rccp
Revista Colombiana de Ciencias Pecuarias

Literature Review

Avian influenza in Colombia: A One Health perspective on surveillance, intervention, and policy integration

Influenza Aviar en Colombia: una perspectiva de Una Salud sobre vigilancia, intervención e integración de políticas

Gripe aviária na Colômbia : uma perspectiva de Saúde Única em vigilância, intervenção e integração de políticas

Karl A Ciuoderis*

Corporacion Para la Investigacion en Salud Tropical- CORPOTROPICA, Medellín, Colombia.

To cite this article:
Ciuoderis KA. Avian Influenza in Colombia: A One Health perspective on surveillance, intervention, and policy integration. Rev Colomb Cienc Pecu. 2025; 38(4):e357741. DOI: https://doi.org/10.17533/udea.rccp.e357741

Received: July 11, 2024.
Accepted: March 7, 2025.
Published: October 27, 2025.

***Corresponding author:** Karl Ciuoderis. Corporacion para la Investigacion en Salud Tropical,, Cra 75#61-85. Medellín, Colombia. E-mail: corpotropica@gmail.com

Abstract

Background: Avian influenza remains a significant global health issue, threatening animal and human populations. The natural reservoirs of influenza A viruses (IAVs) are wild birds, and their transmission dynamics can influence disease outbreaks in domestic poultry and humans. Colombia, due to its geographic location and diverse ecosystems, faces unique challenges in the surveillance and control of avian influenza. **Objective:** This work aims to provide a comprehensive overview of avian influenza in Colombia from a One Health perspective, highlighting surveillance, intervention strategies, and policy integration to mitigate disease spread. **Methods:** A literature review was conducted to consolidate data on avian influenza cases in Colombia, including reports of outbreaks in poultry and wild birds. Risk factors, transmission routes, and prevention strategies were analyzed, emphasizing the role of migratory birds and ecological influences. **Results:** Colombia has experienced highly pathogenic avian influenza (HPAI) outbreaks, primarily affecting backyard poultry and wild birds. The review identifies key risk areas influenced by migratory bird pathways, poultry farming practices, and biosecurity measures. Effective surveillance systems and rapid response protocols are essential to prevent further spread. **Conclusions:** Adopting a One Health approach that integrates veterinary, public health, and environmental efforts is critical to mitigating avian influenza in Colombia. Strengthening surveillance, improving vaccination strategies, and enhancing biosecurity measures can reduce transmission risks. International cooperation is also necessary to monitor migratory bird movements and implement preventive measures against potential outbreaks.

Keywords: *avian influenza; Colombia; disease surveillance; epidemiology; global health; One Health; poultry biosecurity; public health; zoonotic diseases.*

Resumen

Antecedentes: La influenza aviar sigue siendo un problema de salud pública global, representando un riesgo para poblaciones animales y humanas. Las aves silvestres son reservorios naturales de los virus influenza A (IAVs), y su dinámica de transmisión puede influir en la presentación de brotes en aves domésticas y humanos. Colombia, por su ubicación geográfica y diversidad de ecosistemas, enfrenta desafíos únicos en la vigilancia y el control de la influenza aviar. **Objetivo:** Este trabajo tiene como objetivo proporcionar una visión integral de la influenza aviar en Colombia desde la perspectiva de Una Salud, resaltando estrategias de vigilancia, intervención e integración de políticas para mitigar la propagación de la enfermedad. **Métodos:** Se realizó una revisión de la literatura para consolidar datos sobre casos de influenza aviar en Colombia, incluyendo reportes de brotes en aves de corral y silvestres. Se analizaron factores de riesgo, transmisión y estrategias de prevención, con énfasis en el papel de las aves migratorias y la influencia ecológica. **Resultados:** Colombia ha experimentado brotes de influenza aviar altamente patógena (IAAP), afectando principalmente aves de corral y aves silvestres. La revisión identifica áreas de alto riesgo influenciadas por rutas migratorias, prácticas de producción avícola y medidas de bioseguridad. La implementación de sistemas de vigilancia efectivos y protocolos de respuesta rápida es clave para prevenir la propagación del virus. **Conclusiones:** La adopción de un enfoque de Una Salud que integre esfuerzos veterinarios, de salud pública y ambientales es fundamental para mitigar la influenza aviar en Colombia. El fortalecimiento de la vigilancia, la mejora de estrategias de vacunación y la implementación de medidas de bioseguridad pueden reducir el riesgo de transmisión. Además, la cooperación internacional es esencial para monitorear el movimiento de aves migratorias y establecer medidas preventivas contra posibles brotes.

Palabras clave: *Bioseguridad avícola; Colombia; enfermedades zoonóticas; epidemiología; influenza aviar; salud pública; salud global; Una Salud; vigilancia de enfermedades.*

Resumo

Antecedentes: A gripe aviária continua sendo um problema de saúde global, representando riscos para populações animais e humanas. As aves selvagens são reservatórios naturais dos vírus da influenza A (IAVs), e sua dinâmica de transmissão pode influenciar surtos em aves domésticas e humanos. A Colômbia, devido à sua localização geográfica e diversidade de ecossistemas, enfrenta desafios específicos na vigilância e no controle da gripe aviária. **Objetivo:** Este estudo visa fornecer uma visão abrangente da gripe aviária na Colômbia a partir de uma perspectiva de Saúde Única, destacando a vigilância, estratégias de intervenção e integração de políticas para mitigar a propagação da doença. **Métodos:** Foi realizada uma revisão da literatura para consolidar dados sobre casos de gripe aviária na Colômbia, incluindo registros de surtos em aves domésticas e selvagens. Foram analisados fatores de risco, rotas de transmissão e estratégias de prevenção, com ênfase no papel das aves migratórias e na influência ecológica. **Resultados:** A Colômbia registrou surtos de gripe aviária altamente patogênica (HPAI), afetando principalmente aves de quintal e selvagens. A revisão identifica áreas de alto risco influenciadas por rotas migratórias, práticas de avicultura e medidas de biossegurança. Sistemas eficazes de vigilância e protocolos de resposta rápida são essenciais para evitar a propagação do vírus. **Conclusões:** A adoção de uma abordagem de Saúde Única que integre esforços veterinários, de saúde pública e ambientais é crucial para mitigar a gripe aviária na Colômbia. O fortalecimento da vigilância, a melhoria das estratégias de vacinação e a implementação de medidas de biossegurança podem reduzir os riscos de transmissão. Além disso, a cooperação internacional é essencial para monitorar o movimento das aves migratórias e implementar medidas preventivas contra surtos potenciais..

Palavras-chave: *Biossegurança avícola; Colômbia; doenças zoonóticas; epidemiologia; gripe aviária; saúde global; One Health; saúde pública; vigilância de doenças.*

Introduction

Influenza is a significant global health concern due to its potential impact on animal and human populations. This emerging infectious disease, primarily caused by type A influenza viruses (IAV), has been the subject of extensive study worldwide as its incidence has increased over the past decades [1]. IAVs have caused one of the most prevalent acute respiratory diseases, with millions of severe illnesses and human deaths throughout history [2]. Besides the regular seasonal outbreaks caused by human IAV, infections may be caused by IAV from animals, notably birds and swine [3]. Therefore, in addition to the seasonal burden of IAV in humans, there is a constant risk of developing novel IAV strains with pandemic potential [4]. In Colombia, the presence and dynamics of animal influenza pose significant challenges to public health and the agricultural sectors. Understanding the current landscape of avian influenza in Colombia is essential for devising effective prevention and control strategies. This introduction sets the stage for a comprehensive examination of avian influenza in Colombia, emphasizing the need for research and multidisciplinary collaboration to address this complex issue. The aim of this work is to consolidate existing research on avian influenza, offering a comprehensive understanding of its prevalence, impact, and management strategies. This paper emphasizes the importance of a One Health approach, advocating for enhanced multisectoral collaboration between veterinary, medical, ecological, and public health sectors. It seeks to highlight factors and vulnerable regions susceptible to outbreaks, promote early detection systems and vaccination programs, and integrate several considerations for public and animal health decision makers to protect both animal and human populations in Colombia.

Ecoepidemiology of avian influenza

The eco-epidemiology of the avian influenza virus encompasses the intricate interplay between ecological factors and the epidemiology of the virus within avian populations and their environments. Avian influenza, caused by various subtypes of IAVs, poses significant threats to animal and human health worldwide. Understanding the eco-epidemiology of IAVs is essential for elucidating the transmission dynamics, spatial distribution, and risk factors associated with avian IAV outbreaks.

Influenza viruses are negative-sense single-stranded RNA viruses in the family Orthomyxoviridae. There are four types (A, B, C, and D), of which only types A and B are the most relevant for animal and human health [5]. Their genome comprises eight segments (Figure 1) with a total length of approximately 13.6 kb [6]. Type A Influenza viruses are categorized into subtypes based on their surface proteins, hemagglutinin (HA) and neuraminidase (NA). To date, 19 types of HA and 11 types of NA have been recognized [7,8]. Over 130 influenza A subtype combinations have been identified in nature, primarily from wild birds, which are considered the natural reservoir of influenza A viruses (IAVs) with the greatest diversity of subtypes [9]. Only type A influenza viruses (IAV) are known to cause natural infections in avian species. The HA protein is essential for cell entry and interactions with the host immune system, while the NA protein catalyzes viral release from infected cells [10].

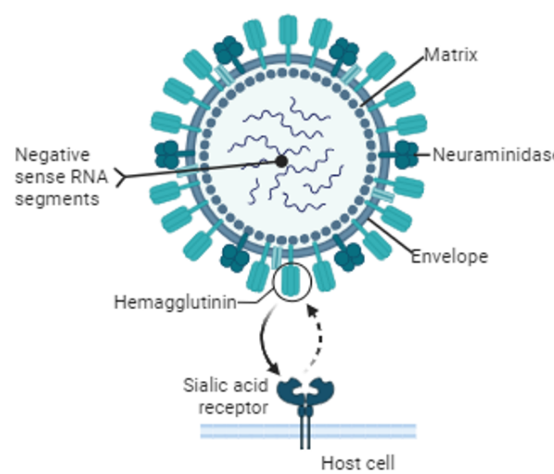

Figure 1. Schematic diagram representing the structure and composition of type A Influenza Virus. Two surface proteins, hemagglutinin (HA) and neuraminidase (NA). The matrix protein and the viral envelope are derived from the host plasma membrane. The ribonucleoprotein complex is where each viral RNA segment is covered with nucleoproteins and a polymerase and serves as a fundamental unit for the transcription and replication of the viral genome. Created in Biorender.com

Influenza A viruses are highly adaptable, evading host immune responses and infecting new host species [11]. This is mainly because the RNA-dependent RNA polymerase, an enzyme that catalyzes the replication of the viral RNA, is error-prone. Therefore, there is no error correction during virus replication. In addition, the segmented genome structure of the virus allows genetic reassortment, which is the exchange of entire segments between viruses co-infecting a cell, a primary process for virus evolution [12].

Host tissue tropism is a crucial element in the transmission of IAVs. For example, in avian hosts, most IAVs primarily infects intestinal tissue and, to a lesser degree, respiratory organs, which are thus shed via feces and respiratory secretions. Thus, the pathogenicity of avian influenza also varies. IAVs generally cause mild disease in wild birds [6]. However, some strains (e.g., H5N1) can cause systemic and highly pathogenic disease in avian and mammal hosts [13–15]. Influenza A viruses that infect poultry can be categorized into two groups according to their capacity to induce illness in chickens [16]. Currently, there is a designation for IAVs as high- or low-pathogenicity strains based on the severity of illness in poultry. The hallmark of highly pathogenic IAVs is the presence of specific mutations in the hemagglutinin (HA) gene, particularly in the cleavage site, allowing the virus to be processed by a wider range of enzymes, facilitating systemic infection in birds when compared to similar low pathogenicity forms [17–19]. The group of viruses causing low pathogenic avian influenza (LPAI), can cause asymptomatic or mild disease, whereas viruses causing highly pathogenic avian influenza (HPAI) cause severe disease with rapid mortality [16].

The ecology of IAVs depends on the complex virus transmission patterns, which are driven by interactions between the host community, the environment, and co-evolution between the host and pathogen [20]. Globalization, climate change, land use, and other factors related to anthropogenic environmental changes have altered the ecology and evolution of IAVs; therefore, understanding these complex relationships would enable the identification of ways to mitigate the emergence of future pandemic strains [21–23]. To date, there is extensive knowledge of ecological and molecular determinants responsible for IAV interspecies transmission. Most documented transmission events are focused specifically on avian-derived influenza subtypes, which involve zoonotic and epizootic transmission to other hosts (Figure 2).

Current status of avian influenza

Avian influenza represents a significant infectious disease threat to wild bird populations and domestic poultry worldwide. Aquatic birds of the orders Anseriformes (ducks and geese) and Charadriiformes (shorebirds and gulls) are the primary reservoirs of IAV. These groups of species have been found infected with most known IAV subtypes [24]. Co-infections within the same avian host by two viral subtypes enable the reassortment of viral genetic segments and contribute to the diversity of IAV strains globally [20]. In addition, the high diversity and spread of some of these viruses are linked to the migratory nature of the wild birds [25–28]. Viruses are shed in bird feces and later acquired by other birds sharing the same habitat along migratory flyways [27,29–31]. Thus, the migration of wild birds between locations poses a persistent risk of transmission of avian influenza [27,32].

In passerine birds, the low prevalence of infection suggests that they act as spillover hosts; however, some peri-domestic species (such as house sparrows) may be involved in virus spread between poultry farms [4]. Pigeons have been naturally infected and are susceptible to highly pathogenic avian influenza. However, their role in virus transmission remains unknown [33]. Several factors affect IAV transmission in avian populations. Among them, virus shedding, stability in the environment, and the degree of interaction with other species are the most commonly described [34]. Prolonged virus shedding from bird species facilitates the efficient

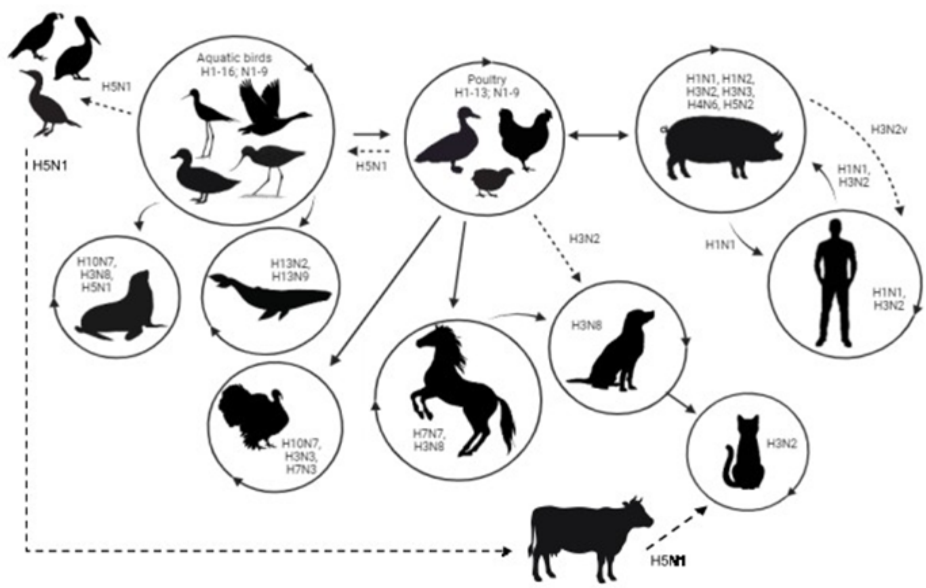

Figure 2. Representative diagram of interspecies transmission events of influenza A viruses and the subtypes involved in these events. Solid arrows represent direct transmission events with sustained transmission. Dashed arrows represent sporadic infections with no sustained transmission. Created using Inkscape.

transmission of IAV in aquatic ecosystems [31]. The environmental persistence and infectivity of IAV depend on several ecological factors, including atmospheric and environmental conditions [35–38]. Additionally, virus shedding is related to the age and development of the avian immune system [39,40].

In poultry, the introduction and spread of avian IAV can have devastating effects, leading to high mortality rates and significant economic losses [41,42]. The rapid transmission of avian IAV within densely populated poultry farms can result in widespread outbreaks, requiring stringent biosecurity measures and rapid response protocols to prevent further dissemination [43]. The emergence and spread of avian influenza, particularly in poultry, have become a growing global concern, with both HPAI and LPAI strains posing significant threats to animal health, public health, and international trade [44]. While waterfowl and other wild birds seem to be responsible, either directly or indirectly, for most IAV transmissions to domestic poultry, other possibilities should not be dismissed [45]. For example, IAV can be transmitted from infected pigs to poultry [46]. Furthermore, the virus spread by personnel, fomites, or shared contaminated water or food may become relevant in transmitting IAV in poultry [47].

Since the 1990s, outbreaks of LPAI in poultry have been commonly reported in several regions worldwide [47]. However, sporadic outbreaks of HPAI have been of significant concern due to their pandemic potential and considerable threat to public health [48]. HPAI has also had a catastrophic impact on backyard poultry [20,49–51]. Transmission of HPAI viruses from domestic poultry to wild bird populations has also been reported [42]. Since 2014, a highly pathogenic avian influenza virus of the H5 subtype, particularly clade 2.3.4.4, has caused global outbreaks in domestic poultry, occasional transmission to humans, and a growing number of deaths among various wild bird species [25].

Furthermore, diagnostic techniques and laboratory testing play a critical role in the prevention, control, and surveillance of avian influenza. Rapid and accurate detection of the virus through molecular methods, such as RT-PCR testing, allows for timely intervention to contain outbreaks and prevent further spread [52,53]. In countries like Colombia, where the poultry industry is vital for the economy, the ability to quickly detect and respond to avian influenza is crucial. However, limited access to advanced diagnostic infrastructure, poses challenges, making it harder to contain outbreaks and prevent spillover into human populations, potentially leading to economic and public health impacts [54–56]. Strengthening laboratory capacities and international collaborations is essential for countries like Colombia to effectively manage the threat of avian influenza.

Human-animal health and avian influenza

The interface between human and animal health plays a crucial role in the epidemiology and control of infectious diseases, including avian influenza. Animal influenza, particularly avian and swine influenza, can have important consequences for human health due to the possibility of transmission between animals and humans [57]. In rare instances, avian IAV can cross the species barrier to infect humans, leading to severe respiratory illness and, in some cases, death [58]. Several avian IAV strains have been fatal in a small proportion of infected individuals, most of whom had close contact with domestic poultry [31,59]. Notable examples include the H5N1 and H7N9 avian IAV, which have caused sporadic outbreaks in humans with high mortality rates in certain instances [60]. The outbreak of H7N9 in China, which caused high morbidity and case fatality in humans, has been one of the most severe zoonotic infections from avian IAV [61,62]. Poultry markets have been demonstrated to harbor a variety of IAVs [63–65]. Since 2019, individuals in 17 countries across five continents have been reported as infected with avian IAV from five emerging subtypes (H5N8, H10N3, H3N8, H10N5, and H5N2) and four re-emerging subtypes (H5N1, H5N6, H7N9, and H9N2) [60].

In recent years, the role of backyard poultry in the transmission dynamics of IAV has garnered increasing attention. Backyard poultry, often kept by households for subsistence or small-scale production purposes, can serve as reservoirs for various influenza strains, including those with zoonotic potential [66]. While commercial poultry operations have historically been the focus of surveillance and control efforts, backyard poultry populations have emerged as significant contributors to influenza transmission due to their proximity to humans and other animals and to limited biosecurity measures [67–69]. The interaction between backyard poultry and humans presents a unique challenge in influenza management. In this scenario, individuals who maintain backyard flocks are often in close contact with their birds, increasing the risk of zoonotic transmission of IAV [70]. Furthermore, mixing diverse bird species within backyard settings can facilitate the exchange of influenza viruses, leading to novel reassortant strains with unpredictable pathogenicity and transmissibility [71]. In Colombia, the recent outbreak of avian influenza significantly impacted backyard poultry (Fig 3.). The virus, introduced through migratory wild birds, spread quickly among domestic flocks, leading to high mortality rates in affected areas [72]. Backyard birds, often raised in less controlled environments, are particularly vulnerable to infection due to close contact with wild birds and the lack of biosecurity measures. Despite their importance in influenza ecology, backyard poultry populations are often overlooked in surveillance and control strategies [73]. Limited resources, infrastructure, and awareness among backyard poultry keepers compound the challenges of monitoring and managing influenza outbreaks in these settings [67,70]. Nevertheless, proactive measures such as educational campaigns, improved biosecurity practices, and enhanced surveillance efforts can help mitigate the risk of IAV transmission in backyard poultry populations and reduce the potential for zoonotic spillover events [74,75].

Four influenza pandemics—occurring in 1918, 1957, 1968, and 2009—have resulted in millions of deaths worldwide [2,76]. The most recent pandemic, which occurred a decade ago, was caused by a novel reassortant strain of IAV of the H1N1 subtype. This strain, which originated in Mexico, contained genetic material from swine, avian, and human influenza viruses [77]. While efforts to prevent and control influenza have largely focused on the 2009 H1N1 pandemic strain, there are deep concerns over the pandemic potential of avian IAV, particularly the HPAI H5N1 subtype, which has become panzootic in poultry globally [78]. While H1N1, a human-adapted virus, demonstrated its pandemic potential during the 2009 outbreak, spreading rapidly through human-to-human transmission and affecting millions globally [79], among the avian strains, the H5N2, primarily a bird-adapted virus, has caused widespread outbreaks in poultry with devastating effects on agriculture [80]. Although H5N2 has caused only limited human infections, its potential to reassort or mutate poses a future threat of cross-species transmission [81]. Moreover, the H5N1 IAV subtype has garnered significant attention due to its imminent pandemic risk and its high fatality rate in humans [82,83]. Recent outbreaks of H5N1 IAV in animals such as alpacas, cats, cattle, and humans across North America [84–87] clearly illustrate the interconnectedness of human and animal health in the context of zoonotic diseases. These cases highlight the critical need for robust surveillance, early detection, and control measures to prevent the emergence of novel influenza strains with pandemic potential [48,57].

Agriculture, globalization, land use, climate change, and influenza

The interplay between agriculture, globalization, land use, climate change, and influenza represents a complex web of factors influencing IAV transmission and emergence dynamics. Changes in agricultural practices due to globalization and shifts in land use have transformed landscapes and ecosystems, thus changing the dynamics among humans, animals, and the environment [88,89]. These alterations can significantly impact the ecology and epidemiology of IAVs, influencing how they spread, survive, and evolve [90,91].

Avian IAV H5N1 (clade 2.3.4.4b) has recently emerged as a highly pathogenic strain with significant implications for livestock, including outbreaks affecting cows and other domestic species in the United States [92]. While avian influenza primarily impacts birds, the spread of the virus to cattle poses a unique threat to the agricultural sector. Outbreaks among livestock can lead to severe economic losses, as affected herds may require quarantine and testing to prevent further spread [93]. As mentioned before, some avian species (passerine birds) may play a role as possible vectors for the dissemination of IAV, such as the LPAI H7N9 strain [94], a virus that has caused infections in humans and poultry in Asia [95,96]. Thus, the interconnection between humans, wildlife, and domestic livestock, particularly through shared environments and water sources, heightens the risk of transmission [97], and effective control measures are essential to mitigate the impact of these outbreaks on the animal industry and maintain agricultural stability [75].

Globalization has enabled the swift transportation of goods, individuals, and animals across borders, fostering greater interconnectedness among regions and continents [98]. Intensive livestock production systems, characterized by large-scale farming operations and high animal densities, such as pork production, have become common in many parts of the world to meet the demands of a growing global population [99]. However, these systems can create ideal conditions for the emergence and spread of IAV, promoting transmission between animals and facilitating spillover events to humans [100,101].

Changes in land use, driven by urbanization, deforestation, and agricultural expansion, can alter the habitats of wildlife and domestic animals, bringing them closer to humans [102].

This encroachment into natural ecosystems can disrupt ecological balances and increase the risk of cross-species transmission of zoonotic viruses [103]. Additionally, climate change can potentially influence the distribution and behavior of influenza hosts, such as migratory birds, further complicating efforts to predict and control influenza outbreaks [104].

Ecosystems, such as wetlands, provide critical ecological services and habitat for wild birds; however, over the past centuries, these natural ecosystems have been subjected to anthropogenic changes for development, agriculture, and domestic water use [4,105]. Land use transformation and the increased demand for freshwater by humankind, in association with global climate change, are expected to alter the availability of natural wetlands drastically [4]. However, some species, like waterfowl, have adapted well to human-altered landscapes and have thrived over the past decades [106,107]. The impact of these changes on avian influenza ecology is still unexplored. Changes in land use that result in higher concentrations of waterfowl, stress, or close proximity to domestic birds are likely to increase transmission of influenza within flocks and across different species [108,109]. Using IAV surveillance data from 2006–2020 in Denmark, researchers identified strong associations between IAV and landscape factors, particularly coastal areas and wetlands, which significantly influenced IAV presence due to the attraction of waterfowl and migrating birds [110]. Recent research on the migration of northern pintail and Eurasian wigeon in the East Asian-Australasian Flyway demonstrated the role of these species in avian IAV transmission, with both species showing a preference for rice paddies, thereby increasing outbreak risks in these rapidly changing landscapes [111]. Another study highlighted the significant role of wild waterfowl, particularly Anatidae species, in the transmission of avian IAV to domestic livestock, specifically poultry, through shared habitats. GPS telemetry data revealed that wild ducks frequently utilized dairy and beef cattle feed lots, retention ponds, and occasionally poultry facilities for roosting and foraging, increasing the risk of IAV transmission [112].

In addition, universities and other institutions play a crucial role in the research, management, and prevention of avian influenza outbreaks. Through interdisciplinary research, they contribute to understanding virus transmission dynamics, developing vaccines, and improving diagnostic techniques [113]. Universities also collaborate with public health agencies to create evidence-based strategies for disease control and prevention [114,115], while training future scientists and policymakers in the process [116]. Furthermore, their role in public awareness campaigns has been key in preventing the spread of misinformation during outbreaks [117,118].

Thus, the complex interactions between agriculture, globalization, land use, the ecology of avian influenza resorvoirs/hosts, and climate change underscore the need for a One Health approach to influenza surveillance and control [119,120]. By acknowledging the interdependence of human, animal, and environmental health, policymakers and researchers can create comprehensive approaches to reduce the impact of this disease on public health and agriculture [121]. These approaches may include improved biosecurity practices, early warning systems for emerging diseases, sustainable land management practices, and efforts to mitigate climate change. Ultimately, addressing these multifaceted challenges are essential for preventing and controlling influenza outbreaks and safeguarding the health and well-being of populations worldwide [122].

Current status of avian influenza in Colombia

Colombia is situated in a region known for its rich avian biodiversity and agricultural importance at the crossroads of South and Central America. The country faces unique challenges in mitigating the spread of avian influenza and preventing outbreaks among poultry populations. Despite efforts to monitor and control the spread of the disease, avian influenza remains a persistent threat in Colombia. In this nation, the presence of avian IAV has been documented in both wild bird populations and domestic poultry [123–125]. Colombia's varied ecosystems offer habitats for numerous bird species, including migratory birds [126] that could act as carriers for transmitting IAV.

Migratory bird routes in the Americas, known as flyways, are critical pathways that many avian species follow during their seasonal migrations between breeding and wintering grounds [127]. These routes stretch from North America to South America, passing through key areas such as Colombia. The country plays a crucial role in these migrations due to its location in the heart of the continent and its diverse ecosystems, which provide essential stopover sites for birds to rest and refuel (Fig. 3). However, as seen in other locations, the movement of large numbers of birds through the region also increases the risk of disease transmission, particularly avian influenza [128]. Migratory birds can spread avian influenza viruses along their flyways, as seen recently, at the beginning 2024, when an important outbreak of avian influenza affecting wild bird species and poultry occurred in several Latin American countries, including Colombia [72] (Fig. 3).

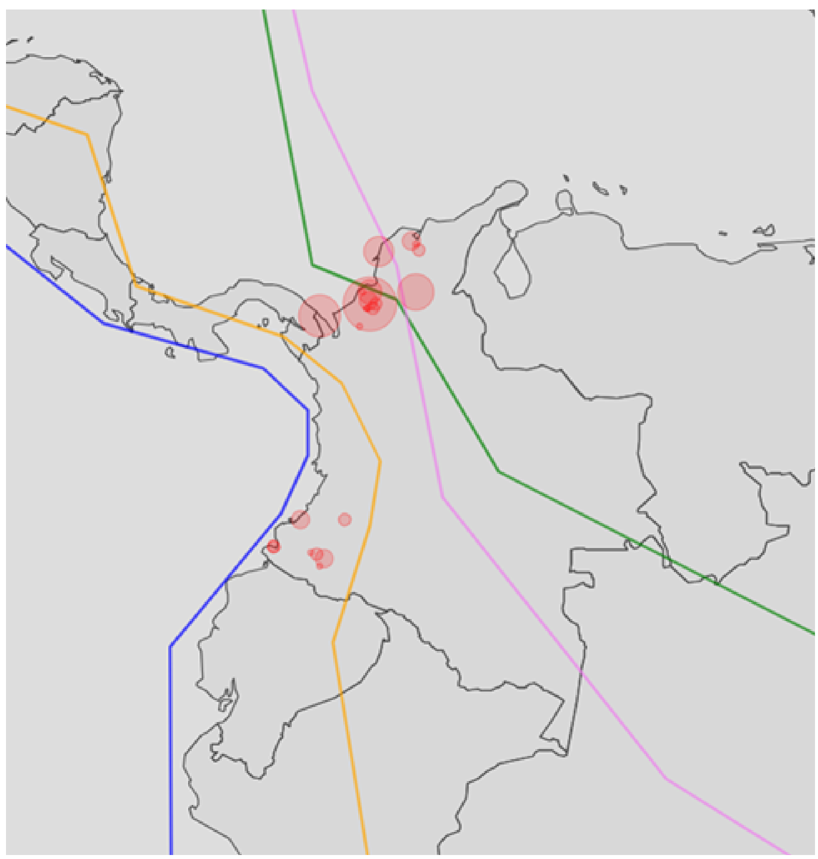

Figure 2. Map showing the location of the avian influenza outbreaks confirmed in Colombia during 2022-2024. The figure also illustrates the migratory flyways followed every year by austral and boreal migratory birds species. Red circles indicate the number of outbreaks reported in backyard poultry and wild birds. Pacific flyway (blue), Central flyway (yellow), Austral flyway (violet), Mississippi and Atlantic flyways (green). Created using Openstreet maps (Leaflet package) and R software v.4.4.1.

Additionally, Colombia's poultry industry, although smaller in scale than that of some other countries, plays a crucial role in domestic food production and rural livelihoods [129,130]. Colombia is the fourth largest broiler and egg producer in Latin America [131]. Moreover, backyard poultry represents an important source of food security for rural communities in Latin American countries such as Colombia [132–134]. In 2013, H5N2 viruses were isolated from resident species of whistling ducks (*Dendrocygna* genus) in wthe Llanos region of Colombia. These viruses were similar to wild bird viruses from North America, and exhibited low pathogenicity in chickens and mammals. However, these findings within a small area of Colombia underscored the need for impproved monitoring of animal influenza across regions in the country, including the potential transmission of low-pathogenic H5N2 viruses from wild birds to domestic poultry and the emergence of reassortant viruses in domestic swine [123]. Live animal markets play a crucial role in providing food and supporting trade in many countries, but they also have the potential to act as hubs for the emergence and transmission of avian influenza viruses [135,136]. In 2015, Avian H11 influenza virus was isolated from domestic poultry in a live animal market located in the northern region of Colombia. In this study, the genetic similarity of the Colombian H11 viruses to North and South American shorebirds strains suggested that the occurrence may have been the result of a spillover event from wild birds to domestic poultry [124]. In addition, between 2022 and February 2024, Colombia experienced a rise in avian influenza outbreaks, reporting a total of 66 cases. Of these, 60 occurred in backyard poultry, while 6 were detected in wild bird populations, along with 740 reported alerts or notifications [72,137]. Stringent biosecurity measures within the poultry industry managed to keep the virus out of commercial production. This situation showed the high potential economic and social impact of the spread of the HPAI virus in this country, triggering and forcing private and public sectors to work on regulatory frameworks and guidelines for implementing a national vaccination program against avian influenza in poultry [138].

Several factors contribute to the risk of avian IAV outbreaks in Colombia. The country's geographical location makes it susceptible to the introduction of avian IAV through migratory bird routes and trade activities. Domestic poultry production ranges from high biosecurity commercial farms to backyard poly-culture farming, where domestic poultry often come into contact with wild birds [139]. Furthermore, the movement and mixing of domestic poultry to live poultry markets, where multiple species are usually housed together regardless of origin, enhances the spread and mixing of IAVs [124,136,140]. Socio-economic factors such as limited biosecurity measures in informal poultry production systems increase the likelihood of virus transmission within domestic poultry populations [70].

To address the threat of avian IAV, Colombia should enforce and implement robust surveillance and control measures aimed at early detection and containment of outbreaks. These efforts may include regular monitoring of poultry farms, wild birds, and backyard animals and establishing rapid response protocols when suspected cases in high-risk areas are detected. Furthermore, it is crucial to collaborate with international organizations and neighboring countries to exchange information and coordinate responses to avian IAV threats. Despite these efforts, challenges remain in effectively managing avian IAV in Colombia. Limited resources and infrastructure pose barriers to comprehensive surveillance and control measures for infectious diseases [141–144]. Furthermore, the emergence of HPAI strains with zoonotic potential underscores the need for ongoing vigilance and preparedness in the face of evolving influenza threats. Moving forward, a multidisciplinary approach that integrates veterinary, public health, and environmental expertise is essential for addressing the complex challenges posed by avian IAV in Colombia. By enhancing surveillance systems, improving biosecurity practices, and promoting collaboration across sectors, Colombia can better protect both animal and human populations from the impacts of avian influenza.

One Health approach to avian influenza management

Avian influenza presents a complex challenge at the intersection of human, animal, and environmental health. The One Health (OH) approach recognizes the interconnectedness of these domains and emphasizes collaborative efforts to address health threats that transcend species boundaries [145]. In the context of avian IAV management, the OH approach is paramount, as the virus can potentially infect various avian and mammalian species, including humans. This approach integrates expertise from diverse disciplines, including veterinary medicine, public health, ecology, epidemiology, and social sciences [146]. Influenza outbreaks in Asia prompted the adoption of the OH approach [147–149]. Evaluation and ongoing surveillance of poultry systems and investigations at the animal-human interface have identified human exposure routes and viral persistence factors [150]. Epidemiological studies and molecular analyses revealed the role of live poultry markets and interventions in interrupting transmission [151]. Enhanced biosecurity and vaccination have prevented further human H5N1 cases and reduced poultry outbreaks [152]. Similar strategies have aided in understanding and preventing other disease outbreaks [122]. Therefore, the OH approach is effective in identifying pathways for zoonotic transmission in different epidemiological scenarios, understanding the genetic evolution of the virus, and highlighting the need for early detection, the improvement of biosecurity practices, and awareness among poultry farmers, traders, and consumers [149,153]. By fostering interdisciplinary collaboration, the OH approach allows for a more thorough comprehension of the factors that impact avian IAV transmission, spread, and impact. One key aspect of this approach is surveillance. Surveillance systems that monitor avian IAV in animal and human populations are essential for the early detection of outbreaks and timely response efforts [154]. Veterinary surveillance in poultry farms, backyard systems, and wild bird populations can provide valuable data on virus circulation [114]. In contrast, human surveillance helps identify cases of zoonotic transmission and monitor potential pandemic strains [155]. In addition to surveillance, prevention and control measures are critical. Even though vaccination has not yet been officially implemented in avian and swine species in Colombia, strict biosecurity measures on poultry farms and improved prevention in backyard systems can reduce the risk of virus introduction, transmission, and spread [156]. In this scenario, promoting vaccination in human and animal populations is key [157]. Educating stakeholders about safe handling practices and the risks associated with avian IAV is highly recommended [158].

Furthermore, the OH approach recognizes the role of environmental factors in avian IAV transmission. Environmental surveillance, which involves monitoring water sources and ecosystems for the presence of avian IAV viruses, can also provide valuable insights into the ecological drivers of virus circulation and inform targeted intervention strategies [159,160]. Climate change patterns appear to be related to the global spread of HPAI, causing mass mortalities in previously unaffected bird species and posing threats to agriculture and human health due to mutations and sustained presence in poultry systems [161]. The introduction of HPAI H5 clade (2.3.4.4b) viruses into the Americas in 2021–2022 marked an unprecedented expansion in the geography and impact of HPAI [162]. Anthropogenic climate change may intensify HPAI dynamics in wild birds through temperature shifts, extreme weather events, and alterations in bird behavior and disease risks [163,164]. Advancing HPAI research in this climate change era demands interdisciplinary and international collaboration [165]. Studying host ecology, virus dynamics, and anthropogenic-climate interactions at various scales poses integration challenges [164]. International collaboration is also vital for the OH approach to infectious disease management [166]. Given the global nature of avian IAV, coordinated efforts between countries are essential for sharing information, resources, and best practices [167]. Collaborative research initiatives, capacity-building programs, and cross-border surveillance networks will strengthen global preparedness and response to infectious disease threats [168].

In Colombia, several studies have shown the circulation of animal influenza viruses in several populations [72,123,124,144,169,170], but few have focused on exploring interspecies transmission patterns. However, the fact that swine and poultry populations, horses, and wild bird species have been reported infected by IAV in this country, together with experiences observed in other countries regarding interspecies transmission patterns, and the effect of globalization, climate, and other factors, emphasizes the need for collaborative efforts between disciplines to address IAV from a wider approach.

The OH approach should also involve the creation of a collaborative framework that emphasizes the roles and synergies between national entities like agricultural authorities and the Ministry of Health, alongside universities [171]. International organizations (World Health Organization, Food and Agriculture Organization of the United Nations, United Nations Environment Programme and World Organisation for Animal Health) have provided a framework for integrating human, animal, and environmental health sectors to collaboratively address health challenges such as zoonotic diseases, antimicrobial resistance, and ecosystem health [172]. Within this framework, each entity contributes to infectious disease surveillance, prevention, and response at different levels (Fig. 4). The Ministry of Health leads in monitoring human health impacts, while agricultural authorities oversee animal health and biosecurity measures. Universities, as research hubs, play a central role in generating scientific knowledge, developing diagnostic tools, and training future experts in zoonotic diseases. This integration would fosters a more coordinated effort to figth zoonoses like avian influenza, with universities playing a key role in translating research into policy and actionable strategies.

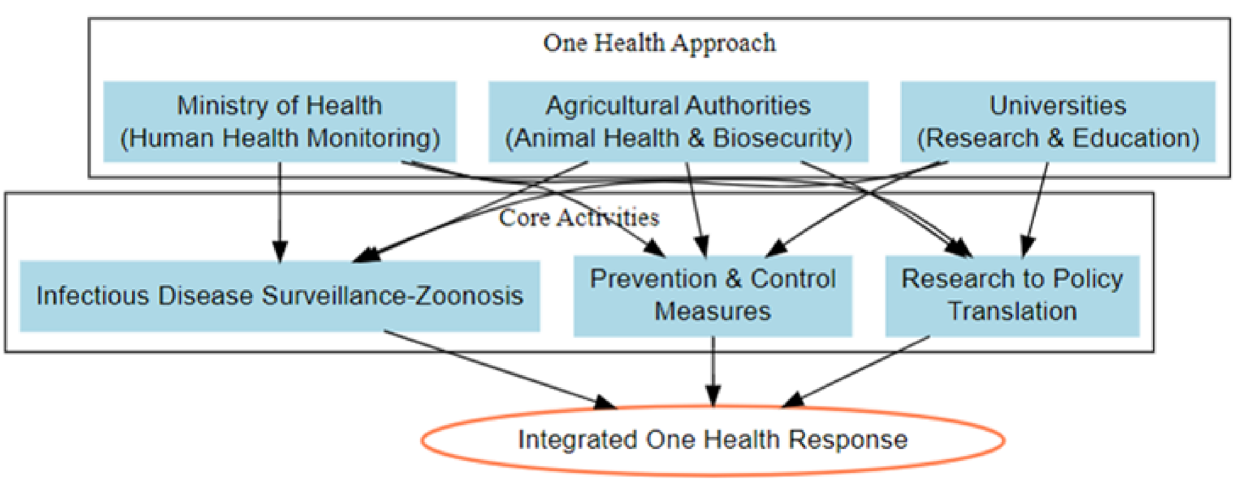

Figure 2. One Health framework showing relationships and contributions at different levels of entities and key stakeholders for infectious disease surveillance, prevention, and response.

Bridging gaps

Effective IAV surveillance and rapid response are critical for animal influenza control efforts [173]. In Colombia, enhancing surveillance systems and response strategies is essential for early detection and containment of avian influenza outbreaks. By leveraging innovative surveillance tools, strengthening laboratory capacity, and improving coordination among stakeholders, the country can enhance its ability to detect, monitor, and respond to avian influenza threats [148]. While Colombia has made strides in monitoring and controlling avian influenza outbreaks, significant gaps remain in its surveillance and response mechanisms. These gaps challenge early detection, effective containment, and the prevention of avian influenza from spreading within the country [114]. Despite the implementation of surveillance programs, coverage in certain regions of Colombia may be limited or sporadic. Remote and rural areas, where small-scale and backyard poultry farming is prevalent, often lack sufficient surveillance infrastructure and resources [174]. As a result, avian influenza outbreaks in these areas may go undetected or underreported, delaying response efforts and allowing the virus to spread unchecked. The ability to rapidly and accurately diagnose avian influenza infections is crucial for effective surveillance and response [175]. However, Colombia may face challenges in terms of diagnostic capacity, including access to reliable diagnostic tests, trained personnel, and laboratory facilities equipped to handle avian influenza testing. Delays or inaccuracies in diagnosis can hamper timely intervention measures and exacerbate the risk of avian influenza transmission.

Effective surveillance and response to avian influenza require strong coordination and communication among various stakeholders, including government agencies, veterinary and public health authorities, poultry producers, and international partners [176]. In Colombia, gaps in coordination and communication may hinder the timely sharing of information, coordination of response activities, and dissemination of guidance and recommendations to relevant stakeholders. In addition, while biosecurity measures are critical for preventing avian influenza introduction and spread, their implementation and enforcement may be inconsistent across production systems and backyard settings as seen in some studies [67,68,177]. This scenario may also be occurring in Colombia. Limited awareness, resources, and technical support for animal producers may contribute to gaps in biosecurity practices, increasing the risk of avian influenza transmission within and between animal populations [178].

Furthermore, wild birds serve as natural reservoirs and potential vectors for avian influenza transmission, highlighting the importance of surveillance in these populations [179]. However, surveilling wild bird populations can be challenging due to logistical constraints, including difficulty in accessing remote habitats and capturing and testing birds. As a result, surveillance efforts may overlook potential sources of avian influenza introduction and spread. Molecular epidemiology, based on genomic surveillance, plays an increasingly important role in monitoring IAV, especially those that cause sporadic zoonotic disease and that may represent a potential risk of future influenza pandemics [3]. Technological advances have allowed for fast sequencing of whole viral genomes, and genomic sequences of IAV can be examined to monitor the spread and development of outbreaks [3]. Moreover, molecular epidemiology tools have been applied to determine the origin of pandemic viruses and understand what made them successful pathogens. An excellent example is the recent phylogenetic genome analysis of the 1918 pandemic IAV [180]. Other examples include the application of these molecular methods to investigate the recent outbreaks of avian H5N1 and H9N2 influenza viruses [181–183]. Although many questions remain, advances in genomic surveillance over the past two decades have demonstrated its utility in defining the genetic constitution and molecular structure of viral agents [184]. Therefore, understanding and addressing these shortcomings is essential for enhancing Colombia's capacity to manage avian influenza and mitigate its impact on public health and the agricultural sector.

Identifying hotspots and vulnerable regions in Colombia

Avian influenza outbreaks in Colombia exhibit a varied geographical distribution influenced by ecological, environmental, and socioeconomic factors. Identifying these hotspots and vulnerable regions is crucial for prioritizing surveillance and efforts to control the spread of the virus and reduce its impact on poultry and public health. Information about the epidemiology of avian IAV in Colombia is minimal, mainly due to the lack of robust animal influenza surveillance programs. The latest HPAI H5N1 avian IAV outbreaks were documented in at least 17 countries across Latin America, incluiding Colombia [185]. Bird migrations have been historically correlated with outbreaks of HPAI, showing a notable concentration in some specific wild bird migratory pathways [27,186]. In Colombia, HPAI H5N1 outbreaks primarily affected backyard poultry, with a smaller number affecting wild bird populations. Cases were reported in regions including Córdoba, Chocó, Cartagena, Sucre, Magdalena, Nariño, and Cauca, indicating a widespread virus distribution across the country [138,187]. Efforts to contain the spread of these HPAI outbreaks in the country were significant. Fortunately, no human cases of infection with avian influenza were reported in connection with the registered outbreaks. However, since 2013 researchers made recommendations on strengthening animal influenza surveillance in this country based on identification of important IAV with potential impact to animal and public health [123,124,144]. Thus, continued surveillance and collaboration between public health authorities, veterinary agencies, academia and local communities are essential to prevent further transmission and mitigate the risk of zoonotic transmission to humans.

Nearly 300 species of wild birds, representing vast populations, migrate between the Neotropics and North America [188]. These Nearctic-Neotropical migrants rely on several stopover sites along their migratory path for essential resources like fuel, safe roosting spots, and emergency shelters [189]. Central America's geography and northern Colombia are concentrated areas, funneling millions of birds through critical stopover sites [190]. Additionally, these regions present challenges with barriers like the Caribbean Sea and the Gulf of Mexico, necessitating stopover locations for birds to refuel safely [191]. Colombia's unique position in South America, with coastal marine territories, is crucial for several bird groups, with three significant flyways identified for Neotropical migrants [192]. Colombia's significance in the context of avian influenza lies in its privileged position along major migratory routes for several migratory bird groups. These migratory pathways could potentially facilitate the spread of avian influenza viruses between locations, making countries, like Colombia, a critical focal point for surveillance and monitoring efforts to detect and prevent the transmission of bird influenza among animal populations [112].

To date, the few reports of avian influenza cases in Colombia may reveal that higher avian influenza outbreak rates occur more consistently in certain regions than others. These hotspots may coincide with areas characterized by stopover areas for migratory birds, intensive poultry production, dense poultry populations, and/or high poultry trade and movement levels. Departments such as Cundinamarca, Santander, and Valle del Cauca may be more severely affected by avian influenza outbreaks due to their significant poultry farming activities and proximity to major urban centers. In addition to human activities and poultry production practices, ecological risk factors may significantly shape Colombia's geographical distribution of avian influenza cases. Environmental factors such as proximity to wetlands and water bodies, which serve as natural habitats for wild bird populations and potential reservoirs for avian influenza viruses, contribute to the transmission dynamics of the virus [193]. Regions with high concentrations of migratory bird habitats and bird migration routes may experience increased transmission of avian flu risk due to the interaction between wild and domestic bird populations [42]. Identifying potential hotspots and vulnerable regions for avian influenza outbreaks involves a comprehensive assessment of epidemiological and ecological factors [194]. Geographic Information Systems mapping and spatial analysis techniques can help visualize and analyze avian influenza surveillance data concerning environmental variables, enabling the identification of high-risk areas and disease transmission patterns [195].

Prioritizing surveillance and control measures in avian influenza hotspots and vulnerable regions is essential for effectively managing avian flu in Colombia. Targeted surveillance efforts, including increased sampling and testing of poultry and wild bird populations in high-risk areas, can enhance early detection and response capabilities, enabling prompt intervention to prevent further virus spread [196]. Furthermore, implementing biosecurity measures, vaccination campaigns, and public awareness initiatives tailored to specific geographical regions can help mitigate the risk of avian influenza outbreaks and protect both animal and human health [74]. By leveraging epidemiological data and ecological risk factors to identify and prioritize avian influenza hotspots and vulnerable regions, countries like Colombia can strengthen their surveillance and control strategies, ultimately reducing the burden of bird influenza on the poultry industry and safeguarding public health [43,175]. Implementing new technologies, along with continued monitoring and adaptive management approaches are essential for effectively addressing the dynamic nature of avian influenza transmission [175] and ensuring the resilience of Colombia's poultry sector in the face of emerging infectious disease threats.

Strategies for intervention and prevention

In Colombia's fight against avian influenza, a multifaceted approach incorporating intervention and prevention measures is essential to mitigate the disease´s risk to poultry populations and public health. Implementing vaccination campaigns, biosecurity protocols, and public awareness campaigns can significantly reduce the spread of avian influenza and limit its impact on agricultural productivity and human health [74].

Vaccination of poultry populations against IAV is a crucial preventive measure to minimize the disease transmission risk and reduce the severity of outbreaks [197]. In Colombia, targeted vaccination campaigns can be implemented in high-risk areas, such as regions with a history of avian influenza outbreaks or where large poultry populations are concentrated. Vaccinating susceptible birds, such as chickens and turkeys, against prevalent avian influenza strains can significantly reduce the likelihood of virus transmission within poultry flocks [197]. Furthermore, vaccination can also help protect human health by decreasing the risk of zoonotic transmission of avian influenza viruses from infected poultry to humans [198].

Improving biosecurity measures on poultry farms and in backyard poultry settings is vital for preventing the introduction and spread of avian influenza viruses [156,199]. Biosecurity protocols should include restricting access to production facilities, implementing strict hygiene practices, and maintaining clean and sanitized equipment. Additionally, separating poultry from wild birds and other animals, such as swine, controlling the movement of people and vehicles, and ensuring proper disposal of poultry waste are essential components of effective biosecurity measures [70]. Training and educating farmers and workers on the importance of biosecurity and providing them with the necessary resources and support to implement these measures are critical for their success [200].

Public awareness campaigns aimed at poultry producers (especially backyard), workers, and consumers can help increase knowledge and understanding of avian influenza and promote the adoption of preventive measures [158]. These campaigns can utilize various communication channels, including television, radio, social media, and community outreach programs, to disseminate information about the risks associated with avian influenza, the importance of vaccination and biosecurity, and the signs and symptoms of avian flu infection in animals and humans. Public awareness campaigns can empower individuals and communities to proactively prevent avian influenza outbreaks and protect their health and livelihoods by raising awareness and promoting behavioral changes [201].

Integrating avian influenza considerations into public health policies

Integrating avian influenza considerations into public health policies is essential for effectively managing the risks associated with avian influenza outbreaks and safeguarding animal and human health [202,203]. As avian flu poses a significant threat to poultry populations and can potentially cause zoonotic infections in humans, addressing this public health challenge requires a coordinated and proactive approach at the policy level [48]. By incorporating avian influenza considerations into public health policies, Colombia can enhance its capacity to prevent, detect, and respond to avian influenza outbreaks, mitigate the impact of the disease on agricultural productivity and public health, and strengthen its overall preparedness and resilience against emerging infectious diseases.

While integrating avian influenza considerations into public health policies offers numerous benefits, there are challenges and opportunities associated with policy implementation in Colombia. One of the main challenges facing policy implementation is the limited resources and infrastructure available for disease surveillance, prevention, and control efforts in Colombia. As seen in other similar countries, insufficient funding, inadequate laboratory capacity, and a shortage of trained personnel may hinder the effective implementation of avian influenza policies and programs [204]. To overcome these challenges, Colombia must prioritize investments in infectious disease surveillance systems, laboratory infrastructure, and workforce development to strengthen its capacity to detect and respond to avian influenza outbreaks and other emerging threats. In addition, effective policy implementation requires coordination and collaboration among multiple stakeholders, including government agencies, veterinary and public health authorities, poultry producers, and international partners [205]. However, achieving consensus and cooperation among diverse stakeholders may be challenging due to competing priorities, conflicting interests, and limited communication channels [206]. Colombia can establish multi-sectoral task forces, interagency working groups, and public-private partnerships to facilitate information sharing, resource mobilization, and joint decision-making and enhance coordination and collaboration.

In addition, developing and enforcing regulatory frameworks for avian influenza control and prevention can be complex and challenging [205,207]. In Colombia, ensuring compliance with biosecurity measures, vaccination requirements, and reporting protocols may require strengthened regulatory enforcement mechanisms, enhanced monitoring and surveillance systems, and increased penalties for non-compliance, as seen in other countries [208]. Moreover, engaging with local communities and stakeholders to raise awareness about the importance of avian influenza regulations and incentivize compliance can help promote voluntary adherence to regulatory requirements [67]. Furthermore, effective communication and public engagement are essential for building trust, fostering cooperation, and encouraging behavior change among stakeholders and the general public [209]. However, communicating complex scientific information about avian influenza risks and preventive measures in a clear, accessible, and culturally sensitive manner can be challenging [207]. Colombia, as reported in other countries, can leverage traditional and digital media channels, community outreach programs, and public awareness campaigns to disseminate avian influenza-related information, address misconceptions, and engage stakeholders in dialogue and decision-making processes [210].

Strategies for the establishment of influenza early monitoring and prevention programs in Colombia

Like other tropical and middle income countries, Colombia faces several challenges to improve the early monitoring and prevention of avian influenza outbreaks. Vaccination campaigns, enforced biosecurity protocols, and public awareness campaigns are valuable tools for mitigating the burden of avian influenza worldwide [66,68,201,211]. By integrating these intervention and prevention measures into a coordinated and adaptive strategy, countries such as Colombia can strengthen their capacity to prevent, detect, and respond to avian influenza outbreaks, ultimately safeguarding poultry populations and public health. However, these measures require the allocation of a considerable amount of resources and the political/governmental willingness of the decision makers in the country [148]. In addition, the implementation of such measures and their effectiveness depend on a sustained investment and ongoing monitoring and evaluation of these programs. Nevertheless, based on some experiences reported in other locations, here are some recommendations that can be applied in the context of Colombia:

Developing early detection systems

- **Community-based monitoring:** Training local farmers and community members to identify symptoms of avian flu in birds [212]. Provide basic training in bird health and data collection using mobile apps or local reporting centers to ensure real-time monitoring.
- **Rapid diagnostic kits:** Introducing affordable and easy-to-use diagnostic kits for early detection of avian flu in remote areas [213]. These kits can be distributed to community health centers, poultry farmers, and wildlife observers (i.e. natural parks or protected natural areas) for quick and reliable results.
- **Mobile surveillance teams:** Establishing mobile veterinary teams that can visit backyard poultry farms in rural areas to collect samples and assess the health of bird populations [214]. These teams could be organized by government agencies or through partnerships with universities and NGOs.
- **Partnership with universities and research centers:** Leverage the expertise of academic institutions to design real-time data analytics systems that track bird movement patterns, environmental factors, and symptoms of avian flu [215,216]. They can also contribute to conducting field tests for avian flu detection.

Vaccination programs

- **Targeted vaccination campaigns:** Prioritizing high-risk areas based on previous outbreaks, bird migration routes, and areas with dense backyard poultry populations [217]. Working with local governments to map out these regions and schedule regular vaccination campaigns.
- **Subsidized or free vaccines:** Provision of government-funded vaccines to small-scale farmers and backyard poultry keepers [67]. To ensure the participation of low-income communities, offer vaccines either for free or at a subsidized rate.
- **Mobile vaccination clinics:** In rural areas, mobile veterinary units could travel to high-risk regions, conducting vaccination drives [218]. This approach could ensure access to hard-to-reach populations and offer educational outreach on maintaining healthy flocks.

Biosecurity and public awareness

- **Educational workshops:** Public instittutions whould offer training workshops for stakeholders [116] and poultry farmers, particularly those in backyard settings [199,219], on the importance of biosecurity measures, such as controlling bird movement, sanitation practices, and isolating sick birds.

- **Awareness campaigns:** Use radio, television, and social media to educate farmers and stakeholders about the signs of avian flu, how to report outbreaks, and where to access vaccines or testing services. This could help in building trust and increasing program adoption in rural communities [148,155,176,201].

Conclusions

As in other locations, the examination of avian influenza in Colombia highlights the urgent need for a robust, collaborative approach to managing the virus, integrating human, animal, and environmental health through a One Health framework. Avian influenza poses significant threats to public health and agricultural sectors, with its zoonotic potential and impact on the poultry industry, which is vital for food security and rural livelihoods. Factors such as migratory bird patterns, climate change, and inconsistent biosecurity measures across commercial and backyard poultry farms exacerbate the risks of transmission. Given Colombia's location along major migratory routes, international cooperation is crucial to monitor avian migration and prevent cross-border transmission. To mitigate outbreak risks, key strategies include strengthening surveillance, enhancing biosecurity practices, and targeting interventions in identified hotspots and vulnerable regions. Public health policies should prioritize avian influenza considerations, implementing proactive vaccination programs, early detection systems, and community engagement to protect both animal and human populations. By advancing multisectoral collaboration and aligning with global efforts, Colombia can improve its capacity to prevent and control avian influenza, reducing its socio-economic and health impacts.

References

1. Daszak P, Cunningham AA, Hyatt AD. Emerging Infectious Diseases of Wildlife-- Threats to Biodiversity and Human Health. Science. 2000;287:443–449. https://doi.org/10.1126/science.287.5452.443

2. Cox NJ, Subbarao K. Global Epidemiology of Influenza: Past and Present. Annu Rev Med. 2000;51:407–421. https://doi.org/10.1146/annurev.med.51.1.407

3. Lam TT, Pybus OG. Genomic surveillance of avian-origin influenza A viruses causing human disease. Genome Med. 2018;10:50. https://doi.org/10.1186/s13073-018-0560-3

4. Vandegrift KJ, Sokolow SH, Daszak P, Kilpatrick AM. Ecology of avian influenza viruses in a changing world. Ann N Y Acad Sci. 2010;1195:113–128. https://doi.org/10.1111/j.1749-6632.2010.05451.x

5. Arbeitskreis Blut, Untergruppe "Bewertung Blutassoziierter Krankheitserreger". Influenza Virus. Transfus Med Hemother. 2009;36:32–39. https://doi.org/10.1159/000197314

6. Webster RG, Bean WJ, Gorman OT, Chambers TM, Kawaoka Y. Evolution and ecology of influenza A viruses. Microbiol Rev. 1992;56:152–179. https://doi.org/10.1128/mr.56.1.152-179.1992

7. Kackos CM, Webby RJ. Influenza virus. Reference Module in Life Sciences. Elsevier; 2023. https://doi.org/10.1016/b978-0-12-822563-9.00101-3

8. Fereidouni S, Starick E, Karamendin K, Genova CD, Scott SD, Khan Y, et al. Genetic characterization of a new candidate hemagglutinin subtype of influenza A viruses. Emerg Microbes Infect. 2023;12:2225645. https://doi.org/10.1080/22221751.2023.2225645

9. Philippa JD. Avian Influenza. In: Fowler ME, Miller RE, editors. Zoo and Wild Animal Medicine, Vol 6. Saint Louis: Elsevier; 2008. p. 79-87. https://doi.org/10.1016/B978-141604047-7.50013-0

10. Rashid F, Xie Z, Li M, Xie Z, Luo S, Xie L. Roles and functions of IAV proteins in host immune evasion. Front Immunol. 2023;14:1323560. https://doi.org/10.3389/fimmu.2023.1323560

11. Lu L, Lycett SJ, Leigh Brown AJ. Reassortment patterns of avian influenza virus internal segments among different subtypes. BMC Evol Biol. 2014;14:16. https://doi.org/10.1186/1471-2148-14-16

12. Bahl J, Vijaykrishna D, Holmes EC, Smith GJD, Guan Y. Gene flow and competitive exclusion of avian influenza A virus in natural reservoir hosts. Virology. 2009;390(2): 289–297. https://doi.org/10.1016/j.virol.2009.05.002

13. Korteweg C, Gu J. Pathology, Molecular Biology, and Pathogenesis of Avian Influenza A (H5N1) Infection in Humans. Am J Pathol. 2008;172(5):1155–1170. https://doi.org/10.2353/ajpath.2008.070791

14. de Wit E, Kawaoka Y, de Jong MD, Fouchier RAM. Pathogenicity of highly pathogenic avian influenza virus in mammals. Vaccine. 2008;26(4):D54–D58. https://doi.org/10.1016/j.vaccine.2008.07.072

15. Swayne DE, Pantin-Jackwood M. Pathogenicity of avian influenza viruses in poultry. Dev Biol . 2006;124:61–67. https://www.ncbi.nlm.nih.gov/pubmed/16447495

16. Alexander DJ. A review of avian influenza in different bird species. Vet Microbiol. 2000;74(1-2):3–13. https://doi.org/10.1016/s0378-1135(00)00160-7

17. Donatelli I, Campitelli L, Di Trani L, Puzelli S, Selli L, Fioretti A, et al. Characterization of H5N2 influenza viruses from Italian poultry. J Gen Virol. 2001;82(3):623–630. https://doi.org/10.1099/0022-1317-82-3-623

18. Hulse DJ, Webster RG, Russell RJ, Perez DR. Molecular Determinants within the Surface Proteins Involved in the Pathogenicity of H5N1 Influenza Viruses in Chickens. J Virol. 2004;78(18): 9954–9964. https://doi.org/10.1128/JVI.78.18.9954-9964.2004

19. Steinhauer DA. Role of Hemagglutinin Cleavage for the Pathogenicity of Influenza Virus. Virology. 1999;258(1):1–20. https://doi.org/10.1006/viro.1999.9716

20. Olsen B, Munster VJ, Wallensten A, Waldenström J, Osterhaus ADME, Fouchier RAM. Global Patterns of Influenza A Virus in Wild Birds. Science. 2006;312(5772):384–388. https://doi.org/10.1126/science.1122438

21. Wille M, Holmes EC. The Ecology and Evolution of Influenza Viruses. Cold Spring Harb Perspect Med. 2020;10:a038489. https://doi.org/10.1101/cshperspect.a038489

22. Sooryanarain H, Elankumaran S. Environmental Role in Influenza Virus Outbreaks. Annu Rev Anim Biosci. 2015;3:347–373. https://doi.org/10.1146/annurev-animal-022114-111017

23. Joseph U, Su YCF, Vijaykrishna D, Smith GJD. The ecology and adaptive evolution of influenza A interspecies transmission. Influenza Other Respir Viruses. 2017;11:74–84. https://doi.org/10.1111/irv.12412

24. Kawaoka Y, Chambers TM, Sladen WL, Gwebster R. Is the gene pool of influenza viruses in shorebirds and gulls different from that in wild ducks? Virology. 1988;163(1):247–250. https://doi.org/10.1016/0042-6822(88)90260-7

25. Yang Q, Wang B, Lemey P, Dong L, Mu T, Wiebe RA, et al. Synchrony of bird migration with global dispersal of avian influenza reveals exposed bird orders. Nat Commun. 2024;15:1126. https://doi.org/10.1038/s41467-024-45462-1

26. Tian H, Zhou S, Dong L, Van Boeckel TP, Cui Y, Newman SH, et al. Avian influenza H5N1 viral and bird migration networks in Asia. Proc Natl Acad Sci U S A. 2015;112(1):172–177. https://doi.org/10.1073/pnas.1405216112

27. Fourment M, Darling AE, Holmes EC. The impact of migratory flyways on the spread of

avian influenza virus in North America. BMC Evol Biol. 2017;17:118. https://doi.org/10.1186/s12862-017-0965-4

28. Guinat C, Valenzuela Agüí C, Vaughan TG, Scire J, Pohlmann A, Staubach C, et al. Disentangling the role of poultry farms and wild birds in the spread of highly pathogenic avian influenza virus in Europe. Virus Evol. 2022;8(2):veac073. https://doi.org/10.1093/ve/veac073

29. Bahl J, Krauss S, Kühnert D, Fourment M, Raven G, Pryor SP, et al. Influenza A Virus Migration and Persistence in North American Wild Birds. PLoS Pathog. 2013;9(8):e1003570. https://doi.org/10.1371/journal.ppat.1003570

30. Slingenbergh J, Gilbert M, BALOGH de K, Wint W. Ecological sources of zoonotic diseases. Rev Sci Tech. 2004;23(2):467–484. https://doi.org/10.20506/rst.23.2.1492

31. Runstadler J, Hill N, Hussein ITM, Puryear W, Keogh M. Connecting the study of wild influenza with the potential for pandemic disease. Infect Genet Evol. 2013;17:162–187. https://doi.org/10.1016/j.meegid.2013.02.020

32. Anderson T, Capua I, Dauphin G, Donis R, Fouchier R, Mumford E, Peiris M, Swayne D, Thiermann A. FAO-OIE-WHO Joint Technical Consultation on Avian Influenza at the Human-Animal Interface. Influenza Other Respir Viruses. 2010;4(1):1–29. https://doi.org/10.1111/j.1750-2659.2009.00114.x

33. Mansour SMG, ElBakrey RM, Ali H, Knudsen DEB, Eid AAM. Natural infection with highly pathogenic avian influenza virus H5N1 in domestic pigeons (Columba livia) in Egypt. Avian Pathol. 2014;43(4):319–324. https://doi.org/10.1080/03079457.2014.926002

34. Spackman E. The ecology of avian influenza virus in wild birds: What does this mean for poultry? Poult Sci. 2009;88(4):847–850. https://doi.org/10.3382/ps.2008-00336

35. Shoham D, Jahangir A, Ruenphet S, Takehara K. Persistence of Avian Influenza Viruses in Various Artificially Frozen Environmental Water Types. Influenza Res Treat. 2012(1);1–11. https://doi.org/10.1155/2012/912326

36. Keeler SP, Berghaus RD, Stallknecht DE. PERSISTENCE OF LOW PATHOGENIC AVIAN INFLUENZA VIRUSES IN FILTERED SURFACE WATER FROM WATERFOWL HABITATS IN GEORGIA, USA. J Wildl Dis. 2012;48(4):999–1009. https://doi.org/10.7589/2011-11-314

37. Causey D, Edwards SV. Ecology of Avian Influenza Virus in Birds. J Infect Dis. 2008;197(1):S29–S33. https://doi.org/10.1086/524991

38. Stallknecht DE, Shane SM, Kearney MT, Zwank PJ. Persistence of Avian Influenza Viruses in Water. Avian Dis. 1990;34:406. https://doi.org/10.2307/1591428

39. Germeraad EA, Sanders P, Hagenaars TJ, de Jong MCM, Beerens N, Gonzales JL. Virus Shedding of Avian Influenza in Poultry: A Systematic Review and Meta-Analysis. Viruses. 2019;11(9):812. https://doi.org/10.3390/v11090812

40. Reemers SS, van Leenen D, Groot Koerkamp MJ, van Haarlem D, van de Haar P, van Eden W, et al. Early host responses to avian influenza A virus are prolonged and enhanced at transcriptional level depending on maturation of the immune system. Mol Immunol. 2010;47(9):1675–1685. https://doi.org/10.1016/j.molimm.2010.03.008

41. Rehman S, Effendi MH, Witaningruma AM, Nnabuikeb UE, Bilal M, Abbas A, et al. Avian influenza (H5N1) virus, epidemiology and its effects on backyard poultry in Indonesia: a review. F1000Res. 2023;11:1321. https://doi.org/10.12688/f1000research.125878.2

42. Blagodatski A, Trutneva K, Glazova O, Mityaeva O, Shevkova L, Kegeles E, et al. Avian influenza in wild birds and poultry: Dissemination pathways, monitoring methods, and virus ecology. Pathogens. 2021;10(5):630. https://doi.org/10.3390/pathogens10050630

43. Simancas-Racines A, Cadena-Ullauri S, Guevara-Ramírez P, Zambrano AK, Simancas-Racines D. Avian influenza: Strategies to manage an outbreak. Pathogens. 2023;12(4):610. https://doi.org/10.3390/pathogens12040610

44. Afanador-Villamizar A, Gomez-Romero C, Diaz A, Ruiz-Saenz J. Avian influenza in Latin America: A systematic review of serological and molecular studies from 2000-2015. PLoS ONE. 2017;12(6):e0179573. https://doi.org/10.1371/journal.pone.0179573

45. Hill NJ, Bishop MA, Trovão NS, Ineson KM, Schaefer AL, Puryear WB, et al. Ecological divergence of wild birds drives avian influenza spillover and global spread. PLoS Pathog. 2022;18(5):e1010062. https://doi.org/10.1371/journal.ppat.1010062

46. Mohan R, Saif YM, Erickson GA, Gustafson GA, Easterday BC. Serologic and epidemiologic evidence of infection in turkeys with an agent related to the swine influenza virus. Avian Dis. 1981;25(1):11–16. https://doi.org/10.2307/1589822

47. Alexander DJ. An overview of the epidemiology of avian influenza. Vaccine. 2007;25(30):5637–5644. https://doi.org/10.1016/j.vaccine.2006.10.051

48. Charostad J, Rezaei Zadeh Rukerd M, Mahmoudvand S, Bashash D, Hashemi SMA, Nakhaie M, et al. A comprehensive review of highly pathogenic avian influenza (HPAI) H5N1: An imminent threat at doorstep. Travel Med Infect Dis. 2023;55:102638. https://doi.org/10.1016/j.tmaid.2023.102638

49. Dutta P, Islam A, Sayeed MA, Rahman MA, Abdullah MS, Saha O, et al. Epidemiology and molecular characterization of avian influenza virus in backyard poultry of Chattogram, Bangladesh. Infect Genet Evol. 2022;105:105377. https://doi.org/10.1016/j.meegid.2022.105377

50. Djurdjević B, Polaček V, Pajić M, Petrović T, Vučićević I, Vidanović D, et al. Highly pathogenic avian influenza H5N8 outbreak in backyard chickens in Serbia. Animals. 2023;13(4):700. https://doi.org/10.3390/ani13040700

51. Abdelwhab EM, Hafez HM. An overview of the epidemic of highly pathogenic H5N1 avian influenza virus in Egypt: epidemiology and control challenges. Epidemiol Infect. 2011;139(5):647–657. https://doi.org/10.1017/s0950268810003122

52. Gradisteanu Pircalabioru G, Iliescu FS, Mihaescu G, Cucu AI, Ionescu ON, Popescu M, et al. Advances in the rapid diagnostic of viral respiratory tract infections. Front Cell Infect Microbiol. 2022;12:807253. https://doi.org/10.3389/fcimb.2022.807253

53. Wang R, Taubenberger JK. Methods for molecular surveillance of influenza. Expert Rev Anti Infect Ther. 2010;8(5):517–527. https://doi.org/10.1586/eri.10.24

54. Madhav N, Oppenheim B, Gallivan M, Mulembakani P, Rubin E, Wolfe N. Pandemics: Risks, impacts, and mitigation. In: Jamison DT, Gelband H, Horton S, Jha P, Laxminarayan R, Mock CN, Nugent R, editors. Disease Control Priorities, Third Edition (Volume 9): Improving Health and Reducing Poverty. Washington, D.C. : World Bank Group; 2017. p. 315–345. https://doi.org/10.1596/978-1-4648-0527-1_ch17

55. Meadows AJ, Stephenson N, Madhav NK, Oppenheim B. Historical trends demonstrate a pattern of increasingly frequent and severe spillover events of high-consequence zoonotic viruses. BMJ Glob Health. 2023;8(11):e012026. https://doi.org/10.1136/bmjgh-2023-012026

56. Kojima N, Adlhoch C, Mitja O, Dat VQ, Lescano AG, Klausner JD. Building global preparedness for avian influenza. Lancet. 2024;403(10443):2461–2465. https://doi.org/10.1016/S0140-6736(24)00934-6

57. Abdelwhab EM, Mettenleiter TC. Zoonotic animal influenza virus and potential mixing vessel hosts. Viruses. 2023;15(4):980. https://doi.org/10.3390/v15040980

58. Kang M, Li H-P, Tang J, Wang X-Y, Wang L-F, Baele G, et al. Changing epidemiological patterns in human avian influenza virus infections. Lancet Microbe. 2024;5(11):100918. https://doi.org/10.1016/S2666-5247(24)00158-7

59. Smith GJD, Bahl J, Vijaykrishna D, Zhang J, Poon LLM, Chen H, et al. Dating the emergence of pandemic influenza viruses. Proc Natl Acad Sci U.S.A.. 2009;106(28):11709–11712. https://doi.org/10.1073/pnas.0904991106

60. To KKW, Chan JFW, Chen H, Li L, Yuen K-Y. The emergence of influenza A H7N9 in human beings 16 years after influenza A H5N1: a tale of two cities. Lancet Infect Dis. 2013;13(9):809–821. https://doi.org/10.1016/S1473-3099(13)70167-1

61. Bao C-J, Cui L-B, Zhou M-H, Hong L, Gao GF, Wang H. Live-animal markets and influenza A (H7N9) virus infection. N Engl J Med. 2013;368(24):2337–2339. https://doi.org/10.1056/nejmc1306100

62. Lam TT-Y, Wang J, Shen Y, Zhou B, Duan L, Cheung C-L, et al. The genesis and source of the H7N9 influenza viruses causing human infections in China. Nature. 2013;502:241–244. https://doi.org/10.1038/nature12515

63. Lebarbenchon C, Feare CJ, Renaud F, Thomas F, Gauthier-Clerc M. Persistence of highly pathogenic avian influenza viruses in natural ecosystems. Emerg Infect Dis. 2010;16(7):1057–1062. https://doi.org/10.3201/eid1607.090389

64. Pepin KM, Wang J, Webb CT, Hoeting JA, Poss M, Hudson PJ, et al. Anticipating the prevalence of avian influenza subtypes H9 and H5 in live-bird markets. PLoS One. 2013;8(2):e56157. https://doi.org/10.1371/journal.pone.0056157

65. Chen Z, Li K, Luo L, Lu E, Yuan J, Liu H, et al. Detection of avian influenza A(H7N9) virus from live poultry markets in Guangzhou, China: a surveillance report. PLoS One. 2014;9(9):e107266. https://doi.org/10.1371/journal.pone.0107266

66. Graham JP, Leibler JH, Price LB, Otte JM, Pfeiffer DU, Tiensin T, et al. The animal-human interface and infectious disease in industrial food animal production: rethinking biosecurity and biocontainment. Public Health Rep. 2008;123(3):282–299. https://doi.org/10.1177/003335490812300309

67. Jewitt S, Smallman-Raynor M, McClaughlin E, Clark M, Dunham S, Elliott S, et al. Exploring the responses of smallscale poultry keepers to avian influenza regulations and guidance in the United Kingdom, with recommendations for improved biosecurity messaging. Heliyon. 2023;9(9):e19211. https://doi.org/10.1016/j.heliyon.2023.e19211

68. Islam A, Rahman MZ, Hassan MM, Epstein JH, Klaassen M. Farm biosecurity practices affecting avian influenza virus circulation in commercial chicken farms in Bangladesh. One Health. 2024;18:100681. https://doi.org/10.1016/j.onehlt.2024.100681

69. Islam A, Islam S, Amin E, Shano S, Samad MA, Shirin T, et al. Assessment of poultry rearing practices and risk factors of H5N1 and H9N2 virus circulating among backyard chickens and ducks in rural communities. PLoS One. 2022;17(10):e0275852. https://doi.org/10.1371/journal.pone.0275852

70. Grace D, Knight-Jones TJD, Melaku A, Alders R, Jemberu WT. The public health importance and management of infectious poultry diseases in smallholder systems in Africa. Foods. 2024;13(3):411. https://doi.org/10.3390/foods13030411

71. Sun Y, Shen Y, Zhang X, Wang Q, Liu L, Han X, et al. A serological survey of canine H3N2, pandemic H1N1/09 and human seasonal H3N2 influenza viruses in dogs in China. Vet Microbiol. 2014;168(1):193–196. https://doi.org/10.1016/j.vetmic.2013.10.012

72. Paternina D, Herazo R, Oviedo M, Mattar S. Dramatic re-emergence of avian influenza in Colombia and Latin America. Travel Med Infect Dis. 2024;59:102711. https://doi.org/10.1016/j.tmaid.2024.102711

73. Hinjoy S, Thumrin P, Sridet J, Chaiyaso C, Suddee W, Thukngamdee Y, et al. An overlooked poultry trade network of the smallholder farms in the border provinces of Thailand, 2021: implications for avian influenza surveillance. Front Vet Sci. 2024;11:1301513. https://doi.org/10.3389/fvets.2024.1301513

74. European Food Safety Authority (EFSA), European Centre for Disease Prevention and Control (ECDC), Adlhoch C, Alm E, Enkirch T, Lamb F, et al. Drivers for a pandemic due to avian influenza and options for One Health mitigation measures. EFSA J. 2024;22(4):e8735. https://doi.org/10.2903/j.efsa.2024.8735

75. Vora NM, Hannah L, Walzer C, Vale MM, Lieberman S, Emerson A, et al. Interventions to reduce risk for pathogen spillover and early disease spread to prevent outbreaks, epidemics, and pandemics. Emerg Infect Dis. 2023;29(3):1–9. https://doi.org/10.3201/eid2903.221079

76. Taubenberger JK, Morens DM. Influenza: the once and future pandemic. Public Health Rep. 2010;125(3):16–26. https://www.ncbi.nlm.nih.gov/pubmed/20568566

77. Fraser C, Donnelly CA, Cauchemez S, Hanage WP, Van Kerkhove MD, Hollingsworth TD, et al. Pandemic potential of a strain of influenza A (H1N1): Early findings. Science. 2009;324(5934):1557–1561. https://doi.org/10.1126/science.1176062

78. Peiris JSM, de Jong MD, Guan Y. Avian Influenza Virus (H5N1): a Threat to Human Health. Clin Microbiol Rev. 2007;20(2):243–267. https://doi.org/10.1128/CMR.00037-06

79. Farley MM. 2009 H1N1 influenza: a twenty-first century pandemic with roots in the early twentieth century. Am J Med Sci. 2010;340(3):202–208. https://doi.org/10.1097/MAJ.0b013e3181e937b0

80. DeJesus E, Costa-Hurtado M, Smith D, Lee D-H, Spackman E, Kapczynski DR, et al. Changes in adaptation of H5N2 highly pathogenic avian influenza H5 clade 2.3.4.4 viruses in chickens and mallards. Virology. 2016;499:52–64. https://doi.org/10.1016/j.virol.2016.08.036

81. Huang P, Sun L, Li J, Wu Q, Rezaei N, Jiang S, et al. Potential cross-species transmission of highly pathogenic avian influenza H5 subtype (HPAI H5) viruses to humans calls for the development of H5-specific and universal influenza vaccines. Cell Discov. 2023;9(58):1-13. https://doi.org/10.1038/s41421-023-00571-x

82. Subbarao K, Klimov A, Katz J, Regnery H, Lim W, Hall H, et al. Characterization of an Avian Influenza A (H5N1) Virus Isolated from a Child with a Fatal Respiratory Illness. Science. 1998;279(5349):393–396. https://doi.org/10.1126/science.279.5349.393

83. Webster RG, Peiris M, Chen H, Guan Y. H5N1 Outbreaks and Enzootic Influenza. Emerg Infect Dis. 2006;12(1):3–8. https://doi.org/10.3201/eid1201.051024

84. Ly H. Highly pathogenic avian influenza H5N1 virus infections of dairy cattle and livestock handlers in the United States of America. Virulence. 2024;15(1):1-3. https://doi.org/10.1080/21505594.2024.2343931

85. Centers for Disease Control and Prevention (CDC). Highly Pathogenic Avian Influenza A (H5N1) Virus Infection Reported in a Person in the U.S. Atlanta: CDC; 2024. https://www.cdc.gov/media/releases/2024/p0401-avian-flu.html

86. Centers for Disease Control and Prevention (CDC). Considerations for Veterinarians: Evaluating and Handling of Cats Potentially Exposed to Highly Pathogenic Avian Influenza A(H5N1) Virus. Atlanta: CDC; 2024. https://asprtracie.hhs.gov/technical-resources/resource/12358/considerations-for-veterinarians-evaluating-and-handling-of-cats-potentially-exposed-to-highly-pathogenic-avian-influenza-ah5n1-virus

87. Animal and Plant Health Inspection Service (APHIS). Highly Pathogenic Avian Influenza (HPAI) H5N1 Detections in Alpacas; 2024. https://www.aphis.usda.gov/livestock-poultry-disease/avian/avian-influenza/hpai-detections/mammals/highly-pathogenic-avian

88. Xie H, Sun Q, Song W. Exploring the ecological effects of rural land use changes: A bibliometric overview. Land. 2024;13(3):303. https://doi.org/10.3390/land13030303

89. Myers SS. Land Use Change and Human Health. In: Ingram J, DeClerck F, Rumbaitis del Rio C. editors. Integrating Ecology and Poverty Reduction. New York, NY: Springer; 2012. p. 167–186. https://doi.org/10.1007/978-1-4419-0633-5_11

90. Ruiz S, Jimenez-Bluhm P, Di Pillo F, Baumberger C, Galdames P, Marambio V, et al. Temporal dynamics and the influence of environmental variables on the prevalence of avian influenza virus in main wetlands in central

Chile. Transbound Emerg Dis. 2021;68(3):1601–1614. https://doi.org/10.1111/tbed.13831

91. Ruiz-Philipps SA, Baumberger C, Jimenez-Bluhm P, Marambio V, Salazar C, Hamilton-West C. Factores ambientales relacionados con la presentación de virus influenza A en aves silvestres. Rev MVZ Cordoba. 2020;25(2):e1845. https://doi.org/10.21897/rmvz.1845

92. Burrough ER, Magstadt DR, Petersen B, Timmermans SJ, Gauger PC, Zhang J, et al. Highly pathogenic avian influenza A(H5N1) clade 2.3.4.4b virus infection in domestic dairy cattle and cats, United States, 2024. Emerg Infect Dis. 2024;30(7):1335–1343. https://doi.org/10.3201/eid3007.240508

93. Kappes A, Tozooneyi T, Shakil G, Railey AF, McIntyre KM, Mayberry DE, et al. Livestock health and disease economics: a scoping review of selected literature. Front Vet Sci. 2023;10:1168649. https://doi.org/10.3389/fvets.2023.1168649

94. Jones JC, Sonnberg S, Webby RJ, Webster RG. Influenza A(H7N9) virus transmission between finches and poultry. Emerg Infect Dis. 2015;21(4):619–628. https://doi.org/10.3201/eid2104.141703

95. Liu D, Shi W, Shi Y, Wang D, Xiao H, Li W, et al. Origin and diversity of novel avian influenza A H7N9 viruses causing human infection: phylogenetic, structural, and coalescent analyses. Lancet. 2013;381(9881):1926–1932. https://doi.org/10.1016/S0140-6736(13)60938-1

96. Lee SS, Wong NS, Leung CC. Exposure to avian influenza H7N9 in farms and wet markets. Lancet. 2013;381(9880):1815. https://doi.org/10.1016/S0140-6736(13)60949-6

97. Jori F, Hernandez-Jover M, Magouras I, Dürr S, Brookes VJ. Wildlife-livestock interactions in animal production systems: what are the biosecurity and health implications? Anim Front. 2021;11(5):8–19. https://doi.org/10.1093/af/vfab045

98. Viña A, Liu J. Effects of global shocks on the evolution of an interconnected world. Ambio. 2023;52:95–106. https://doi.org/10.1007/s13280-022-01778-0

99. Maes DGD, Dewulf J, Piñeiro C, Edwards S, Kyriazakis I. A critical reflection on intensive pork production with an emphasis on animal health and welfare. J Anim Sci. 2020;98(1):S15–S26. https://doi.org/10.1093/jas/skz362

100. Gilbert M, Xiao X, Robinson TP. Intensifying poultry production systems and the emergence of avian influenza in China: a "One Health/Ecohealth" epitome. Arch Public Health. 2017;75:48. https://doi.org/10.1186/s13690-017-0218-4

101. Kessler S, Harder TC, Schwemmle M, Ciminski K. Influenza A viruses and zoonotic events-are we creating our own reservoirs? Viruses. 2021;13(11):2250. https://doi.org/10.3390/v13112250

102. Ortiz DI, Piche-Ovares M, Romero-Vega LM, Wagman J, Troyo A. The impact of deforestation, urbanization, and changing land use patterns on the ecology of mosquito and tick-borne diseases in Central America. Insects. 2022;13(1):20. https://doi.org/10.3390/insects13010020

103. Karesh WB, Dobson A, Lloyd-Smith JO, Lubroth J, Dixon MA, Bennett M, et al. Ecology of zoonoses: natural and unnatural histories. Lancet. 2012;380(9857):1936–1945. https://doi.org/10.1016/S0140-6736(12)61678-X

104. Lane MA, Walawender M, Carter J, Brownsword EA, Landay T, Gillespie TR, et al. Climate change and influenza: A scoping review. J Clim Chang Health. 2022;5:100084. https://doi.org/10.1016/j.joclim.2021.100084

105. Sterling S, Ducharne A. Comprehensive data set of global land cover change for land surface model applications. Global Biogeochem Cycles. 2008;22(3):GB3017. https://doi.org/10.1029/2007gb002959

106. van Eerden MR, Drent RH, Stahl J, Bakker JP. Connecting seas: Western Palaearctic continental flyway for water birds in the perspective of changing land use and climate. Global Chang Biol. 2005;11(6):894-908. https://doi.org/10.1111/j.1365-2486.2005.00940.x

107. Fouque C, Guillemain M, Benmergui M. et al. Mute swan (Cygnus olor) winter distribution and

numerical trends over a 16-year period (1987/1988-2002/2003) in France. J Ornithol. 1987;148:477-487. https://doi.org/10.1007/s10336-007-0183-8

108. Beatty WS, Kesler DC, Webb EB, Naylor LW, Raedeke AH, Humburg DD, et al. How will predicted land-use change affect waterfowl spring stopover ecology? Inferences from an individual-based model. J Appl Ecol. 2017;54(3):926–934. https://doi.org/10.1111/1365-2664.12788

109. Liu X, Qiu Y, Zheng Z, Hong Q, Zhang Y, Qian Q, et al. Spatiotemporal changes in waterfowl habitat suitability in the Caohai Lake wetland and responses to human activities. Sustainability. 2022;14(21):14409. https://doi.org/10.3390/su142114409

110. Kjaer LJ, Hjulsager CK, Larsen LE, Boklund AE, Halasa T, Ward MP, et al. Landscape effects and spatial patterns of avian influenza virus in Danish wild birds, 2006-2020. Transbound Emerg Dis. 2022;69(2):706–719. https://doi.org/10.1111/tbed.14040

111. Sullivan JD, Takekawa JY, Spragens KA, Newman SH, Xiao X, Leader PJ, et al. Waterfowl spring migratory behavior and avian influenza transmission risk in the changing landscape of the east Asian-Australasian flyway. Front Ecol Evol. 2018;6:206. https://doi.org/10.3389/fevo.2018.00206

112. McDuie F, Matchett EL, Prosser DJ, Takekawa JY, Pitesky ME, Lorenz AA, et al. Pathways for avian influenza virus spread: GPS reveals wild waterfowl in commercial livestock facilities and connectivity with the natural wetland landscape. Transbound Emerg Dis. 2022;69(5):2898–2912. https://doi.org/10.1111/tbed.14445

113. Branda F, Ciccozzi M. Navigating novel viral challenges: Understanding, tracking, and mitigating emerging threats. Microorganisms. 2024;12(4):807. https://doi.org/10.3390/microorganisms12040807

114. Duan C, Li C, Ren R, Bai W, Zhou L. An overview of avian influenza surveillance strategies and modes. Sci One Health. 2023;2:100043. https://doi.org/10.1016/j.soh.2023.100043

115. Odoom JK, Bel-Nono S, Rodgers D, Agbenohevi PG, Dafeamekpor CK, Sowa RML, et al. Troop education and avian influenza surveillance in military barracks in Ghana, 2011. BMC Public Health. 2012;12:957. https://doi.org/10.1186/1471-2458-12-957

116. Beltran-Alcrudo D, Bunn DA, Sandrock CE, Cardona CJ. Avian flu school: a training approach to prepare for H5N1 highly pathogenic avian influenza. Public Health Rep. 2008;123(3):323–332. https://doi.org/10.1177/003335490812300312

117. Rehman S, Rantam FA, Batool K, Rahman A, Effendi MH, Rahmahani J, et al. Knowledge, attitude, and practices associated with avian influenza among undergraduate university students of East Java Indonesia: A cross-sectional survey. F1000Res. 2022;11:115. https://doi.org/10.12688/f1000research.74196.1

118. Knudsen J, Perlman-Gabel M, Uccelli IG, Jeavons J, Chokshi DA. Combating misinformation as a core function of public health. NEJM Catal Innov Care Deliv. 2023;4(2). https://doi.org/10.1056/cat.22.0198

119. Horefti E. The importance of the One Health concept in combating zoonoses. Pathogens. 2023;12(8):977. https://doi.org/10.3390/pathogens12080977

120. Shafique M, Khurshid M, Muzammil S, Arshad MI, Malik IR, Rasool MH, et al. Traversed dynamics of climate change and One Health. Environ Sci Eur. 2024;36:135. https://doi.org/10.1186/s12302-024-00931-8

121. Danasekaran R. One Health: A holistic approach to tackling global health issues. Indian J Community Med. 2024;49(2):260–263. https://doi.org/10.4103/ijcm.ijcm_521_23

122. Ellwanger JH, Veiga ABG da, Kaminski V de L, Valverde-Villegas JM, Freitas AWQ de, Chies JAB. Control and prevention of infectious diseases from a One Health perspective. Genet Mol Biol. 2021;44(1):e20200256. https://doi.org/10.1590/1678-4685-GMB-2020-0256

123. Karlsson EA, Ciuoderis K, Freiden PJ, Seufzer B, Jones JC, Johnson J, et al. Prevalence and characterization of influenza viruses in diverse

species in Los Llanos, Colombia. Emerg Microbes Infect. 2013;2(1):1-10. https://doi.org/10.1038/emi.2013.20

124. Jiménez-Bluhm P, Karlsson EA, Ciuoderis KA, Cortez V, Marvin SA, Hamilton-West C, et al. Avian H11 influenza virus isolated from domestic poultry in a Colombian live animal market. Emerg Microbes Infect. 2016;5(1):1-9. https://doi.org/10.1038/emi.2016.121

125. Ospina-Jimenez AF, Gomez AP, Osorio-Zambrano WF, Alvarez-Munoz S, Ramirez-Nieto GC. Sequence-based epitope mapping of high pathogenicity avian influenza H5 clade 2.3.4.4b in Latin America. Front Vet Sci. 2024;11:1347509. https://doi.org/10.3389/fvets.2024.1347509

126. Bayly NJ, Gómez C, Hobson KA, Rosenberg KV. Prioritizing tropical habitats for long-distance migratory songbirds: an assessment of habitat quality at a stopover site in Colombia. Avian Conserv Ecol. 2016;11(2):5. https://doi.org/10.5751/ace-00873-110205

127. Trierweiler C, Klaassen RHG, Drent RH, Exo K-M, Komdeur J, Bairlein F, et al. Migratory connectivity and population-specific migration routes in a long-distance migratory bird. Proc Biol Sci. 2014;281:20132897. https://doi.org/10.1098/rspb.2013.2897

128. Keawcharoen J, van den Broek J, Bouma A, Tiensin T, Osterhaus ADME, Heesterbeek H. Wild birds and increased transmission of highly pathogenic avian influenza (H5N1) among poultry, Thailand. Emerg Infect Dis. 2011;17(6):1016–1022. https://doi.org/10.3201/eid1706.100880

129. Calle C, Estrada M, Barrios D, Agudelo G. Construcción de un índice de competitividad para el sector avícola colombiano. Lect Econ. 2015;83:193–228. https://doi.org/10.17533/udea.le.n83a07

130. Gómez Londoño J, Cerón-Muñoz MF, Duque Noreña JH, David Jaramillo E, Múnera Bedoya OD. Caracterización de Sistemas de Producción Industrial de Pollo de Engorde en el Departamento de Santander- Colombia. Rev Lasallista Investig. 2022;19(1):84–100. https://doi.org/10.22507/rli.v19n1a5

131. Ruiz B. Top Latin American broiler, layer rankings for 2023. WATTPoultry; 2024 https://www.poultryinternational-digital.com/poultryinternational/april_may_2024/MobilePagedArticle.action?articleId=1965719#articleId1965719

132. Gentile N, Carrasquer F, Marco-Fuertes A, Marin C. Backyard poultry: exploring non-intensive production systems. Poult Sci. 2024;103(2):103284. https://doi.org/10.1016/j.psj.2023.103284

133. Hortúa-López L, Cerón-Muñoz M, Zaragoza-Martínez M, Angulo-Arizala J. Caracterización y tipificación de la avicultura de traspatio en Boyacá, Colombia, y su efecto sobre la seguridad alimentaria. Rev Investig Vet Peru. 2022;33(6):e22753. https://doi.org/10.15381/rivep.v33i6.22753

134. Hotúa-López LC, Cerón-Muñoz MF, Zaragoza-Martínez MDL, Angulo-Arizala J. Avicultura de traspatio: aportes y oportunidades para la familia campesina. Agron Mesoam. 2021;32(3):1019–1033. https://doi.org/10.15517/am.v32i3.42903

135. Wan X-F, Dong L, Lan Y, Long L-P, Xu C, Zou S, et al. Indications that live poultry markets are a major source of human H5N1 influenza virus infection in China. J Virol. 2011;85(24):13432–13438. https://doi.org/10.1128/JVI.05266-11

136. Cardona C, Yee K, Carpenter T. Are live bird markets reservoirs of avian influenza? Poult Sci. 2009;88(4):856–859. https://doi.org/10.3382/ps.2008-00338

137. Federación Nacional de Avicultores de Colombia (FENAVI). Boletín sanitario avícola: Influenza aviar, enfermedad de Newcastle notificable y salmonelosis aviar. Edición 50; 2023. https://fenavi.org/wp-content/uploads/2024/01/Boletin_Sanitario_ed_50.pdf

138. Instituto Colombiano Agropecuario (ICA). Gestión Influenza Aviar Altamente Patógena

(IAAP): Informe 3; 2024. https://www.ica.gov.co/areas/pecuaria/servicios/enfermedades-animales/influenza-aviar/informe_ia-final-informe-no-3.aspx

139. Guan Y, Smith GJD. The emergence and diversification of panzootic H5N1 influenza viruses. Virus Res. 2013;178(1):35–43. https://doi.org/10.1016/j.virusres.2013.05.012

140. Cheung CL, Vijaykrishna D, Smith GJD, Fan XH, Zhang JX, Bahl J, et al. Establishment of influenza A virus (H6N1) in minor poultry species in southern China. J Virol. 2007;81(19):10402–10412. https://doi.org/10.1128/JVI.01157-07

141. Olivera MJ, Porras Villamil JF, Toquica Gahona CC, Rodríguez Hernández JM. Barriers to diagnosis access for Chagas disease in Colombia. J Parasitol Res. 2018;2018(1):1-14. https://doi.org/10.1155/2018/4940796

142. Herazo R, Torres-Torres F, Mantilla CAG, Carillo LP, Cuervo A, Camargo MAM, et al. On-site experience of a project to increase access to diagnosis and treatment of Chagas disease in high-risk endemic areas of Colombia. Acta Trop. 2022;226:106219. https://doi.org/10.1016/j.actatropica.2021.106219

143. Ciuoderis KA, Perez LS, Cardona A, Hernandez-Ortíz JP, Osorio JE. Use of oral fluids for efficient monitoring of influenza viruses in swine herds in Colombia. Rev Colomb Cienc Pecu. 2022;35(3):141–152. https://doi.org/10.17533/udea.rccp.v35n3a02

144. Ciuoderis-Aponte K, Diaz A, Muskus C, Peña M, Hernández-Ortiz J, Osorio J. Farm management practices, biosecurity and influenza a virus detection in swine farms: a comprehensive study in colombia. Porcine Health Manag. 2022;8:42. https://doi.org/10.1186/s40813-022-00287-6

145. Zheng Z, Lu Y, Short KR, Lu J. One health insights to prevent the next HxNy viral outbreak: learning from the epidemiology of H7N9. BMC Infect Dis. 2019;19:138. https://doi.org/10.1186/s12879-019-3752-6

146. Franklin SI. Can One Health fight H5N1 avian influenza?. Lancet Planet Health. 2023;7(6):E442–E443. https://doi.org/10.1016/S2542-5196(23)00086-4

147. Nguyen-Viet H, Lam S, Nguyen-Mai H, Trang DT, Phuong VT, Tuan NDA, et al. Decades of emerging infectious disease, food safety, and antimicrobial resistance response in Vietnam: The role of One Health. One Health. 2022;14:100361. https://doi.org/10.1016/j.onehlt.2021.100361

148. Innes GK, Lambrou AS, Thumrin P, Thukngamdee Y, Tangwangvivat R, Doungngern P, et al. Enhancing global health security in Thailand: Strengths and challenges of initiating a One Health approach to avian influenza surveillance. One Health. 2022;14:100397. https://doi.org/10.1016/j.onehlt.2022.100397

149. Sims LD, Peiris M. One health: the Hong Kong experience with avian influenza. Curr Top Microbiol Immunol. 2013;365:281–298. https://doi.org/10.1007/82_2012_254

150. Chaudhry M, Webby R, Swayne D, Rashid HB, DeBeauchamp J, Killmaster L, et al. Avian influenza at animal-human interface: One-health challenge in live poultry retail stalls of Chakwal, Pakistan. Influenza Other Respi Viruses. 2020;14(3):257–265. https://doi.org/10.1111/irv.12718

151. Offeddu V, Cowling BJ, Malik Peiris JS. Interventions in live poultry markets for the control of avian influenza: a systematic review. One Health. 2016;2:55–64. https://doi.org/10.1016/j.onehlt.2016.03.002

152. Islam A, Munro S, Hassan MM, Epstein JH, Klaassen M. The role of vaccination and environmental factors on outbreaks of high pathogenicity avian influenza H5N1 in Bangladesh. One Health. 2023;17:100655. https://doi.org/10.1016/j.onehlt.2023.100655

153. Hassan MM, Dutta P, Islam MM, Ahaduzzaman M, Chakma S, Islam A, Magalhaes RJS. The One

Health Epidemiology of Avian Influenza Infection in Bangladesh: Lessons Learned from the Past 15 Years. Transbound Emerg Dis. 2023;2023:6981327. https://doi.org/10.1155/2023/6981327

154. Moriguchi S, Hosoda R, Ushine N, Kato T, Hayama S-I. Surveillance system for avian influenza in wild birds and implications of its improvement with insights into the highly pathogenic avian influenza outbreaks in Japan. Prev Vet Med. 2021;187:105234. https://doi.org/10.1016/j.prevetmed.2020.105234

155. Sharan M, Vijay D, Yadav JP, Bedi JS, Dhaka P. Surveillance and response strategies for zoonotic diseases: a comprehensive review. Sci One Health. 2023;2:100050. https://doi.org/10.1016/j.soh.2023.100050

156. Islam Z, Hsan K, Ripon RK, Madhu J, Hossain S, Masud AA, et al. Assessment of biosecurity measures in commercial poultry farms of Rajshahi district in Bangladesh. Prev Vet Med. 2023;219:106027. https://doi.org/10.1016/j.prevetmed.2023.106027

157. Kibenge FSB. A One Health approach to mitigate the impact of influenza A virus (IAV) reverse zoonosis is by vaccinating humans and susceptible farmed and pet animals. Am J Vet Res. 2023;84(6):1–9. https://doi.org/10.2460/ajvr.23.03.0053

158. MacMahon KL, Delaney LJ, Kullman G, Gibbins JD, Decker J, Kiefer MJ. Protecting poultry workers from exposure to avian influenza viruses. Public Health Rep. 2008;123(3):316–322. https://doi.org/10.1177/003335490812300311

159. Indriani R, Samaan G, Gultom A, Loth L, Irianti S, Adjid R, et al. Environmental sampling for avian influenza virus A (H5N1) in live-bird markets, Indonesia. Emerg Infect Dis. 2010;16(12):1889–1895. https://doi.org/10.3201/eid1612.100402

160. Dlamini M, Msolo L, Ehi Ebomah K, Nontongana N, Ifeanyi Okoh A. A systematic review on the incidence of influenza viruses in wastewater matrices: Implications for public health. PLoS One. 2024;19(4):e0291900. https://doi.org/10.1371/journal.pone.0291900

161. Harvey JA, Mullinax JM, Runge MC, Prosser DJ. The changing dynamics of highly pathogenic avian influenza H5N1: Next steps for management & science in North America. Biol Conserv. 2023;282:110041. https://www.sciencedirect.com/science/article/pii/S0006320723001428

162. James J, Billington E, Warren CJ, De Sliva D, Di Genova C, Airey M, et al. Clade 2.3.4.4b H5N1 high pathogenicity avian influenza virus (HPAIV) from the 2021/22 epizootic is highly duck adapted and poorly adapted to chickens. J Gen Virol. 2023;104(5):1-16. https://doi.org/10.1099/jgv.0.001852

163. Altizer S, Ostfeld RS, Johnson PTJ, Kutz S, Harvell CD. Climate change and infectious diseases: from evidence to a predictive framework. Science. 2013;341(6145):514–519. https://doi.org/10.1126/science.1239401

164. Prosser DJ, Teitelbaum CS, Yin S, Hill NJ, Xiao X. Climate change impacts on bird migration and highly pathogenic avian influenza. Nat Microbiol. 2023;8:2223–2225. https://doi.org/10.1038/s41564-023-01538-0

165. King JS, Manning J, Woodward A. In this together: International collaborations for environmental and human health. J Law Med Ethics. 2023;51(2):271–286. https://doi.org/10.1017/jme.2023.82

166. Mackenzie JS, Jeggo M. The one health approach-why is it so important? Trop Med Infect Dis. 2019;4(2):88. https://doi.org/10.3390/tropicalmed4020088

167. Machalaba CC, Elwood SE, Forcella S, Smith KM, Hamilton K, Jebara KB, et al. Global avian influenza surveillance in wild birds: a strategy to capture viral diversity. Emerg Infect Dis. 2015;21(4):e1-e7. https://doi.org/10.3201/eid2104.141415

168. Walker J, Liebenberg M, Burnett JM, Maphanga T, King J. Cross-border collaboration and capacity-building for improved health emergency response planning in Southern Africa. S Afr Health Rev. 2023;25. https://doi.org/10.61473/001c.81023

169. Ciuoderis K, Usuga J, Pérez-Restrepo LS, Gonzalez-Ramirez M, Carvajal L, Cardona A, et al. Genomic diversity and evolutionary dynamics of Influenza A viruses in Colombian swine: implications for one health surveillance and control. Emerg Microbes Infect. 2024;13(1):2368202. https://doi.org/10.1080/22221751.2024.2368202

170. Gonzalez-Obando J, Zuluaga-Cabrera A, Moreno I, Úsuga J, Ciuderis K, Forero JE, et al. First molecular detection and epidemiological analysis of equine influenza virus in two regions of Colombia, 2020-2023. Viruses. 2024;16(6):839. https://doi.org/10.3390/v16060839

171. Fasina FO, Fasanmi OG, Makonnen YJ, Bebay C, Bett B, Roesel K. The one health landscape in Sub-Saharan African countries. One Health. 2021;13:100325. https://doi.org/10.1016/j.onehlt.2021.100325

172. World Health Organization, Food and Agriculture Organization of the United Nations, United Nations Environment Programme, World Organisation for Animal Health. A guide to implementing the One Health Joint Plan of Action at national level. Geneva: WHO; 2023. https://www.who.int/publications/i/item/9789240082069

173. Salvesen HA, Whitelaw CBA. Current and prospective control strategies of influenza A virus in swine. Porcine Health Manag. 2021;7:23. https://doi.org/10.1186/s40813-021-00196-0

174. Wong JT, de Bruyn J, Bagnol B, Grieve H, Li M, Pym R, et al. Small-scale poultry and food security in resource-poor settings: A review. Glob Food Sec. 2017;15:43–52. https://doi.org/10.1016/j.gfs.2017.04.003

175. Astill J, Dara RA, Fraser EDG, Sharif S. Detecting and predicting emerging disease in poultry with the implementation of new technologies and big data: A focus on avian influenza virus. Front Vet Sci. 2018;5:263. https://doi.org/10.3389/fvets.2018.00263

176. Wilson J, Cereno T, Petrik M, Esfandiari N, Davy D, Mahdi A, et al. It's time to apply outbreak response best practices to avian influenza: A national call to action. Can J Vet Res. 2024;88(3):94–98. https://www.ncbi.nlm.nih.gov/pubmed/38988336

177. Catalan Saenz HS, Cruz-Ausejo L. Preventive, safety and control measures against Avian Influenza A(H5N1) in occupationally exposed groups: A scoping review. One Health. 2024;19:100766. https://doi.org/10.1016/j.onehlt.2024.100766

178. Hautefeuille C, Dauphin G, Peyre M. Knowledge and remaining gaps on the role of animal and human movements in the poultry production and trade networks in the global spread of avian influenza viruses - A scoping review. PLoS One. 2020;15(3):e0230567. https://doi.org/10.1371/journal.pone.0230567

179. Hoye BJ, Munster VJ, Nishiura H, Klaassen M, Fouchier RAM. Surveillance of wild birds for avian influenza virus. Emerg Infect Dis. 2010;16(12):1827–1834. https://doi.org/10.3201/eid1612.100589

180. Taubenberger JK, Baltimore D, Doherty PC, Markel H, Morens DM, Webster RG, et al. Reconstruction of the 1918 Influenza Virus: Unexpected Rewards from the Past. MBio. 2012;3(5):1-5. https://doi.org/10.1128/mBio.00201-12

181. Sangsiriwut K, Noisumdaeng P, Uiprasertkul M, Prasertsopon J, Payungporn S, Auewarakul P, et al. Full Genomic Sequences of H5N1 Highly Pathogenic Avian Influenza Virus in Human Autopsy Specimens Reveal Genetic Variability and Adaptive Changes for Growth in MDCK Cell Cultures. Biomed Res Int. 2021;2021(1):1–13. https://doi.org/10.1155/2021/3890681

182. Rehman S, Prasetya RR, Rahardjo K, Effendi MH, Rantam FA, Rahmahani J, et al. Whole-genome sequence and genesis of an avian influenza virus H5N1 isolated from a healthy chicken in a live bird market in Indonesia: accumulation of mammalian adaptation markers in avian hosts. PeerJ. 2023;11:e14917. https://doi.org/10.7717/peerj.14917

183. Ren X, Yang F, Hu Y, Zhang T, Liu L, Dong J, et al. Full Genome of Influenza A (H7N9) Virus

Derived by Direct Sequencing without Culture. Emerg Infect Dis. 2013;19(11):1881-1884. https://doi.org/10.3201/eid1911.130664

184. Palese P, Young JF. Molecular Epidemiology of Influenza Virus. In: Palase P, Kingsbury DW, editors. Genetics of Influenza Viruses. Vienna: Springer; 1983. p. 321–336. https://doi.org/10.1007/978-3-7091-8706-7_11

185. Animal and Plant Health Inspection Service (APHIS). Detections of Highly Pathogenic Avian Influenza in Wild Birds; 2024. https://www.aphis.usda.gov/livestock-poultry-disease/avian/avian-influenza/hpai-detections/wild-birds

186. Harvey JA, Mullinax JM, Runge MC, Prosser DJ. The changing dynamics of highly pathogenic avian influenza H5N1: Next steps for management & science in North America. Biol Conserv. 2023;282:110041. https://doi.org/10.1016/j.biocon.2023.110041

187.Instituto Colombiano Agropecuario (ICA). Influenza Aviar; 2024. https://www.ica.gov.co/getdoc/9cde2d77-673f-4225-9990-d67593ab4f36/influenza-aviar.aspx

188. Reed KD, Meece JK, Henkel JS, Shukla SK. Birds, migration and emerging zoonoses: west nile virus, lyme disease, influenza A and enteropathogens. Clin Med Res. 2003;1(1):5–12. https://doi.org/10.3121/cmr.1.1.5

189. Bonter DN, Moore FR. Stopover ecology of nearctic-neotropical landbird migrants: Habitat relations and conservation implications. J Wildl Manage. 2001;65(2):368. https://doi.org/10.2307/3802919

190. Bayly NJ, Rosenberg KV, Easton WE, Gómez C, Carlisle J, Ewert DN, et al. Major stopover regions and migratory bottlenecks for Nearctic-Neotropical landbirds within the Neotropics: a review. Bird Conserv Int. 2018;28(1):1–26. https://doi.org/10.1017/s0959270917000296

191. Albert S, Wolfe JD, Kellerman J, Sherry T, Stutchbury BJM, Bayly NJ, et al. Habitat ecology of Nearctic–Neotropical migratory landbirds on the nonbreeding grounds. Condor. 2020;122(4):1-18. https://doi.org/10.1093/condor/duaa055

192. Franco A, Devenish C, Barrero M, Romero M. Important Bird Areas Americas - Priority sites for biodiversity conservation. Quito, Ecuadro: BirdLife International; 2009. https://biblioteca.cenicafe.org/bitstream/10778/274/1/Cap_aves.pdf

193. Pérez-Ramírez E, Acevedo P, Allepuz A, Gerrikagoitia X, Alba A, Busquets N, et al. Ecological factors driving avian influenza virus dynamics in Spanish wetland ecosystems. PLoS One. 2012;7(11):e46418. https://doi.org/10.1371/journal.pone.0046418

194. Islam A, Amin E, Munro S, Hossain ME, Islam S, Hassan MM, et al. Potential risk zones and climatic factors influencing the occurrence and persistence of avian influenza viruses in the environment of live bird markets in Bangladesh. One Health. 2023;17:100644. https://doi.org/10.1016/j.onehlt.2023.100644

195. Ward MP. Geographic information system-based avian influenza surveillance systems for village poultry in Romania. Vet Ital. 2007;43(3):483–489. https://www.ncbi.nlm.nih.gov/pubmed/20422525

196. Wade D, Ashton-Butt A, Scott G, Reid SM, Coward V, Hansen RDE, et al. High pathogenicity avian influenza: targeted active surveillance of wild birds to enable early detection of emerging disease threats. Epidemiol Infect. 2023;151:e15. https://doi.org/10.1017/S0950268822001856

197. EFSA Panel on Animal Health and Animal Welfare (AHAW), European Union Reference Laboratory for Avian Influenza, Nielsen SS, Alvarez J, Bicout DJ, Calistri P, Canali E, et al. Vaccination of poultry against highly pathogenic avian influenza – part 1. Available vaccines and vaccination strategies. EFSA J. 2023;21(10):e08271. https://doi.org/10.2903/j.efsa.2023.8271

198. Carpenter A, Waltenburg MA, Hall A, Kile J, Killerby M, Knust B, et al. Vaccine preventable zoonotic diseases: Challenges and opportunities for public health progress. Vaccines. 2022;10(7):993. https://doi.org/10.3390/vaccines10070993

199. Conan A, Goutard FL, Sorn S, Vong S. Biosecurity measures for backyard poultry in developing countries: a systematic review. BMC Vet Res. 2012;8:240. https://doi.org/10.1186/1746-6148-8-240

200. Msimang V, Rostal MK, Cordel C, Machalaba C, Tempia S, Bagge W, et al. Factors affecting the use of biosecurity measures for the protection of ruminant livestock and farm workers against infectious diseases in central South Africa. Transbound Emerg Dis. 2022;69(5):e1899–e1912. https://doi.org/10.1111/tbed.14525

201. Adolf M, K. BD, Karin S. Influence of awareness campaigns conducted in Uganda regarding prevention of HPAI in poultry in three districts of Kampala, Lira and Kanungu. Rome, Italy: Food & Agriculture Organization of the United Nations (FAO); 2009. https://www.fao.org/4/al688e/al688e00.pdf

202. Abdulkader RS, Potdar V, Mohd G, Chadwick J, Raju MK, Devika S, et al. Protocol for establishing a model for integrated influenza surveillance in Tamil Nadu, India. Front Public Health. 2023;11:1236690. https://doi.org/10.3389/fpubh.2023.1236690

203. Lin JS, Webber EM, Bean SI, Martin AM, Davies MC. Rapid evidence review: Policy actions for the integration of public health and health care in the United States. Front Public Health. 2023;11:1098431. https://doi.org/10.3389/fpubh.2023.1098431

204. Oshitani H, Kamigaki T, Suzuki A. Major issues and challenges of influenza pandemic preparedness in developing countries. Emerg Infect Dis. 2008;14(6):875–880. https://doi.org/10.3201/eid1406.070839

205. McPake B, Gilbert K, Vong S, Ros B, Has P, Khuong AT, et al. Role of regulatory capacity in the animal and human health systems in driving response to zoonotic disease outbreaks in the the Mekong region. One Health. 2022;14:100369. https://doi.org/10.1016/j.onehlt.2022.100369

206. Murphy J, Qureshi O, Endale T, Esponda GM, Pathare S, Eaton J, et al. Barriers and drivers to stakeholder engagement in global mental health projects. Int J Ment Health Syst. 2021;15:30. https://doi.org/10.1186/s13033-021-00458-y

207. Food and Agriculture Organization of the United Nations (FAO). Lessons from HPAI – A technical stocktaking of coutputs, outcomes, best practices and lessons learned from the fight against highly pathogenic avian influenza in Asia 2005–2011. Rome, Italy: FAO Animal Production and Health Paper No. 176; 2013. https://www.fao.org/4/i3183e/i3183e.pdf

208. Jonsson CB, Cole KS, Roy CJ, Perlin DS, Byrne G, members of the RBL-NBL Directors Network. Challenges and practices in building and implementing biosafety and biosecurity programs to enable basic and translational research with select agents. J Bioterror Biodef. 2013;3(15):12634. https://doi.org/10.4172/2157-2526.S3-015

209. Elwy AR, Maguire EM, Kim B, West GS. Involving stakeholders as communication partners in research dissemination efforts. J Gen Intern Med. 2022;37:123–127. https://doi.org/10.1007/s11606-021-07127-3

210. Borges do Nascimento IJ, Pizarro AB, Almeida JM, Azzopardi-Muscat N, Gonçalves MA, Björklund M, et al. Infodemics and health misinformation: a systematic review of reviews. Bull World Health Organ. 2022;100:544–561. https://doi.org/10.2471/BLT.21.287654

211. Guyonnet V, Peters AR. Are current avian influenza vaccines a solution for smallholder poultry farmers? Gates Open Res. 2020;4:122. https://doi.org/10.12688/gatesopenres.13171.1

212. Kurscheid J, Millar J, Abdurrahman M, Ambarawati IGAA, Suadnya W, Yusuf RP, et al. Knowledge and perceptions of highly Pathogenic Avian Influenza (HPAI) among poultry traders in live bird markets in Bali and Lombok, Indonesia. PLoS One. 2015;10(10):e0139917. https://doi.org/10.1371/journal.pone.0139917

213. Fu X, Wang Q, Ma B, Zhang B, Sun K, Yu X, et al. Advances in detection techniques for the H5N1 avian influenza virus. Int J Mol Sci. 2023;24(24):17157. https://doi.org/10.3390/ijms242417157

214. Pires AFA, Peterson A, Baron JN, Adams R, Martínez-López B, Moore D. Small-scale and backyard livestock owners needs assessment in the western United States. PLoS One. 2019;14(2):e0212372. https://doi.org/10.1371/journal.pone.0212372

215. Proulx P, Tandon S, Bodnar A, Schroh D, Harper R, Wright W. Avian flu case study with nSpace and GeoTime. Baltimore, MD, USA: 2006 IEEE Symposium On Visual Analytics And Technology; 2006. p. 27-34. https://doi.org/10.1109/vast.2006.261427

216. Wu H-DI, Lin R-S, Hwang W-H, Huang M-L, Chen B-J, Yen T-C, et al. Integrating citizen scientist data into the surveillance system for avian influenza virus, Taiwan. Emerg Infect Dis. 2023;29(1):45–53. https://doi.org/10.3201/eid2901.220659

217. Velkers FC, Manders TTM, Vernooij JCM, Stahl J, Slaterus R, Stegeman JA. Association of wild bird densities around poultry farms with the risk of highly pathogenic avian influenza virus subtype H5N8 outbreaks in the Netherlands, 2016. Transbound Emerg Dis. 2021;68(1):76–87. https://doi.org/10.1111/tbed.13595

218. Zhang X, Tulloch JSP, Knott S, Allison R, Parvulescu P, Buchan IE, et al. Evaluating the impact of using mobile vaccination units to increase COVID-19 vaccination uptake in Cheshire and Merseyside, UK: a synthetic control analysis. BMJ Open. 2023;13(10):e071852. https://doi.org/10.1136/bmjopen-2023-071852

219. Conan A, Ponsich A, Luce Goutard F, Khiev R, Tarantola A, Sorn S, et al. A community-based education trial to improve backyard poultry biosecurity in rural Cambodia. Acta Trop. 2013;125(3):294–302. https://doi.org/10.1016/j.actatropica.2012.12.006