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The role of wild waterfowl in avian influenza transmission and a one health perspective: A review

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Abstract

Avian influenza (AI) is a highly transmissible and potentially lethal disease caused by Avian Influenza Virus (AIV) that affects birds, has zoonotic potential, and impacts the economy, conservation, and public health globally. Wildlife, particularly birds, plays an important role in transmitting and disseminating AIV. The objective of this narrative review though data based search is to examine the role of wild waterfowls in the spread of AI and the public health consequences of AI. Literature on AI transmission, including investigations in wild birds, domestic poultry, other animals, and humans, was accessed and reviewed. Our findings indicate that wild birds, especially migrating waterfowl, are natural reservoirs of AIV and play an important role in transmitting AIVs to domestic poultry and humans. Out of 30 notable strains which were the first reported outbreaks; H5N1 is the most dominant viral strain with Asia, Europe, North America, Africa, and South America being the most affected geographic regions. The transmission of AIV from waterfowl to domestic poultry and humans can have serious animal, environmental and public health consequences, including morbidity, mortality, and socio-economic impact. The role of wild waterfowl in the spread of AIVs is complex and multifactorial. Therefore, understanding the dynamics of AI spill-over transmission in wild waterfowls, domestic poultry, and people is important for establishing effective AI outbreak prevention and control strategies. This review emphasizes the necessity for deepening research, surveillance, and collaboration across animal, human, and environmental health in the frame of one health and engagement with local communities and stakeholders to mitigate the threats of AI.

Keywords: Avian influenza, One health, Transmission, Waterfowl, Wildlife, Zoonosis

Introduction

Avian influenza (AI), known as bird flu, is a highly contagious and potentially deadly disease that affects birds worldwide (Webster *et al.,* 1992a; Taubenberger *et al*., 2006; Swayne *et al.,* 2013a). The disease is caused by a type of influenza A virus, which

can be transmitted between birds and, in rare cases, from birds to humans (Mounts *et al.,* 1999; Peiris *et al.,* 2004; Meseko *et al.,* 2024a). The transmission of AIVs from birds to humans is a complex process, influenced by various factors, including bird migration patterns (Kilpatrick *et al.,* 2006), habitat sharing (Olsen *et al.,* 2006), and human activities (Liu *et al.,* 2013).

We aim to examine the state of science regarding waterfowl's contribution to the spread of avian influenza and to investigate, from a One Health perspective, the consequences of avian influenza transmission from wild waterfowl to domestic poultry, humans, and other species. This research is justified by: Public Health Significance: With the potential for zoonotic transmission and pandemic outbreaks, avian influenza presents a serious threat to human health. Significance for Animal Health: Avian influenza can have a catastrophic impact on domestic chicken populations, resulting in financial losses and issues with animal welfare. Environmental Significance: Avian influenza viruses are maintained and spread in the environment by wild waterfowl and One Health Approach: In order to comprehend and address the spread of avian influenza, this article shall be used to emphasize the significance of a One Health approach, which acknowledges the interdependence of human, animal, and environmental health.

The role of wild birds in the transmission and spread of AIVs is significant because, as natural reservoirs, wild birds can harbour AIV without exhibiting symptoms, permitting the persistence and evolution of viruses. (Hulse *et al.,* 2004; Kuiken *et al.,* 2019a; Meseko *et al.,* 2024a). Additionally, the migration of wild birds can help spread AIVs across different regions, increasing the risk of transmission to humans and pets (Kilpatrick *et al.,* 2006; Olsen *et al.,* 2006; Meseko *et al.,* 2024b). With the potential for widespread illness and death, as well as significant economic impacts on the poultry industry and local economies, the public health implications of AI transmission are far-reaching (Swayne *et al.,* 2013b; WHO, 2014; Abiayi *et al.,* 2021). A comprehensive One Health approach that involves collaboration between animal health, public health, and environmental agencies, as well as engagement with local communities and stakeholders, is necessary to develop effective strategies to mitigate these risks and protect animal and human health (WHO, 2014).

The ecology and epidemiology of avian influenza

Wild birds are essential to the spread and maintenance of the virus, making avian influenza a serious threat to world health. Predicting and containing outbreaks requires an understanding of the ecology and epidemiology of avian influenza.

Avian influenza viruses naturally occur in wild aquatic birds, especially in the Anseriformes (ducks, geese, and swans) and Charadriiformes (gulls and shorebirds) families (Olsen *et al.,* 2006). The virus can remain and propagate in the environment because these birds can carry and shed it without exhibiting any symptoms. AI outbreaks can occur in: Domestic poultry (Chickens, turkeys, and other domestic birds) and Wild birds (Wild waterfowl, shorebirds, and other bird species).

Wild birds' yearly migrations promote species mixing, which drives infection dynamics, reassortment, and the virus's worldwide expansion (Webster *et al.,* 1992b). This emphasizes how crucial it is to comprehend bird migration patterns and how they contribute to the spread of avian influenza, which is found worldwide, with varying levels of prevalence.

In order to live and infect birds during breeding seasons, avian influenza viruses can endure in environmental matrices such as lake water and ice (Langstaff *et al.,* 2018). Temperature, pH, and salinity are some of the variables that affect this persistence. The ecology of avian influenza viruses is influenced by host factors, such as bird behaviour, migration patterns, and population dynamics (Hill *et al.,* 2012). Understanding these interactions is crucial for predicting and mitigating outbreaks. The transmission of AIV from animals to humans typically occurs through: Direct contact: Close contact with infected birds, such as touching or handling them, Indirect contact: Contact with contaminated surfaces, equipment, or environments and Airborne transmission: Inhalation of aerosolized AI viruses (Peiris *et al.,* 2003; Meseko *et al.,* 2022a).

The potential risk and role of mixing vessels in influenza virus transmission

The importance of "mixing vessels," where several influenza viruses can reassort and form new strains with heightened pandemic potential, is crucial in the creation of novel influenza viruses. Particularly, pigs are a possible host for swine, human, and avian influenza viruses to interact. Pigs are a promising host for reassortment since they may contract influenza viruses from both humans and birds. Co-infection with distinct influenza viruses is possible because the pig respiratory system has a comparable distribution of avian-type and human-type receptors as the human respiratory tract. This co-infection can lead to the generation of new reassortant viruses with

pandemic potential (Abdelwhab *et al.,* 2013b). Other species might potentially be involved in the reassortment of influenza viruses, even though pigs are thought to be the main mixing vessel. These consist of: Minks, Ferrets and Seals. (Abdelwhab *et al.,* 2013a; Kessler *et al.,* 2021).

Symptoms of avian influenza (AI) infection in birds

According to World Health Organization (WHO) and World Organisation for Animal Health (WOAH), birds infected with avian influenza may show mild to moderate symptoms, including respiratory signs such as coughing, sneezing, abnormal lung sounds (rales), and nasal discharge. Affected birds may appear lethargic, seem depressed or sleepy, and show a general reduction in activity. Loss of appetite is common, often accompanied by decreased intake of feed and water. Feathers may appear ruffled or dishevelled, and laying birds may experience a noticeable drop in egg production.

Severe clinical signs, as documented by OIE (2020a), Food and Agriculture Organization (FAO, 2020), include sudden death without any preceding signs, as well as severe respiratory distress characterized by gasping, open-mouth breathing, and laboured respiration. Cyanosis, or bluish discolouration of the skin and mucous membranes, may develop. Swelling of the head, face, or eyes is also observed, along with neurological signs such as tremors, seizures, and loss of coordination. Other reported signs include increased mortality rates within the flock, decreased activity levels, and abnormal droppings such as diarrhoea or greenish-coloured faeces.

Symptoms of avian influenza (AI) infection in humans

Human infection can range from mild to severe, presenting with febrile signs, cough, which may be dry or productive, sore throat, dyspnea and pneumonia (Beigel *et al.,* 2005; WHO, 2018a; CDC, 2020; Meseko *et al.,* 2022b). Numerous strategies have been put forth to lessen the dangers of AI transmission, such as human and poultry immunization (Although the latter is not yet legal in some countries), biosecurity measures on poultry farms, and surveillance and monitoring of wild bird populations, including excess mortality (Swayne *et al*., 2013b; Abiayi *et al.,* 2021). According to studies, these strategies may be useful in reducing the spread of AI viruses (Perdue *et al.,* 2011; Meseko *et al.,* 2018c). It is exceptional but potentially fatal when people contract AIV from wildlife (Beigel *et al.,* 2005). According to studies, humans can contract AI viruses by coming into close contact with contaminated objects or infected birds (Mounts *et al.,* 1999). With the potential for widespread sickness and death, AI transmission has serious public health impact. It can also have an economic impact on local economies and the poultry industry (Sims *et al.,* 2005; Meseko *et al.,* 2018a).

According to the World Health Organization (WHO, 2022a), several cases of human infection with AIV have been reported. Between 2003 and 2022, there were 863 confirmed human cases of H5N1 infection, resulting in 456 deaths, which corresponds to a case fatality rate of 52.8%. Additionally, from 2013 to 2022, a total of 1,668 human infections with the H7N9 virus were reported, leading to 616 deaths and a fatality rate of 36.9% (WHO, 2022a).

Since 2019, avian influenza virus (AIV) infections have been reported in 17 countries across five continents (WHO, 2022b). Several AIV subtypes, including H5N1, H5N6, H7N9, and H3N8, have been associated with human infections, predominantly in Asia, particularly China (WHO, 2022a). Notably, three human cases of H3N8 infection were reported in China between 2022 and 2023, including one fatality, with cases originating from the Henan and Hunan provinces (WHO, 2023). Furthermore, during the 2013–2022 H7N9 epidemics in China, a total of 1,567 laboratory-confirmed human cases and 615 deaths were recorded (WHO, 2022b).

Wildlife as Natural Reservoirs of AIV

Several studies have demonstrated that avian influenza (AI) viruses occur naturally in wild birds, which serve as their primary reservoirs (Webster *et al.,* 1992b; Olsen *et al.,* 2006). These birds can harbour and disseminate AIVs asymptomatically, facilitating long-distance transmission during migration (Hulse *et al.,* 2004; Meseko & Dzikwi-Emennaa*,* 2023). According to Kuiken *et al. (*2019b), AIVs can persist and replicate within wild bird populations without causing significant morbidity or mortality. Multiple AIV subtypes, particularly H5, H7, and H9, have been detected in wild bird species, underscoring their pivotal role in the maintenance and global spread of these viruses (Gao *et al.,* 2019; Abiayi *et al.,* 2021; Meseko *et al*., 2024a).

Waterfowls as natural reservoirs of AIVs

Waterfowl are recognized as the natural reservoirs of avian influenza viruses (AIVs) (Webster *et al.,* 1992b; Olsen *et al.,* 2006). Their global migration patterns facilitate the dissemination of AIVs across continents (Kilpatrick *et al.,* 2006b; Meseko *et al.,* 2018b).

In Asia, a late 2002 outbreak of highly pathogenic H5N1 avian influenza in waterfowl and wild birds in Hong Kong highlighted the role of migratory birds in viral transmission (Feare, 2007). Between 2005 and 2016, multiple H5N1 outbreaks occurred in China, with migrating birds significantly contributing to the spread of the virus along the East Asian flyway (Takekawa *et al.,* 2010; Hill *et al.,* 2012). In Vietnam (2004-2006), both poultry trade and migratory birds were implicated in H5N1 outbreaks, with importation of live poultry from outside ASEAN countries increasing the risk of viral introduction (Gilbert *et al.,* 2006).

In 2006, Denmark reported the first cases of highly pathogenic H5N1 in both domestic and wild birds, highlighting the role of migratory birds in viral spread (OIE, 2019). Similarly, in 2023, H5N1 infection was detected in a wild red fox in Sweden, suggesting possible interspecies transmission between wild birds and mammals (EFSA, 2023). The Netherlands has also reported multiple avian influenza outbreaks, with migratory birds implicated in viral dissemination (EFSA, 2023).

In Africa, Nigeria experienced multiple introductions of H5N1 in 2006, with both migratory birds and poultry trade contributing to virus spread (Afolabi *et al*., 2019). From 2004 to 2016, several West African countries, including Nigeria, reported H5N1 outbreaks linked to migratory bird movements and intra-regional trade (Cappelle *et al.,* 2014).

In North America, outbreaks of H5N2 avian influenza were documented in Canada and the United States for 2014-2015 in commercial poultry and wild birds, with migratory birds likely introducing the virus (Pasick *et al.,* 2015; Lee *et al.,* 2015). The Eurasian HPAI H5N1 strain was later detected in Canada in 2021-2022, beginning in Newfoundland and Labrador and spreading to commercial poultry and wild bird populations (CFIA, 2022). During the same period, HPAI EA H5 and EA H5N1 viruses were confirmed in U.S. commercial and backyard flocks, wild birds, and wild mammals, reaffirming the role of migratory birds in transmission (USDA, 2022).

AIVs, particularly the H5 and H7 subtypes, remain a major global concern for both animal and human health (Li *et al.,* 2021; Abiayi *et al.,* 2021). Waterfowl, including ducks, geese, and swans, are critical to the ecology and epidemiology of AIVs (Wu *et al.,* 2020; Meseko *et al.,* 2023a). For instance, H7N9 outbreaks in humans have been linked to introductions of AIVs from wild birds into domestic poultry farms (Swayne *et al.,* 2013a; Meseko *et al.,* 2023c).

Overall, wildlife plays a complex and multifaceted role as natural reservoirs of AIVs. To fully elucidate the transmission dynamics between wild birds and domestic poultry, and to assess the potential risk to human populations, further integrative research is urgently needed (Hill *et al.,* 2012; von Rüden *et al*., 2021; Rimlinger *et al.,* 2022).

Migration routes and AIV spread

Wild birds migrate along specific routes, known as flyways, which can facilitate the spread of AIVs across different regions (Kilpatrick *et al.,* 2006a; Meseko *et al.,* 2021). For example, the East Asian-Australasian Flyway, which spans from China to Australia, is a significant route for the spread of AIVs (Chen *et al.,* 2018).

There are eight major migratory routes for birds in the world. Three of them pass by China: purple line, orange line and blue line. The light green region represents China, and the red star represents the location of the H7N9 outbreak, which is the Yangtze River delta area (Figure 1).

BirdLife International (2019) states that approximately 300 bird species use the East Atlantic Flyway, which links breeding grounds in the Arctic and northern Europe to wintering areas in Africa and Western Europe. The Mediterranean/Black Sea Flyway, which spans the Black Sea region, the Mediterranean Basin, and the Nile Delta, links Europe and Africa for birds migrating between their breeding grounds in Eastern Europe and Western Asia and their wintering areas in Africa (UNEP/CMS Secretariat, 2014). More than 330 bird species use the East Asia/East Africa Flyway, which connects Asia and even Alaska with Southern, Central, and Eastern Africa (BirdLife International, 2019). Nearly 500 species use the East Asian-Australasian Flyway, which stretches from the northern Arctic regions of Alaska and Eastern Russia to the southern region of New Zealand (EAAFP, 2020).

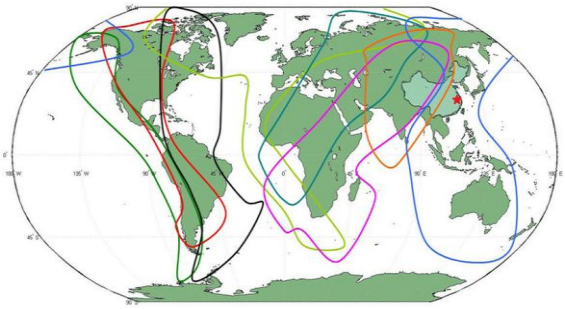

Figure 1: The global migration routes of wild birds. (Zhang *et al.,* 2014)

From Alaska in the north to the west coast of the United States, the Pacific Americas Flyway travels through 18 nations until arriving in Chile in South America via Mexico (USFWS, 2020). Nearly 400 bird species use the Atlantic Americas Flyway, which stretches from Greenland to the southernmost tip of South America along the east coast of both North and South America (BirdLife International, 2019). From Canada to the Gulf of Mexico, the Mississippi Flyway traverses the center parts of North America (USFWS, 2020). Research by Mase *et al.* (2005) revealed that migratory birds from China introduced the H5N1 virus to Japan. Similarly, studies by Liu *et al.* (2013) found that migratory birds were responsible for the spread of the H7N9 virus from China to other parts of Asia. The migration of wild birds is a fascinating phenomenon that has captivated humans for centuries. Every year, millions of birds make incredible journeys across continents and oceans, driven by innate instincts and environmental cues (Meseko *et al.,* 2023b).

The migration of wild birds occurs in different seasons, and most species make two major migrations annually, with the first migration usually taking place in the spring, from February to May, when birds move from their wintering grounds to their breeding grounds (Berthold, 2001; Meseko *et al.,* 2018b). The increase in daylight hours often causes hormonal changes in the birds, preparing them for nesting and breeding (Deutsch, 1998). Birds move from their breeding grounds to their wintering grounds during the second migration, which takes place in the fall between August and November (Elphick, 2017). The waning daylight hours, which alert the birds to the harsher winter circumstances, frequently initiate this trek (Gauthreaux, 1999). Wild birds employ a range of navigation techniques to help them find their way during their migrations. These include the Earth's magnetic field and celestial cues like the sun, stars, and constellations (Mouritsen, 2003). In order to travel, certain birds also mentally sketch out their migration paths utilizing spatial and visual memory (Hein, 2009). Wild birds use these navigational strategies in addition to environmental cues like weather patterns, food availability, and topographical features to direct their migrations (Alerstam, 2001). For instance, many birds migrate along specific routes, like the Atlantic Flyway or the Pacific Flyway, which offer them shelter, food, and favourable wind patterns (Elphick, 2017). Although migratory birds frequently use certain routes and tactics to cross or manoeuvre around huge bodies of water, they do not always avoid oceans. Flying across vast stretches of the open ocean can be energetically costly. To save energy, birds might favour following island chains or coasts along which they can interact directly or indirectly with domestic birds, thereby facilitating the transmission of AI, To get food supplies such as fish, crustaceans, or insects, certain birds travel along the shore. During migration, birds use visual clues such as mountains, coastlines, or landmarks to guide them.

We can better appreciate these amazing animals and the difficulties they encounter during their migrations if we understand how and when wild birds migrate, which is a complicated and fascinating phenomenon that is influenced by both environmental cues and innate instincts.

The global migration patterns of wild birds play a significant role in the spread of AIVs. Understanding the migration routes and patterns of wild birds can help identify areas at high risk of AIV introduction and spread. This information can be utilized to establish effective surveillance and control techniques to decrease the danger of AI outbreaks.

Transmission of AIVs from Waterfowl to Domestic Poultry

A number of factors, such as habitat sharing, bird movement, and human activity, can affect the complicated process of AIV transmission from waterfowl to domestic chicken (Swayne *et al.,* 2013a; Abiayi *et al.,* 2021). Domestic poultry can contract AI viruses by coming into contact with contaminated feathers, feces, or other materials from infected wild birds (Perdue *et al*., 2011; Meseko *et al.,* 2019).The movement of wild birds, the density of domestic poultry, and the presence of infected animals are some of the factors that contribute to the complex process of AIV transmission from wildlife to domestic poultry (Kuiken *et al.,* 2019a).

AIVs can be transferred from wild birds to domestic poultry either directly (for example, when infected wild birds come into contact with domestic poultry) or indirectly (for example, when domestic poultry are exposed to contaminated feed, water, or equipment) (Perdue *et al.,* 2011). The risk of transmission can also be increased by the density of domestic poultry and the presence of infected animals (Swayne *et al.,* 2013a). Several risk factors can increase the likelihood of AI transmission from waterfowl to domestic poultry. Poultry farms located near waterfowl habitats, such as wetlands or lakes, are at higher risk of AI introduction due to increased contact with infected wild birds (Meseko *et al.,* 2022c). Inadequate biosecurity measures, such as poor cleaning,

disinfection, and restricted access, can further facilitate the spread of the virus (Meseko *et al.,* 2022d). Additionally, poor hygiene and unsanitary conditions create an environment conducive to disease transmission within flocks (Igah *et al.,* 2022). Farms practising mixed farming and free-range poultry farming, where multiple species, including waterfowl and domestic poultry, are raised together, also face a heightened risk of AI transmission (Meseko *et al.,* 2022e).

To quantify the relative risk of AIV transmission at the human-animal-environment interface, recent research has employed modeling techniques (Liu *et al.,* 2020). These models consider a number of variables, such as the number of domestic poultry, pigs, and wild birds, as well as the existence of sick animals (Meseko *et al.,* 2023d). Areas with larger numbers of domestic pigs and poultry are more vulnerable to the spread of the AIV, according to studies (Meseko *et al.,* 2018a). Ultimately, creating efficient plans to stop and manage epidemics requires an understanding of how AIVs spread from wildlife to domestic chickens. Vaccinating domestic poultry against AI viruses and putting biosecurity measures in place, like cleaning and disinfection, are examples of this (Swayne *et al.,* 2013a). Various events can occur in an animal-to-animal transmission, such as Wildlife-Poultry Interface, during which wild birds contribute to the spread of AIVs among domestic chickens (Webster *et al.,* 2006). In farm-to-farm transmission, AIV is transmitted between domestic poultries (Ameji *et al.,* 2021), and within-flock transmission, which involves the transmission of AIVs within a poultry flock (Swayne *et al.,* 2008).

In considering Animal-to-Human transmission, we refer to zoonotic transmission whereby AIVs are transmitted from animals to humans. Transmission can occur through direct or indirect contact with diseased birds, their secretions, or contaminated settings, including live bird markets. The risk of transmission may be increased by slaughtering, defeathering, or touching the carcasses of infected birds. The virus may be present in areas where live birds are killed or sold, which raises the possibility of transmission (Peiris *et al.,* 2004).

Human cases and outbreaks are confirmed by the epidemiology and clinical features of human AI cases and outbreaks, as reported by the World Health Organization (2006), and Risk Factors for Human Infection: Which are the factors that increase the risk of human infection with AI viruses (Mounts *et al.,* 1999). such as; direct or close contact with infected birds, exposure to contaminated environments, occupational exposure (e.g., poultry workers, veterinarians), poor hygiene practices, lack of personal protective equipment (PPE), handling or consuming infected poultry, virus characteristics (e.g., specific subtype, such as H5N1 or H7N9), live bird markets, poultry farming practices (e.g., backyard farming, small-scale farming with poor biosecurity), global travel and trade.

Environmental Transmission of AI involves fomites and contaminated surfaces. Contaminated surfaces and fomites play a role in transmitting AIVs (Bean *et al.,* 1982). Waterborne Transmission: AI viruses can be transmitted through contaminated water (Webster *et al.,* 2006) and Airborne Transmission: which is the potential for AIVs to be transmitted through the air (Tellier *et al.,* 2006)

Molecular and virological factors influencing AIV transmission from waterfowl to other susceptible hosts

The viral genome of the AIV consists of eight segments of single-stranded RNA; therefore, mutations or re-assortment of these segments can influence viral transmission. These processes usually take place in an infected host or a carrier host, such as the waterfowl (OIE, 2022; Knipe *et al.,* 2013). The hemagglutinin (HA) protein is essential for viral attachment and entry into host cells; mutations in the HA protein can also affect viral transmissibility to other birds and humans. The neuraminidase (NA) protein is involved in viral release from infected cells; therefore, mutations in the NA protein can affect viral transmission as well (OIE, 2022; Knipe *et al.,* 2013).

AIV mutation arises when there is a change in the genetic material of an AIV. This change can occur through various mechanisms, such as: Point mutation: A single nucleotide change in the viral genome. Deletion: A loss of one or more nucleotides from the viral genome, and insertion: The addition of one or more nucleotides to the viral genome (ECDE, 2022; Ameji *et al.,* 2021). AIV re-assortment refers to the process by which two or more different influenza viruses infect the same cell and exchange genetic material, resulting in a new virus with a mixed genome, re-assortment mechanisms includes, co-infection: where two or more viruses infect the same cell, allowing for genetic exchange, and genetic recombination: which is the exchange of genetic material between viruses, resulting in a new virus with a mixed genome. The consequences of both mutation and re-assortment can lead to changes in the virus's characteristics, such as: Virulence, Transmissibility, and Antigenicity. These changes can

have significant implications for animal and human health, as they can affect the severity of disease outbreaks and the effectiveness of vaccines and treatments. (Webster *et al.,* 1992; Suarez *et al.,* 2000; Ameji *et al.,* 2021).

Antigenic drift and shift have an impact on the transmission and control of AIVs according to Cox & Subbarao (2004). Antigenic drift refers to a gradual, continuous change in the genetic material of a virus, resulting in a change in the virus's surface proteins, such as hemagglutinin (HA) and neuraminidase (NA). This change can lead to: Immune evasion and vaccine mismatch. The amount of virus present (viral load) in an infected bird can impact transmission. The release of the virus from infected birds (viral shedding) can occur through respiratory secretions, feces, or other bodily fluids. The stability of the virus in the environment can affect transmission and the interaction between the virus and the host bird's immune system can also influence transmission (CDC, 2022). Important elements affecting transmission include capacity for viral replication within the host cells, viral ability to bind to host cell receptors (receptor binding), and its capacity to elude the host's immune system (immune evasion) (Garcia-Sastre 2011; WHO, 2022a).

Below is a list of some of the most notable subtypes of avian influenza, these subtypes are not exhaustive, as new ones may emerge due to genetic re-assortment and mutation. However, this list highlights some of the most significant and well-known subtypes of avian influenza (Table 1).

Socio-Economic Implications of AI

Poultry farmers are primarily affected by the loss of income caused by the mass culling of infected birds, which can cause disruptions in the food supply chain, raise food prices, and possibly cause consumers to switch to other protein sources. These factors can eventually have an impact on livelihoods, especially in rural areas where poultry production is a major source of revenue (WHO, 2020; CDC, 2020; Abiayi *et al.,* 2021). They can also result in a decline in investment in the poultry sector and the possible loss of jobs. The widespread culling of diseased birds can disrupt the food supply chain, increase food prices, and potentially lead customers to switch to other protein sources, primarily impacting poultry farmers by lowering their income (WHO 2020; CDC, 2020; Abiayi *et al.,* 2021). This can ultimately have an impact on livelihoods, especially in rural regions where chicken production is a major source of revenue. Additionally, it may lead to a reduction in investment in the poultry industry and the potential loss of jobs (Abiayi *et al.,* 2021).

Economic losses

Poultry farms may suffer significant financial losses as a result of avian influenza epidemics. A research by Fasina *et al.* (2021) found that outbreaks in 2006 cost the Nigerian poultry business more than $1 billion in losses. In a similar vein, Otte *et al*. (2007) calculated that between 2003 and 2005, Vietnam's economic losses from avian influenza outbreaks came to approximately $120 million.

Impact on smallholder farmers

Smallholder farmers are especially susceptible to the effects of outbreaks of avian influenza. According to a case study by Schudel *et al*. (2011), avian influenza outbreaks in Cambodia caused smallholder farmers to suffer severe losses in income and means of subsistence; some farmers reported losses of as much as 50% of their yearly income. Smallholder farmers' susceptibility is increased by a lack of infrastructure and resources to put in place efficient biosecurity measures (Otte *et al*., 2007).

Impact on commercial farmers

Outbreaks of avian influenza also cause large financial losses for commercial farms. A single epidemic of avian influenza on a commercial poultry farm in the United States might cost up to $100 million in losses, according to Greene *et al.* (2018). These losses are caused by several factors, including the culling of a significant number of birds, limitations on travel and commerce, and expenses related to disease prevention and eradication (Greene *et al.,* 2018).

Regional variations

Regional differences exist in the socioeconomic effects of avian influenza outbreaks. For instance, avian influenza epidemics in Africa have significantly impacted smallholder farmers' livelihoods (Abiayi *et al.,* 2021) while in Asia, commercial chicken farms have been particularly affected (Wang *et al.,* 2020). It is essential to comprehend these regional differences to create focused interventions that will lessen the effects of avian influenza epidemics.

Public Health Implications of AI Transmission

There can be serious public health repercussions when avian influenza (AI) viruses are transferred from animals to people. Avian influenza (AI) transmission

Table 1. Show a comprehensive list of Avian Influenza subtypes, their location of first report and species affected, and year detected

S/n	Subtypes	Location of First Report	Notable species First Reported to Have Being Affected	Year Detected	Reference
1	H1N1 virus	Spanish, United States and Turkey	Humans (Spanish flu pandemic) and Turkey	1918	(Taubenberger, 2006; WHO, 2022a)
2	H2N2	Asia and Singapore	Humans (Asian flu pandemic)	1957	(Kilbourn, 2006)
3	H3N2 (Variant of the human seasonal flu)	United States	Pigs	1968	(Kilbourne, 2006)
4	H3N8	United State	Horses	1963	(Webster *et al*., 1992a)
5	H4N6	Canada	Ducks	1975	(Hinshaw *et al*., 1980)
6	H5N1(Highly pathogenic)	Hong Kong (Global outbreak)	Chickens	1997	(Shortridge *et al*., 1998; OIE, 2020a)
7	H5N2 (Highly pathogenic)	United State	Turkey	1983	(Bean *et al*., 1985; OIE, 2020b)
8	H5N3	South Africa	Ostriches	2001	(Abdelwhab *et al*., 2013a)
9	H5N5	China	Ducks	2014	(Bi *et al*., 2015; OIE, 2020a)
10	H5N6 (Highly pathogenic)	Asian, China	Ducks	2014	(Bi *et al*., 2015; OIE, 2020a)
11	H5N8 (Highly pathogenic)	Europe/ Asia South korea	Ducks	2016/ 2014	(Jeong *et al*., 2014; OIE, 2020b)
12	H6N1	Taiwan	Ducks	1972	(Chi *et al*., 1972)
13	H6N2	United State	Turkey	1965	(Johnson *et al*., 1966)
14	H7N1	Italy	Turkey	1999	(Capua *et al*., 2000)
15	H7N2	United State	Chickens	2002	(Akey *et al*., 2003)
16	H7N4	Australia	Chickens	1997	(Selleck *et al*., 2003)

17	H7N3	Canada	Turkey	2004	(Bowes *et al*., 2004; WHO, 2018a)
18	H7N7	Netherlands	Birds and Humans	2003	(Koopmans *et al*., 2004; WHO, 2018a)
19	H7N9	China	Birds and Humans	2013	(Gao *et al*., 2013; WHO, 2018b)
20	H9N2 (Gene donor)	Hong kong	Quails and Humans	1992	(Shortridge *et al*., 1998; Sun *et al*., 2010)
21	H9N7	Hong Kong	Quail	1998	(Shortridge *et al*., 1999)
22	H10N3	China	Humans (first reported human case)	2020	(WHO, 2020)
23	H10N7	Egypt	Humans	2004	(Abdel-Dayem *et al*., 2013
24	H10N8	China	Ducks	2013	(Chen *et al*., 2014)
25	H11N2	United States	Turkey	1984	(Hinshaw *et al*., 1985)
26	H11N6	South Africa	Ostriches	2006	(Abdelwhab *et al*., 2013b)
27	H12N5	United States	Ducks	1980	(Hinshaw *et al*., 1981)
28	H13N6	United States	Gull	1982	(Kawaoka *et al*., 1988)
29	H14N5	Russia	Ducks	2010	(Kovylyaeva *et al*., 2011)
30	H15N9	Australia	Seabirds	2009	(Alvarez *et al*., 2010)

can be understood through a ripple effect model, comprising three distinct waves. Each wave represents a different stage of transmission and impact, with far-reaching consequences for human health, economies, and societies. This essay will explore the three waves of AI transmission, highlighting the key factors and consequences associated with each wave.

Wave one: direct transmission

The first wave of AI transmission occurs through direct animal-to-human transmission. This can happen through various routes, including inhaling aerosolized virus particles (Tellier, 2009), close contact with infected birds or contaminated environments (Kuiken *et al.,* 2019a), and consuming contaminated food or water (Swayne *et al.,* 2013a; Olabode *et al.,* 2023). Direct transmission is a critical stage in the AI transmission process, as it sets the stage for potential human-to-human transmission and amplification.

Wave two: indirect transmission and amplification

The second wave of AI transmission occurs through indirect transmission and amplification. Human-to-human transmission, contaminated environments, and international trade and travel can all contribute to the spread of AI viruses (Li *et al.,* 2014; Perdue *et al.,* 2011; Kilpatrick *et al.,* 2006). If AI viruses acquire the ability to transmit efficiently between humans, it could lead to widespread outbreaks, making this wave a critical concern for public health officials.

Wave three: economic and social disruption

The third wave of AI transmission represents the economic and social disruption caused by the virus. AI outbreaks can result in significant economic losses, particularly in the poultry and agricultural sectors (Swayne *et al.,* 2013b). Widespread illness and death can also occur, potentially overwhelming healthcare systems. Furthermore, social distancing measures, such as isolation and quarantine, can lead to stigma, mental health concerns, and social disruption (Desvars-Larrive *et al.,* 2020).

The three waves of AI transmission highlight the complex and multifaceted nature of this disease. Understanding the different stages of transmission and impact is crucial for developing effective strategies to prevent, detect, and respond to AI outbreaks. By recognizing the potential consequences of AI transmission, we can work towards mitigating its impact on human health, economies, and societies.

Mitigation Strategies

Numerous strategies have been put forth to lessen the dangers of AI transmission, such as human and poultry immunization, bio-security measures on poultry farms, and surveillance and monitoring of wild bird populations (Swayne *et al.,* 2013a). According to studies, these strategies may be useful in lowering the spread of AI viruses (Perdue *et al.,* 2011; Meseko *et al.,* 2023d). The following are some methods for reducing the spread of avian influenza:

Bio-security measures: Cleaning and disinfection: To lower the danger of virus transmission, clean and disinfect poultry farms, machinery, and automobiles on a regular basis. Fencing and netting: Use fencing and netting to lower the danger of virus transmission and keep wild birds out of chicken farms. Bird-proof feed and water: To keep wild birds away from poultry feed and water, use bird-proof feed and water systems (FAO, 2020; OIE, 2020a; CDC, 2020).

Vaccination and surveillance: Vaccination: Vaccinate poultry against Avian Influenza to lower the risk of virus transmission and to prevent disease; test poultry for Avian Influenza on a regular basis to identify infections early and stop the virus from spreading; monitor poultry farms and wild bird populations for signs of Avian Influenza and report any suspicious deaths or illnesses to appropriate authorities (FAO, 2020; OIE, 2020a; CDC, 2020).

Movement controls and quarantine; to lower the danger of virus transmission, movement controls should be implemented for people, equipment, and poultry both inside and outside of poultry farms. In the event of an outbreak of avian influenza, quarantine poultry farms and the surrounding areas to stop the virus's spread. Consider stamping out sick poultry flocks to stop the virus from spreading (FAO, 2020; OIE, 2020b; CDC, 2020).

Public awareness and education - Educate the public and farmers about the risks of Avian Influenza and the importance of bio-security measures Training- Provide training for poultry farmers, veterinarians, and other stakeholders on Avian Influenza diagnosis, surveillance, and control (FAO, 2020; OIE, 2020b; CDC, 2020).

Global coordination and collaboration: International cooperation: Coordinate national efforts to control avian influenza, including surveillance, diagnosis, and control measures; regional cooperation: Coordinate regional organizations and neighboring countries to exchange information and coordinate efforts to control avian influenza; and international cooperation: Work with international organizations, such as the Food and Agriculture Organization (FAO) of the United Nations and the World Organization for Animal Health (WOAH), to share information and coordinate efforts to control avian influenza (FAO, 2020; OIE, 2020a; CDC, 2020).

Control and prevention measures

AI viral infection can simply be controlled and prevented by bio-security measures and vaccination strategies respectively (Swayne *et al.,* 2008; Abiayi *et al.,* 2021; Ameji *et al.,* 2021; Meseko *et al.,* 2022a)

In conclusion, it should be noted that wild waterfowls contribute significantly to the spread of avian influenza viruses (AIVs), which can have detrimental effects on animals, the environment, and human health. A thorough grasp of the mechanics of AI spill-over transmission in humans, farmed poultry, and wild waterfowls is necessary because to the intricate and multifaceted nature of AIV transmission. Developing successful AI outbreak prevention and control techniques requires a One Health strategy that incorporates animal, human, and environmental health.

To lessen the risks posed by AI, it is essential to increase research, surveillance, and cross-sector cooperation in addition to interacting with stakeholders and local communities. By taking a One Health approach, we may better comprehend how

wild waterfowls contribute to the spread of AI and endeavour to lower the likelihood of AI outbreaks and the resulting effects on economies, conservation, and the health of people and animals.

It is recommended that:

Enhanced surveillance: To detect and respond to possible outbreaks early, it is crucial to regularly check domestic poultry and wild waterfowl populations for AIVs.

Multidisciplinary cooperation: Creating successful AI prevention and control plans requires cooperation amongst specialists in animal, human, and environmental health.

Community engagement: Promoting best practices for AI prevention and control, as well as increasing awareness of the risks associated with AI by active interaction with stakeholders and local communities in the value chain across wetland, backyard poultry and live bird markets

Additional study: To inform evidence-based policies and interventions, more research is required on the dynamics of AI transmission in humans, farmed poultry, and wild waterfowl.

By working together and adopting a One Health approach, we can lessen the risks associated with avian influenza and foster a healthier, more sustainable relationship between humans, animals, and the environment.

Conflict of Interest

The authors declare that there is no conflict of interest.

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