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Review

An overview of avian influenza surveillance strategies and modes

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ABSTRACT

The global epidemic of avian influenza has imposed a substantial disease burden, inciting substantial societal panic and economic losses. The high variability and associated uncertainty of the influenza virus present significant challenges in its prevention and control. As a pivotal strategy for the mitigation of avian influenza, the surveillance network has shown considerable growth at both global and regional levels. This includes the expansion of surveillance coverage, continuous refinement of monitoring content and scope, and rapid enhancement of monitoring quality. Although the ultimate goal of avian influenza surveillance remains uniform, strategies and models vary, reflecting regional or national differences in surveillance system frameworks and their implementation. This review collates and examines the features and experiences of global, regional, and national avian influenza surveillance efforts. Furthermore, it delves into the surveillance system modalities in light of the "One Health" concept, which includes the establishment and enhancement of interdisciplinary and cross-sectoral coordination and cooperation among medical, veterinary, and public health institutions, and the sharing of surveillance information for timely alerts.

1. Background

The avian influenza virus (AIV), primarily responsible for bird infections, is a subtype of the influenza A virus. This variant, belonging to the *Orthomyxoviridae* family, is further divided into 19 hemagglutinin (HA) subtypes and 11 neuraminidase (NA) subtypes (ranging from H1 to H19, and N1 to N11, respectively) [1–4]. This classification is based on the existence of two envelope glycoproteins on the virus surface, named HA and NA. Depending on the degree of bird infection, the AIVs are categorized into two groups, low pathogenic avian influenza (LPAI) and high pathogenic avian influenza (HPAI) viruses. Almost all AIV subtypes are maintained and circulated within wild birds [5–8]. The main sources of infection are infected birds or birds carrying the virus. Transmission primarily occurs through interaction with these infected birds or through exposure to their secretions, excretions, or the virus-contaminated environment [9]. AIVs can breach species barriers to infect humans, pigs, horses, minks, and even marine mammals [10–13]. The migratory patterns of birds significantly impact the global distribution of avian influenza, posing a serious threat to both poultry and public health.

AIV has the potential to inflict substantial economic loss on the agricultural industry through the extensive mortality and forced culling of livestock following an AIV outbreak [14]. For instance, the H7N9 outbreak which occurred from February to May 2013 in the Chinese mainland, precipitated an estimated economic loss in the poultry sector reaching up to CNY 11.43 billion [15]. In recent times, there has been an increase in sporadic cases and even outbreaks of HPAI H5 in mammals, including minks, otters, foxes, and sea lions [16]. In 2022, more than 25 million domestic and wild avian animals worldwide contracted the HPAI H5 virus, culminating in an approximate death toll of 5.28 million [17].

AIVs have been known to breach species barriers, transitioning from avian hosts to mammals, including humans. This interspecies transmission constitutes a substantial public health concern due to the high rates of morbidity and mortality associated with human avian influenza infections. Within the past two decades, at least six HA subtypes of AIVs, specifically H3 (H3N8), H5 (HPAI H5N1, H5N6, and H5N8), H6, H7, H9 (LPAI H9N2), and H10, have been reported to cause infections in humans [7,18], resulting in a total of 2,754 infections and 1,120 fatalities worldwide since 1977 [18]. Although human-to-human transmission remains limited and non-sustained [19,20], the potential for H5N1 and

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H7N9 viruses to instigate an influenza pandemic is considerably greater than that of other AIV subtypes [21,22]. Recent avian influenza epidemics have led to significant losses in various animal populations, including poultry, wild birds, and some mammals, as reported by the World Organisation for Animal Health (WOAH); the surveillance data of these outbreaks since 2022 across ten countries and three continents draws particular attention to the escalated infection rates among mammals [23]. This uptick prompts concerns about the virus's potential to adapt and pose an increased infection risk to humans [18,24,25]. Avian influenza surveillance is paramount for early detection and swift response to human avian influenza epidemics. In this paper, we aim to determine an effective avian influenza surveillance model by reviewing various current national, regional, and global avian influenza surveillance systems and mechanisms.

2. Contents and methods of surveillance

Prevention and control of avian influenza disease hinges fundamentally on minimizing exposure risks. Research demonstrates a predilection for human infection with AIVs after either direct or indirect contact with infected or deceased birds, or environments contaminated with virus particles [26]. Further studies have likewise identified interaction with live poultry, particularly in live poultry markets, as a significant risk factor for human infection with HPAI H7N9 [27,28]. Our past case control investigations disclosed that the independent risk factors for H5N1 infection, according to multivariable analyses, were direct contact with sick or dead poultry [odds ratio (OR) = 506.6], indirect exposure to such poultry (OR = 56.9), and visits to wet poultry markets (OR = 15.4) [26]. These findings suggest that AIV monitoring in birds, animals, and potentially contaminated environments would provide reliable and timely inputs for early risk awareness and threat warnings for avian influenza, which is crucial to public health. Presently, global avian influenza surveillance primarily involves wild birds, poultry, related environments, human cases, and high-risk populations (Fig. 1). The surveillance content and methods differ accordingly (Table 1).

2.1. Surveillance of wild birds

Wild birds serve as primary reservoirs for AIVs and play a crucial role in their preservation, dissemination, and cross-species transmission [29]. Commonly seen in major resting areas such as freshwater lakes and wetlands, diverse bird species follow fixed migration routes that are conducive to the transmission of AIVs among them [30]. As such, avian influenza surveillance in wild birds is primarily conducted along the eight significant flyways: Atlantic, Black Sea–Mediterranean, East Africa–West Asia, Central Asia–India, East Asia–Australia, America–Pacific, America–Mississippi, and America–Atlantic.

Avian influenza surveillance in wild birds leverages three key strategies [31]. First, active surveillance is undertaken by trapping birds or hunting waterfowl in specific avian habitats or high-risk areas that have previously reported avian influenza outbreaks [32,33]. Second, passive surveillance is largely performed by investigating unusual bird fatalities and noticeable clinical signs in infected birds [34,35]. Finally, sentinel surveillance is employed in typical habitats by monitoring morbidity and mortality among domestic ducks, often selected as sentinel birds for wild counterparts [36–38]. Samples including cloacal swabs and fecal specimens collected within 24 h, oropharyngeal swabs, environmental samples from water and soil matrices, blood samples, and feathers, are gathered for subsequent serological and pathogenic evaluation [39].

2.2. Surveillance in domestic poultry

The targets for surveillance primarily encompass domestic fowl, waterfowl, and ornamental birds. It is worth noting that duck infection with AIVs has been found to be associated with migratory waterfowl [40], underscoring the importance of enhanced surveillance in ducks. Surveillance methodologies encompass clinical sign observation and laboratory examination. On poultry farms, surveillance may be achieved through monitoring signs associated with AIV infection in poultry. Infected poultry generally exhibit one or more clinical signs [41], including respiratory symptoms such as rhinorrhea, sneezing, coughing, as well as diarrhea, ataxia, diminished egg production, head tissue swelling or discoloration, and mass mortality. Observational surveillance is both convenient and manageable, and it is suitable for large-scale as well as free-range poultry farms. However, this method lacks both industry standardization and operational management protocols. In order to execute laboratory testing for surveillance, periodic collection of samples from pharyngeal and cloacal swabs, serum, and the environmental habitats of the poultry—such as the poultry houses—is required. Samples are then tested for AIVs. This active monitoring approach is more easily executable in large-scale commercial poultry operations.

2.3. Surveillance of cases in humans

Currently, the surveillance of human infection with AIVs primarily depends on medical reporting in healthcare facilities. Thailand, for example, has established a hospital-based sentinel surveillance network for human cases. Under this system, patients with respiratory symptoms, such as fever and cough, coupled with any epidemiological history of AIV exposure are reported by sentinel hospitals as avian influenza cases.

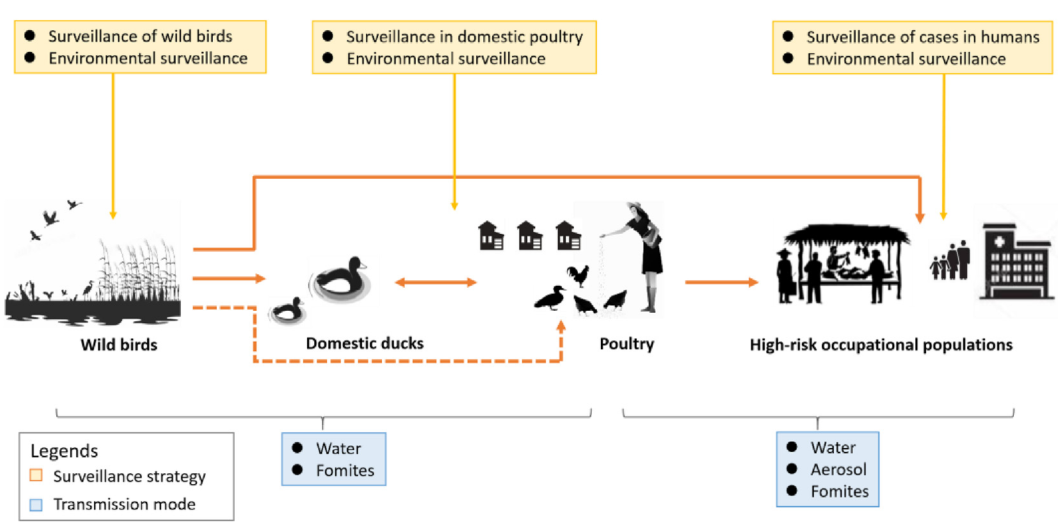

Fig. 1. Strategy and modes of avian influenza surveillance in different populations and settings.

Table 1
Summary of avian influenza surveillance strategies.

Objects	Priorities	Timelines	Areas	Modes
1. Wild birds	Migratory birds, such as wild geese and ducks	Peak migration period (August–December), epidemic prone period (February– March)	Habitats and pathways of migratory birds (wetlands, lakes), supplemented by surrounding areas	Active surveillance mainly Regular surveillance
2. Poultry and environment [52,103]	Live poultry trading markets, poultry slaughterhouses, poultry farms, poultry free-range households, poultry feces and cage surfaces	Year round	Areas and surrounding areas where outbreaks of avian influenza have occurred in humans or animals; areas with densely distributed rivers, lakes and other water bodies and developed waterfowl farming; habitats and pathways of migratory birds [104]	Active surveillance Real-time surveillance [65] Sentinel surveillance
3. Occupationally exposed population [105]	Persons who have direct contact with live birds and persons who have contact with wild migratory birds and their droppings	Winter and spring (October– March)	Same as above	Active surveillance mainly Regular surveillance Sentinel surveillance
4. Human avian influenza infections [52]	Contact with those who have relevant epidemiological history	Year round	Various medical facilities at all levels across the country	Passive surveillance

Various forms of exposure include interactions with poultry, deceased animals, living in areas with widespread poultry infections, a travel history involving influenza or pneumonia transmission areas, direct or indirect contact with pneumonia patients, among others.

Moreover, active surveillance of high-risk occupational populations is conducted in several countries. China, for instance, regularly performs active surveillance among high-risk occupational groups including large-scale poultry farmers, poultry traders, and poultry slaughtering and processing staff. This process involves monitoring symptoms, collecting respiratory and serum samples for pathogenic and serological testing, and investigating exposure histories and risk factors.

However, this type of passive surveillance mode, which hinges on medical reporting, shows a clear disadvantage in terms of timeliness and sensitivity detection and response. The implementation of novel surveillance approaches used extensively and effectively during the COVID-19 response [42–47], such as web surveys, telephone hotlines, or search engine queries, could potentially enhance the efficiency of detecting non-medically attended cases in the community [48].

2.4. Environmental surveillance

Utilized as an effective supplementary method, environmental surveillance has been employed in certain countries to keep track of AIVs in potentially contaminated environments. This process involves the collection and examination of varied sample types including feces, soil, water, avian feed sources, feathers, and surface swabs [49]. In China, surveillance measures entail the collection of poultry feces and surface wipes from live poultry markets, major poultry farms, areas densely populated by independent poultry farmers, poultry slaughter and processing houses, and both rural and urban wild bird habitats [39,50,51]. Typically, environmental surveillance pertaining to wild birds involves the collection and examination of feces, water, sediment or soil, and surface swabs [52].

While environmental samples are relatively easy to collect, the results of their analysis can be substantially influenced by factors such as temperature, pH levels and salinity [53]. Some studies reveal that the prolonged presence of LPAI viruses in lakes suggests the significance of the environmental matrix in the preservation and transmission of these viruses [32]. Notably, the probability of detecting HPAI virus in environmental samples has historically remained considerably low. Moreover, the difficulty in identifying the specific source of positive environmental samples limits the efficacy of environmental surveillance in the tracing and investigation of virus origins. However, with the advent of advanced technologies like third-generation sequencing, it is increasingly achievable to integrate environmental surveillance within standard avian influenza surveillance frameworks [49].

3. National surveillance systems and mechanisms for avian influenza

Currently, four major types of avian influenza early warning systems and mechanisms are being implemented in various countries.

3.1. Vertical veterinary systems

Examples of this surveillance system strategy can be found in both the United States and Australia, where a concerted, synergetic approach is taken that necessitates both federal and state entities working in tandem [54]. In the United States, the Animal and Plant Health Inspection Service (APHIS)—a branch of the United States Department of Agriculture (USDA)—concentrates its efforts on protecting animal health, animal welfare, and plant health. A subdivision of the USDA APHIS, namely the Veterinary Services (VS), takes the reins in facilitating ties with other agencies for monitoring avian influenza epidemics, conducting quality assessments for disease prevention and control measures, performing epidemic environmental and risk analyses, and supervising animal biological products. On the state level, analogous agricultural institutions are active, with responsibilities and roles in animal health agreed upon between APHIS and the individual state's veterinary agency. Turning to Australia, the federal veterinary authorities hold a central coordinating role, with their main duties revolving around international animal health issues. Such responsibilities include quarantine enforcement at points of entry and exit, quality certification, trade agreement negotiation, and policy formulation.

3.2. Inspection and quarantine system

Stringent entry and exit quarantine and inspection procedures have been adopted by countries like the United States, Singapore, and Australia to deter the ingress of avian influenza from external sources [55]. One such instance is Singapore's robust multi-tiered avian influenza surveillance regime developed to stave off the introduction of HPAI AIVs. The first tier involves employing control measures at the source, which includes barring the importation of poultry, eggs, birds, and other poultry products from nations affected by HPAI AIVs. In an effort to maintain the safety of eggs and poultry supply at the source level, the Agri-Food and Veterinary Authority (AVA) has collaborated with corresponding entities to establish Disease-Free Zones (DFZs) in the exporting nations. Controlling measures at borders form the second tier: all imports of poultry, birds, eggs, and avian products are subjected to health certificate inspection by AVA officials at the entry port. Furthermore, all live ducks must test negative for AIV before they qualify for export to Singapore. Poultry and eggs selected at random are also tested for the presence of

HPAI AIVs. The AVA additionally makes vigorous efforts to prevent smuggling of birds and avian products.

3.3. Surveillance and early warning mechanism (passive mode)

A relatively comprehensive surveillance and early warning mechanism for avian influenza has been established by industrialized nations such as the United States and Australia. This system predominantly oversees outbreak reporting, diagnosis, and testing. In the United States, for instance, during the initial stages of outbreak reporting and diagnosis, individuals or official poultry disease diagnostic agencies report all detected avian influenza outbreaks to the state government's Chief Veterinary Officer (1). Should the disease evade immediate diagnosis, the designated veterinarian must submit samples to the state veterinary laboratory within 24 hours (2). In terms of testing, several avian influenza laboratories with standardized management have been established. Notably, this includes the world's most advanced and largest reference laboratory for avian influenza, accredited by the World Organization for Animal Health (OIE). This laboratory is authorized to predict the evolution of avian influenza and adjust surveillance programs accordingly (3). Regarding information collection, surveillance stations for wild birds and an early monitoring information system for HPAI AIVs have been instituted. These measures enable early disease detection, thereby allowing more time to mitigate the disease in its incipient stages. In Australia, a national Animal Health Information System has been established for monitoring avian influenza outbreaks.

3.4. Risk-based avian influenza surveillance program (active mode)

Within the United Kingdom (UK), a risk-based surveillance program, specifically tailored to the unique risk factors and assessment criteria of avian influenza, has been developed for the purposes of ongoing surveillance and early warning. By generating detailed avian influenza risk maps and identifying high-risk areas, the program is capable of directing greater surveillance efforts to the top 20% of these critical zones. This allows the government to conduct active surveillance measures to precisely investigate the inherent risks existing within the interplay between poultry and wild birds, as well as within interactions between healthy and infected poultry. This dynamic surveillance strategy offers a solution to the shortcomings of the conventional passive poultry disease reporting system by emphasizing poultry movement as well as transfer of poultry products and potential contaminants.

Significantly, the swift advancement of new technology has resulted in considerable alterations to the system and mechanisms of avian influenza early warning. The introduction of nanopore sequencing technology allows for efficient collection of AIV strains from wild birds' feces and poultry, as well as promotes rapid, on-site sequencing and subtyping [56], enhancing inquiry and tracking exploration efficiency.

Mathematical modelling studies augment the comprehension of avian influenza outbreak onset and elucidate the involved risk factors [43,57,58]. Various modelling strategies including time-series analyses [59], spatiotemporal risk prediction models [60,61], social media surveillance [62] and network models [63], support effective decision-making for controlling and preventing avian influenza. Furthermore, the regular influx of data amassed from sensors, drones and satellites are utilized for infectious disease surveillance and early warnings [64].

In conclusion, the methodologies and implementation of avian influenza surveillance vary significantly between developed and developing nations. Predominantly, developed countries prioritize avian surveillance, highlighting their focus on detecting and mitigating avian influenza at its provenance. In contrast, many developing nations concentrate on human surveillance, predominantly due to the prevalence of decentralized poultry farming and inadequate biosafety management levels, leading to recurrent outbreaks of human avian influenza infections. The ongoing risk of an avian influenza pandemic instigated by new subtypes of AIVs underscores the importance of human surveillance in these territories. These contrasts are not solely dictated by the progress of surveillance systems and mechanisms but are also influenced by the extent of infrastructure development. Elements for consideration include the necessity for expansive and efficient networks incorporating hospitals and laboratories, as well as the presence of diverse professional and efficient teams.

4. Surveillance of avian influenza in China

China's avian influenza surveillance primarily depends on the National Influenza Surveillance Network (NISN). This system was initially developed under the auspices of a collaborative project between the World Health Organization (WHO) and the United States CDC prior to 2000. It underwent systematic construction in 2004 and was expanded in 2005 to incorporate 63 network laboratories and 197 sentinel hospitals located in 31 provinces, municipalities, and autonomous regions. Following the H1N1 influenza pandemic in 2009, the NISN was further expanded to include all prefectures, cities, and some counties [61].

After more than a decade of continuous development, China's NISN now boasts 408 network laboratories affiliated with provincial and municipal (regional) Centers for Disease Control and Prevention (CDC) and 554 sentinel hospitals, making it the world's largest influenza surveillance network [65]. Further, the laboratory testing activities under NISN have expanded to include nucleic acids, serologic antibody testing, and virus isolation [66].

The Chinese National Influenza Center (CNIC), as the core of NISN, was designated as the reference laboratory for animal influenza viruses in China prior to 2000. It later received certification from the World Health Organization as one of the five WHO global influenza reference laboratories in 2010.

The NISN has been instrumental in preventing and controlling avian influenza in China. As the country's reference laboratory for animal influenza, it identified several outbreaks of the virus in poultry and livestock prior to 2000. In terms of human influenza surveillance, NISN confirmed China's first case of human infection with the H9N2 AIV in 1998 [67], followed by H5N1 in 2005 [66], H5N6 in 2014 [68], and H7N9 in 2013 [69,70]. Notably, during the H7N9 outbreak, the NISN played a critical role in extending fundamental research on pathogenic mechanisms and transmission risks associated with the virus. In addition, the NISN made significant contributions to the development of global vaccines by actively sharing strain and sequence information with the international community [66].

Avian influenza surveillance in China is implemented according to institutional and sectoral functions, typically encompassing both passive and active surveillance mechanisms. Specifically, the health sector is primarily tasked with surveilling individual cases and outbreak incidents of human avian influenza. Passive surveillance in this context relies on case reporting by medical practitioners, while active surveillance is directed at high-risk occupational groups and environments linked to live poultry, such as poultry markets and farms. This includes the gathering of respiratory and blood samples from high-risk individuals, collecting swabs from high-risk environments, and conducting laboratory tests. The data generated from such measures are analyzed to facilitate pathogenic monitoring.

Concurrently, the agricultural sector is chiefly responsible for the surveillance of domestic poultry, including chickens, ducks, geese, and other commercially-raised birds [65]. Domestic poultry surveillance typically involves passive measures based on outbreak reports from farmers, while active surveillance centers on the pathogenic monitoring through sample collection and testing in larger breeding enterprises and environments associated with the transport and trading of live poultry on a national level [71].

Finally, the forestry sector oversees the surveillance of wild birds, specifically focused on understanding the circulation and prevalence of avian influenza within wild bird populations, identifying outbreaks, and tracing potential epidemic sources. This is primarily achieved via a national network designed for active surveillance. The network comprises monitoring stations strategically placed in areas often frequented by migratory birds or along their migration pathways, and is managed and maintained by the forestry sector.

The health, agriculture, and forestry sectors in China have consistently held joint meetings to share surveillance information, research findings, and conduct a joint risk assessment of avian influenza, under the auspices of a multi-sectoral mechanism. While this mechanism has been pivotal in the mitigation and control of previous avian influenza outbreaks in China [72], deficiencies and challenges remain. These areas call for substantial reinforcement and refinement, particularly in regards to the implementation of a multi-sectoral surveillance approach.

Presently, surveillance efforts led by separate sectors run relatively independently and lack a cohesive correlation. This creates a gap in the overall surveillance, notably in areas of human–animal interfaces and the transmission chain between domestic and wild birds. Additionally, current surveillance systems and programs operating across different sectors lack harmony. This discrepancy results in an inadequate reciprocal exchange and sharing of surveillance outcomes.

Furthermore, sectors are primarily utilizing surveillance data internally. This inadequacy and lack of integration effectively render cross-sectoral synergy virtually non-existent, compromising the effectiveness and efficiency of disease control and prevention initiatives. With these considerations in mind, constructive consolidations and operational enhancements are urgently needed to improve efficacy levels in the ongoing fight against avian influenza.

5. Collaboration on global and regional avian influenza surveillance

5.1. Global avian influenza surveillance

For many years, there has been significant cooperation among international organizations to tackle avian influenza outbreaks, leading to the formation of a preliminary global avian influenza surveillance network. The Global Influenza Surveillance Response System (GISRS), established by the WHO and dating back to 1952, currently includes institutions across 129 WHO Member States [73]. GISRS serves as a pivotal technical resource in the prevention and control of both seasonal and avian influenza, as well as global pandemics. Its roles extend beyond recommending vaccine prototype strains for annual seasonal and avian influenza, and maintaining a stockpile of pandemic vaccines. It also continually updates avian influenza detection and surveillance reagents, offers reference evidence for clinical antiviral resistance treatment, and conducts ongoing risk assessments based on surveillance data. Moreover, to bolster the global sharing of influenza virus genetic information, the Global Initiative on Sharing All Influenza Data (GISAID) database was established in 2008 [74,75]. This platform recently contributed towards the identification, sequencing, mutation monitoring and sharing of the SARS-CoV-2 virus [76,77].

Several internationally renowned academic conferences such as the "International Conference on Emerging Infectious Diseases (ICEID)" and "OPTIONS for the Control of Influenza" have instigated discussions related to AIVs. These platforms continually facilitate international collaboration and communication geared toward the prevention and control of avian influenza. Recently, to bolster international cooperation and coordination, four global partners: the Food and Agriculture Organization (FAO), the WOAH, the United Nations Environment Programme (UNEP), and the WHO, founded the interdisciplinary One Health High-Level Expert Panel (OHHLEP). This initiative aims to enhance cross-sectoral collaboration and advocate for the prevention and control of zoonotic diseases under the concept of "One Health" [78]. Over the last two years, this effort has seen the redefinition of "One Health", the development of a model surveillance system, the identification of zoonotic spillovers, and risk assessments, and it has illustrated a systematic change in theory [78–80].

5.2. Regional surveillance of avian influenza

With respect to the sharing of regional data, the European Centre for Disease Prevention and Control (ECDC) regularly holds risk assessment meetings to disseminate information and recent findings and swiftly circulates risk assessment reports among its members following these meetings [81]. The avian influenza outbreak in the winter of 2003 spurred developing nations in South-East Asia to establish the Association of Southeast Asian Nations (ASEAN) to collectively respond to infectious diseases, avian influenza among them [81]. Under the banner of creating a shared future community for mankind, the Lancang-Mekong Cooperation, a sub-regional cooperative mechanism, was established by China and five other nations encompassing the Lancang-Mekong sub-region, namely Laos, Myanmar, Thailand, Cambodia, and Vietnam. Furthermore, the "Belt and Road High-Level Meeting for Health Cooperation: Towards a Health Silk Road" has been initiated and has made significant contributions to global health development [82].

6. Reflection and prospects

Zoonotic diseases have emerged as one of the foremost challenges in securing global public health, with approximately 75% of novel infectious diseases being animal-derived [83]. HPAI outbreaks, for instance, continue to pose significant threats to agriculture, food safety, wildlife and human health [84,85]. The 2021 outbreak of avian influenza H5N1 in Europe, subsequently escalating to expansive outbreaks in North and South America, underscored the gaps in cross-sectoral communication and information sharing while highlighting the necessity of preemptive measures, swift alert mechanisms and a comprehensive approach to managing health threats [86–88]. Moving forward, to truly embody the "One Health" concept [89,90], the paradigm of handling emerging infectious diseases like avian influenza should be transitioned towards an effective proactive model [79]. This includes amplifying coordination, collaboration and cross-disciplinary engagement among medical, veterinary and public health institutions [91,92], assimilating surveillance data from various departments, and leveraging this information for early warning processes, as outlined below.

First, it is essential to establish and enhance multisectoral and interagency collaboration mechanisms and to set a constant channel for information exchange in health, agriculture, environment, forestry and other pertinent departments. This approach has been validated as effective and efficient through its prior execution in responding to two HPAI outbreaks in the United States in 2014 and 2015 [93,94], as well as the H7N9 epidemic response in China [95].

Second, it is necessary to consider environmental and climatic factors. The occurrence of avian influenza outbreaks has been shown to be associated with a range of elements, including climate, topography, as well as poultry and human population density [96]. However, there is a lack of monitoring in relation to the interplay between environmental and climatic changes, avian influenza, and public health. An optimal "animal-human-environment interface" monitoring system could be instituted with the objective of carrying out comprehensive risk assessment and providing early warning for avian influenza on a national, regional, and global scale. This system could integrate multi-dimensional data, which includes activity patterns of wild birds, migratory pathways of birds, climate and seasonal shifts, and human-related social behavior characteristics, all within the framework of the "One Health" concept [78,97].

Third, the adoption of advanced technology is crucial to strengthen multi-sector surveillance and provide early warning mechanisms. Recent years have witnessed an upward trend in applying novel technologies to public health surveillance. Artificial Intelligence (AI) has been proven particularly effective in forecasting seasonal influenza surveillance [98]. The application of Information and Communication Technology (ICT) in Africa's rural areas has bolstered early detection and expedited reporting of health events [99]. In France, the machine-learning-based PADI-web system (Platform for Automated Extraction of Animal Disease Information from the web) has successfully automated the monitoring of emerging animal diseases [100]. Nevertheless, sharing of original surveillance data across different sectors remains a significant challenge due to potential legal complications relating to data security and privacy. This issue underscores the urgent need for a rational and systematically designed mechanism that functions within a legal framework.

Finally, a “whole-society” approach is imperative to effectively address the threat of zoonotic diseases, including avian influenza, using the “One Health” framework. The task of preventing and controlling zoonotic diseases not only falls to relevant departments but also necessitates the involvement of a diverse array of stakeholders [79,89]. The UK's multi-disciplinary, cross-governmental “Human Animal Infections and Risk Surveillance (HAIRS) group”, which includes representatives from the private sector, industry and commerce, academia, and other interest groups, has been a prime example of this approach since its inception in 2004 [101]. Similarly, in China, poultry farming enterprises have an active role in reportage of avian influenza outbreaks and collaborate with the government in poultry vaccination endeavors [102].

In conclusion, outbreaks of avian influenza over recent decades have exerted substantial adverse impacts on poultry, wild birds, select mammalian species including humans, and have precipitated significant economic losses across numerous nations while posing considerable threats to public health. With the critical function of surveillance systems in providing early warnings and controlling avian influenza epidemics in mind, this article underscores the need for further enhancement of the surveillance model, based on a review of the tactics and methodologies employed by contemporary avian influenza surveillance systems at the global, national, and regional levels. An effective surveillance model, in alignment with the “One Health” concept, will necessitate interdisciplinary and cross-sectoral coordination among medical, veterinary, and public health institutions, in addition to information sharing for early warnings. As part of the processes of establishment and enhancement of avian influenza surveillance, due consideration may need to be given to systemic challenges such as legality and ethics surrounding data collection, boundaries between sectors and departments, effectiveness of resource allocation, and issues introduced by emerging technologies including artificial intelligence and big data. Operationally, it is recommended to bolster legislation, enhance the support mechanism for cross-sectoral surveillance systems, strengthen interdepartmental responsibilities and cooperation, increase resource allocation and investment for surveillance, strive for robust ethical reviews related to surveillance, and foster interdisciplinary collaborations with external institutions and entities for the incorporation of new technologies in avian influenza surveillance.

Ethics approval and consent to participate

Not applicable.

Contributions of the authors

Lei Zhou led the conception and design of the research study. Chenlin Duan, Chao Li and Lei Zhou wrote and revised the manuscript. Ruiqi Ren and Wenqing Bai collected data and critically reviewed the article. All authors read and approved the final manuscript.

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Conflicts of interest

The authors declare no conflicts of interest.

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