drone-captured image of integrated rice-farming production in Prey Veng Province, Cambodia *(B)* Cattle on a rice farm in Kampot Province, Cambodia *(C)* Puppy on a rice field in Prey Veng Province, Cambodia *(D)* Ducks in water at a duck farm in Prey Veng Province, Cambodia.

considered "waterbirds," a wide variety of other species also use this natural terrain [59]. These include land birds such as kingfishers and wagtails, marsh-nesting songbirds, other small granivorous birds, and large birds (raptors and owls) that are attracted by the high densities of small mammals present in the field [59].

Aside from rice fields providing avian species with foraging and shelter, rice growers can also benefit from reduced agronomic costs and the need for artificial fertilizers [59]. As domestic and wild birds tear up weeds and prey on pests, they also leave manure behind as organic plant food. This mutualistic approach to integrated rice-duck farming was documented in China some 600 years ago and still remains a popular practice for many rice farmers and duck breeders in Southeast Asian countries [60].

As a habitat, rice fields present a double-edged sword for zoonosis that holds great spillover potential. Zoonotic diseases associated with birds include avian tuberculosis, erysipelas, ornithosis, cryptococcosis, histoplasmosis, salmonellosis, and escherichiosis [61]. The ecology of the avian influenza virus (AIV) in rice paddy fields involves an intricate web of drivers. The abundance of juvenile domestic ducks—immunologically naive and susceptible to infection—and wild aquatic birds feeding in intensive rice cropping areas has been identified as one such risk factor associated with outbreaks of highly pathogenic avian influenza (HPAI) H5N1 virus circulation [61]. Furthermore, with fluctuations in temperature in rice paddy fields, AIV can remain virulent for several months in water and feathers, making indirect contact with active AIV more likely between avian species and other animals [62].

Cambodia continues to serve as a major hub for endemic and emerging infectious diseases, including AIV. A total of approximately 30–50% of ducks and 20–40% of chickens tested positive for AIV in live bird markets (LBMs) [63,64]. Including the emerging avian pathogenic flavivirus and the Avian Tembusu virus (TMUV) [65]. The lack of biosecurity on small-holder farms may act as a driver in increasing the risks of AIV infections, AMR transmission [65], and avian flaviviruses in domestic and wild birds. As rice, waterbird, and livestock farming continue to be coupled and are in high demand in Cambodia, there is a need for improved surveillance and biosecurity in such intensive agricultural areas that serve as an interface between domestic, wild, and vector species.

9. Aquaculture (fish, clams, snails)

Freshwater fish play an integral part of the Cambodian diet. In addition, other freshwater aquatic animals such as amphibians, mollusks, crustaceans, and aquatic insects are a staple source of food for the rural poor due to their abundance and availability, contributing up to 12% of total energy intake [66]. During the rainy season, rice paddy fields become an extension of the floodplain wetlands, allowing these species to flourish (Fig. 2). However, diseases in aquaculture can present a major problem for food production when accompanied by emerging and re-emerging diseases in humans, whose causative agents may be known or unknown [66]. The most common source of infectious waterborne disease exposure in humans is enteric pathogens transmitted mainly through contaminated water used for drinking, cooking, or consumption of filter-feeding bivalve shellfish [67]. Viruses associated with these common foodborne diseases include norovirus, sappovirus, astrovirus, and many others. Hepatitis A virus (HAV) can be transmitted through the consumption of blood clams (*Tegillarca granosa*), a signature dish in Southeast Asia, including Cambodia [68].

A species of snail (*Pomacea canaliculata*), commonly known as golden apple snails, is not only a significant threat to rice crops but also serve as intermediate hosts for rat lungworm (*Angiostrongylus cantonensis)*, a causative agent of human angiostrongyliasis [66–68]. Rat lungworm and fish-borne zoonotic trematodes (FZT) are endemic in parts of East and Southeast Asia [62,64,66]. There are five types of metacercaria found in Cambodia, *Opisthorchis viverrini, Haplorchis yokogawai, Haplorchis pumilio, Centrocestus formosanus, and Procerovum* many of which can cause disease [69]. Of these parasites, *Opistothorchis* viveririni infections are highly prevalent in Cambodia from a 2019 study, and can even cause a rare duct cancer called cholangiocarcinoma [69,70]. In 2012, over 2904 cases of human angiostrongyliasis were recorded globally, including in China, Thailand, Laos, and Cambodia [71]. Infectious diseases like these all have the potential to cause prolonged illnesses and unknown infectivity for humans and other species, such as classical fever of unknown origin (FUO) [72]. In addition, to add to the recurrent issue of AIV, some research suggests the presence of sails in rice fields modulates the retention time of AIV in surface water, increasing the risk of AIV infection in wild and domestic birds that consume them [73].

10. Rice farming in a changing social, economic, and physical climate

The convergence of rapid urbanization and climate change alters traditional rice farming and ultimately increases our collective risk of infectious diseases. Elevated temperatures and shifting precipitation patterns associated with global climate change can disrupt the delicate ecosystem required for rice cultivation. These changes, such as extreme temperatures (low or high) during critical rice growth stages, can significantly decrease total crop yield [74,75]. While rice is a relatively resilient crop, excessive or inadequate rainfall heightens flooding or drought risk, which can devastate rice crops and the fertility of the land [76]. Over the past 20 years, one study found that extreme rainfall reduced rice yields by nearly 8% in China [77]. Climate change also increases the incidence of extreme weather events, such as floods and droughts, both known to ravage agricultural lands and further spread pathogens into areas of contact with humans or wild/domestic animals [74]. Pests and other harmful pathogens to rice can also increase in the warmer and more humid conditions associated with global climate change [78,79]. But climate change isn't just increasing food scarcity. Multiple studies suggest that climate change also increases the chances of spillover [75,76,79]. Many factors contributed to the first Hendra virus spillover event in 1994 in Queensland, Australia, and climate change likely played a large role. Flying foxes, the primary reservoir for Hendra virus, rely on the eucalyptus trees in open forests, and due to poor flowering conditions from climate change, flying foxes ventured further and further into more human-occupied areas, increasing the chance of Hendra virus spillover [11,80,81]. Importantly, the geological characteristics of rice farms make them excellent environments for flying fox habitats, increasing the possibility of disease transmission occurring in these environments [82]. The slow marching overlap between animals and humans increases the chances for spillover events. Changes in the ecological landscape can also change the distribution of wild waterfowl and their flyways, redirect their stopover areas, and alter transmission dynamics of avian influenza viruses, causing novel introductions of AI or new clades in different areas [83].

As cities expand, rapid urbanization also places significant strain on rice production and increases spillover risk. As populations grow, fertile croplands are more often converted into urban settlements, and people enter previously untouched ecosystems, reducing the total land available for rice farming and increasing contact with zoonotic disease [84]. These land changes can create unintended spillover risks as people are inhabiting land that was formerly intended for rice farming, increasing contact between wild animals and humans. However, there are positive qualities brought to rice farming through rapid urbanization. Proximity to urban areas often leads to higher access to farming technology, increasing the efficiency of rice farming. Similarly, rice farmers have more ready access to a global market; however, there is often increased competition in a globalized market. Likewise, urbanization can lead to more developed roads and transportation methods, enabling safer and more efficient movement of rice to the market. However, the transformation and increased proximity of these domestic properties to rice fields also bring people closer to animals, increasing the risk of spillover.

Yet, amidst these challenges lies the potential of innovation and adaptation. In the context of climate change, some farmers are utilizing varieties of rice known for their resilience and techniques to farm rice using less water, while others are exploring transgenic strains that produce 99% less methane and are associated with higher yields [85,86]. In the field of pathogen surveillance, new developments in environmental surveillance systems and technology can improve early warning systems capable of notifying us of pathogen risks of outbreaks before they occur. Although these systems offer significant advantages in the early detection of pathogens within an environment, more cost-effective development may be needed before mass implementation.

11. Discussion

Taken together, the rice paddies could represent a high-risk interface for zoonotic spillover as these environments significantly overlap between animals, disease vectors, and humans. With minimal vaccines and treatment selections for emerging zoonotic diseases, swift and systematic surveillance systems are the first line of defense. In recent years, there has been growing interest in environmental sampling as an early detection strategy for zoonotic pathogens. Southeast Asia represents a hotspot for endemic and emerging infectious diseases, including AIVs, human seasonal viruses, bat-borne henipaviruses and coronaviruses, and rat-borne hantaviruses.

Biosecurity challenges arise as animals are reared outdoors, as it increases contact with disease vectors, including rodents, birds, mosquitoes, and other insects [87,88]. Foods and organic produce from mixed rice and livestock farming are at greater risk for various enteric bacterial pathogens for humans as they are sold in farmers' markets and roadside stands [87]. Since most biosecurity programs require time to implement, it becomes necessary for smallholder farmers to focus on agriculture hygiene and routine vaccinations to protect livestock and crops from pests and disease.

Environmental surveillance paired with animal sampling can meaningfully contribute to preventing future spillover events. A system where local farms, local veterinary services, and research entities can continuously collaborate in which animal and environment samples can be obtained and tracked over time. Environmental sampling in rice fields includes water samples from lakes, ponds, and paddies, swabs from feeding sources, feathers, and surfaces, including cages and defeathering machines, field collected vectors, animal droppings, and air samples. This longitudinal approach enables active surveillance of pathogens in Cambodia, contributing to current knowledge of endemic viruses and acting as a monitoring system for merging zoonotic pathogens of concern [89].

In addition to increasing the use of surveillance systems using environmental and direct animal sampling, marked improvements in biosecurity measures in small-holder farms near rice paddy environments, such as the use of vaccinations for farm animals, proper disposal of animal carcasses, and separation from wild and domestic animals, have the remarkable potential to reduce the risk of spillover. Further, to enhance the association between improved animal health and rural livelihoods, livestock and poultry development programs should implement a systems approach accompanied by public awareness campaigns to enhance small-holder farmer Knowledge, Attitude, and Practice (KAP) in biosecurity, nutrition, and marketing of farm animals. Such biosecurity strategies within least-developed countries such as Cambodia are necessary for the overall improvement of food security, livestock, poultry, and fisheries market development, and agriculture sustainability. Finally, a combinatorial approach of biosecurity and pathogen surveillance in rice paddy fields and surrounding smallholder farms may significantly reduce the potential for zoonotic spillover. Ultimately, the complexity of infectious diseases in aquaculture and other species in rice fields requires a holistic approach, mainly using surveillance of vector-borne diseases and transmission cycles and interventions during different seasonalities.

Declaration of competing interest

We do not hold any competing interests.

Data availability

No data was used for the research described in the article.

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