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REVIEW ARTICLE

Avian Influenza in Low and Middle-Income Countries (LMICs): Outbreaks, Vaccination Challenges and Economic Impact

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ABSTRACT

Avian influenza (AI) outbreaks pose severe challenges to low and middle-income countries such as Nepal, Nigeria, Bangladesh, Ghana, South Africa, and Indonesia, leading to profound economic crises with far-reaching consequences. The multifaceted impacts of AI outbreaks on low-income economies shed light on the intricate relationship between disease control and financial stability. By reviewing the implications for the poultry industry, trade restrictions, food security, public health, government legislation, and socio-economic vulnerabilities, we provide a comprehensive overview of the economic ramifications of AI outbreaks. AI outbreaks cause substantial disruptions in the poultry industry, resulting in significant financial losses for farmers and related businesses. The poultry sector contributes 4%, 1.4-1.6%, 6-8%, and 14% to the national GDPs of Nepal, Bangladesh, Nigeria, and Ghana respectively. Imposing trade restrictions on affected regions also hampers international trade, reducing revenue and foreign exchange earnings. This, in turn, affects food security as poultry products serve as vital sources of protein and nutrition in low and middle-income countries. Moreover, AI outbreaks adversely impact environmental sustainability by culling infected birds.

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INTRODUCTION

Avian influenza (AI), known as bird flu, is a viral infection affecting birds, particularly poultry (Lycett *et al.*, 2019). AI is caused by viruses from the *Orthomyxoviridae* family and is classified as influenza virus A, which has a single-stranded and negative sense RNA genome (Spackman, 2008). Wild birds like waterfowls, gulls, and shore birds act as natural and reservoir hosts for the AIV, thus making it an essential yet tricky pathogen to eradicate from poultry (Naguib *et al.*, 2019). Based on the virulence of AIV, it can be divided into two groups: Low Pathogenic AI (LPAI) and Highly Pathogenic AI (HPAI) (Rebel *et al.*, 2011). The avian influenza virus (AIV) has been known to exist in birds for centuries. However, the first human case was reported in 1997 in Hong Kong (Chan, 2002). Since then, several avian influenza outbreaks have been reported worldwide, with the most significant occurring in Asia and Africa. The virus can be transmitted from birds to humans through direct contact, and the mortality rate is high, particularly among individuals with underlying health conditions (Yamaji *et al.*, 2020).

AI has emerged as a significant challenge for the global poultry industry. It threatens public health and causes economic losses (Alders *et al.*, 2013). The distribution of AI is not uniform worldwide, and it is more prevalent in low and middle-income countries (LMICs)

(Chowdhury *et al*., 2019). In recent years, unprecedented AI outbreaks have affected LMICs, causing economic and public health crises (Magouras *et al*., 2020). It economically affects the poultry industry and other sectors, such as tourism and trade (Hunter, 2022). AI outbreaks have caused the deaths of millions of birds, ultimately affecting the livelihoods of millions of farmers and exacerbating poverty in already vulnerable communities (Haider *et al*., 2008). The economic impact of AI outbreaks in low and middle-income countries is multifaceted.

The direct effect is the loss of poultry, which can account for a significant portion of a household's income (Leight *et al*., 2022; Parvin *et al*., 2020). The indirect impact includes the loss of revenue for businesses that rely on the poultry industry, such as feed suppliers and processors. The reduction in poultry supply can also lead to increased prices, further reducing the purchasing power of low-income households (Apaliya *et al*., 2022). AI outbreaks can also significantly impact international trade, as countries may impose trade restrictions on affected countries to prevent the spread of the virus. This can lead to reduced exports and a loss of foreign exchange earnings for LMICs (Zhou *et al*., 2019). In addition, the increased cost of disease control measures can significantly burden struggling economies (Keogh-Brown *et al*., 2020). The lack of resources and infrastructure to contain the spread of the virus has led to its rapid transmission, resulting in significant economic losses (Gong *et al*., 2020). Many farmers have lost their entire flocks, and there has been a considerable decline in the production of eggs and poultry meat (Thompson *et al*., 2019). This has not only affected the income of farmers but has also led to food shortages, particularly among low-income households. The reduced supply of poultry products has also led to price increases, making them unaffordable for many people (Chand, 2021).

This review paper discusses avian influenza's global distribution, zoonosis, and economic loss. It also explores the impacts of the unprecedented avian influenza outbreaks and the financial crises in LMICs, their causes, and the measures that can be adopted to prevent and control future outbreaks.

Global distribution of avian influenza: The first outbreak of HPAI Avian Influenza in poultry occurred in Italy in 1878; while subsequent outbreaks in domestic birds were also recorded in Italy and other European countries (Lupiani and Reddy, 2009). HPAI in poultry was first observed in the USA from 1924 to 25, which caused massive losses to the poultry sector (Alexander, 2007). By the 1950s, the HPAI virus outbreaks had been documented in several European countries, Asia, Africa, North America, and South America. The first confirmed HPAI H5N1 subtype was isolated from poultry in Scotland in 1959 and since then, it has caused global outbreaks among domestic and wild birds (Lupiani and Reddy, 2009). Similarly, in 1963, the first outbreak of the H7N3 virus in poultry (turkey) occurred in England. Some H5 or H7 subtypes are highly pathogenic for chickens, generating significant worldwide issues for the poultry industry (Dhingra *et al*., 2018).

In 2011, the United Nations Food and Agriculture Organization recognized the H5N1 subtype as enzootic in Bangladesh, China, Egypt, India, Indonesia, and Vietnam (Le and Nguyen, 2014). The new subtypes of H5, formed due to re-assortment between domestic and wild birds, led to the emergence of H5N6 and H5N8, which caused outbreaks across Asia, Europe, Africa, and North America (Saito *et al*., 2015). In 2015, H5N2 and H5N8 caused outbreaks in 21 US states and Canada, and HPAI H5N8 outbreaks occurred in Asia, Europe, and some parts of Africa from late 2016 to 2017 (Brown *et al*., 2017; Pantin-Jackwood *et al*., 2017). During 2020 and 2021, outbreaks of H5N1, H5N6, and H5N8 were observed in commercial poultry flocks, but the worst outbreak in commercial poultry was in 2022 due to the H5N1 subtype (Wille and Barr, 2022).

The global distribution of AI viruses is changing. It is directly linked with some potential anthropogenic changes in the world, such as climate change, agricultural intensification, population growth, and globalization of trade (Vandegrift *et al*., 2010). Climate change could alter the AI virus's ecology, transmission pattern, pathogenicity, warming weather, bird migration pattern, and viral transportation, as shown in Fig. 1 (Lane *et al*., 2022). Migratory birds such as waterfowls, geese, and ducks are the natural reservoir of the AI virus; basically, they are involved in the transmission of the virus and causing antigenic drift and antigenic shift, as shown in Fig. 1 (Blagodatski *et al*., 2021). Ceaseless changes in the global distribution of avian influenza need a sustained surveillance and monitoring system under the loop of One Health (Sun *et al*., 2023).

Zoonotic avian influenza: The Avian Influenza virus is considered a serious concern for public health. Several subtypes of AI viruses, like H5, H7, and H9, have been shown to cross the species barrier and infect and cause mortality in mammals, including humans. Till now, 12 different subtypes of Avian Influenza (H5N1, H7N7, H9N2, H7N2, H7N3, H10N7, H7N9, H6N1, H10N8, H5N6, H7N4, H3N8) have been found to infect humans all over the world with 1096 cases leading to fatality (Philippon *et al*., 2020; Yang *et al*., 2022). The virus identifies the α-2-3 cross-linked sialic acid and targets the receptors in the distal bronchial, type II alveolar cells, and alveolar macrophages to infect humans (Feng *et al*., 2021). The natural ability of re-assortment, increased potential for human-type receptor binding, and constant antigenic variation coupled with the migration of wild birds carrying AIVs over a longer distance has led to the worldwide spread and might have negative consequences for global public health (Feng *et al*., 2021; Medina and García-Sastre, 2011). The primary source of infection in humans has been exposure to poultry, and poultry workers are at an increased risk of acquiring AIV. From 1997 to 2019, a total of 881 human cases of Avian Influenza (H5N1) were found all over the globe, which resulted in the death of 462 (52.4%) individuals (Philippon *et al*., 2020). In 1997, the H5N1 outbreak occurred in Hong Kong SAR, which was the first incidence of human infection by the Avian Influenza virus, and 6 out of 18 confirmed cases led to mortality of infected. Similarly, 7 out of 11 infected children died in Hanoi, Vietnam, in 2004 due to infection with H5N1, and two became critically ill (Guilloux, 2007). Indonesia reports the highest fatalities of 168 out of 200 infected people by

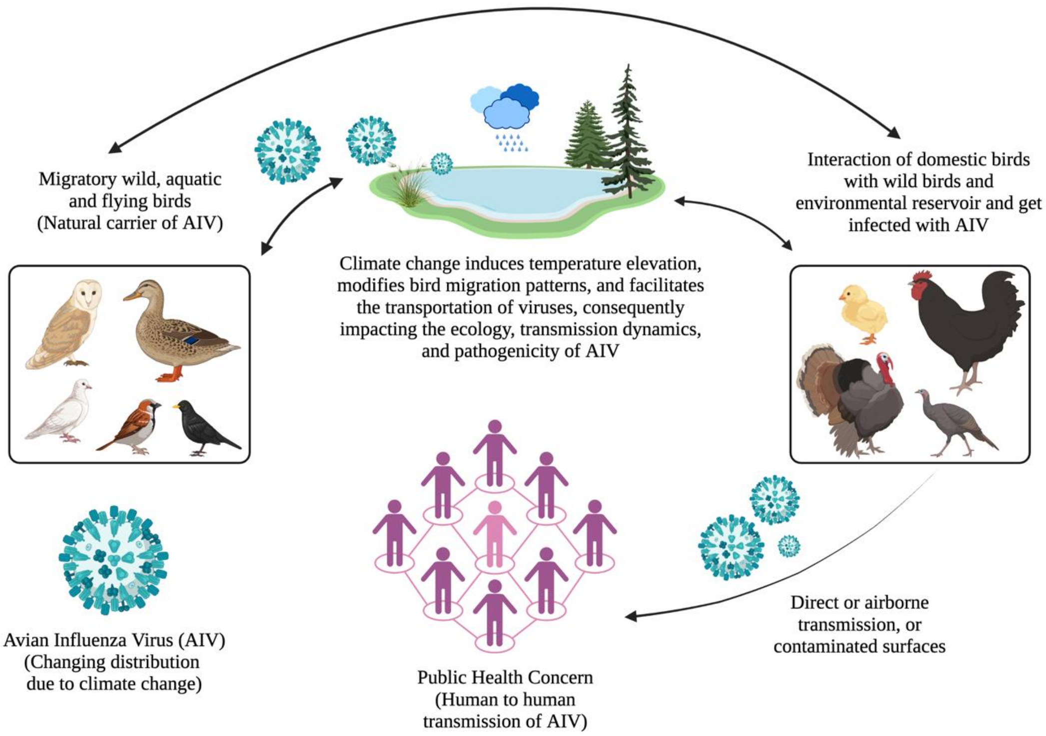

Fig. 1: Climate change and transmission cycle of Avian Influenza. Climate change plays a significant role in the transmission cycle of Avian Influenza. The altered weather patterns and rising temperatures create favorable conditions for the virus's survival and spread. Changes in migration patterns of birds, which can carry the virus, are also influenced by climate shifts. Warmer temperatures may extend the duration of the virus in the environment, increasing the likelihood of infection. Additionally, climate-related disruptions in ecosystems can impact the habitats and behaviors of birds, affecting the dynamics of Avian Influenza transmission.

H5N1 (Wibawa *et al*., 2018). Similarly, H5N6 infected 75 people in China from 2014-2022, of which 49 cases were from January 2021 (Shi *et al*., 2023). Recently, a human case of a novel AIV H3N8 subtype has been documented in China (Yang *et al*., 2022). Human cases of AIV have been reported by surveillance of mainly hospital-based cases, and the mild infections by AIV might have gone unnoticed, causing an underestimation of the approximate value for the infections by AIV in humans (Uyeki and Peiris, 2019). The H7N9 subtype of Avian Influenza has caused 1568 confirmed laboratory cases with a case fatality rate of 39.03%, a potential subtype for human-human transmission, and has the most significant potential to cause a pandemic (Sun *et al*., 2021). Though human-to-human transmission is minimal, managing these viruses in animals is crucial and effective in stopping them from infecting humans before the H5 and H7 viruses may spread from human to human (Table 1) (Poovorawan *et al*., 2013).

Challenges for avian influenza vaccination: A vaccine can be an efficient method and is a cornerstone for preventing AIV (Kim, 2018). The most common commercially available vaccines against avian influenza are inactivated, oil-emulsified, or whole AIV (Lone *et al*., 2017). Vaccination prevents viruses such as avian influenza from producing neutralizing antibodies targeting the HA glycoprotein (a major antigen-determining factor of the influenza virus). However, vaccination for avian influenza comes with its challenges (Webster and Govorkova, 2014). Firstly, the dissimilarity in the genetic base of commercial vaccines and the circulating strain of the virus results in an ineffective vaccination. This is due to frequent strain changes of the avian influenza virus, either due to antigenic drift or antigenic shift (An *et al*., 2022). Secondly, due to limitations in financial and human resources, developing countries are insufficient in vaccine production and the cost of implementing the vaccine (Chattu *et al*., 2021). Influenza A virus, the causative agent of avian, is known for its frequent mutation by antigenic shift and antigenic drift. Antigenic drift involves point mutation in the antibody binding site of the virus protein, which is estimated to occur in each viral replication (Huang *et al*., 2015). This change in the epitope of the virus inhibits the effect of host antibodies that may be acquired by vaccination or natural immunity. This makes the previously immune host susceptible to the disease again (Oidtman *et al*., 2021). In addition, keeping track of the circulating strain of the virus needs intensive surveillance, which can be challenging and affect the efficiency of the available vaccine (Silva *et al*., 2021).

Similarly, the antigenic shift of the virus occurs due to the mixing of genetic materials between different viral strains, which is also called genetic reassortment. This frequent change in the antigenic property of the avian influenza virus makes it challenging to produce an effective vaccine to control the disease (Ghedin *et al*., 2009). Vaccination can be more effective by closely monitoring the spread and change in the avian influenza virus strain (Mahase, 2023). Intensive surveillance is how developed places such as Hong Kong are free of avian influenza (Ninyio *et al*., 2020). However, to implement such strategies nationally, many more resources will be needed, increasing the economic burden of already expensive vaccine production and vaccination (Donadeu *et al*., 2019).

Economic losses due to avian influenza: Avian Influenza virus subtypes like H5N1, H5N2, H5N8, H7N8, H9N7, and H9N2 have expanded widely across the globe, causing severe economic loss to the poultry sector and posing serious public health threats (Blagodatski *et al*., 2021; Liu *et al*., 2020). Monetary damages from AI have varied depending on the viral strain, type of bird affected, number of farms involved, control techniques employed, and the pace at which control, or eradication tactics were implemented (Capua and Alexander, 2006). Significant

Table 1: Human infections caused by H5 viruses in LMICs from January 2003 to April 2022 (WHO)

Country	Total reported cases	Year	AIV subtype	Number infected	Number of fatalities
Azerbaijan	8	2006	H5N1	8	5
Bangladesh	8	2008, 2011-2013, 2015	H5N1	8	1
Cambodia	56	2005-2014	H5N1	56	37
Djibouti	1	2006	H5N1	1	0
Egypt	359	2006-2017	H5N1	359	120
Indonesia	200	2005-2015, 2017	H5N1	200	168
Iraq	3	2006	H5N1	3	2
Lao	4	2007, 2020,	H5N1	3	2
		2021	H5N6	1	0
Myanmar	1	2007	H5N1	1	0
Nepal	1	2019	H5N1	1	1
Nigeria	1	2007	H5N1	1	1
Pakistan	3	2007	H5N1	3	1
Vietnam	127	2003-2005, 2007-2010, 2012-2014	H5N1	127	64

economic losses due to high mortality and a drop in egg production have been observed in the poultry sector due to Avian Influenza (both HPAI and LPAI) (Gompo *et al*., 2020; Subedi *et al*., 2022). The expenditures associated with depopulation and disposal, high morbidity and mortality losses, disinfection and cleaning, quarantine and surveillance costs, and indemnities paid for the birds have all been considered direct losses in HPAI outbreaks (Sims and Swayne, 2016). Indirect costs, however, such as unreimbursed losses to the poultry industry, including a temporary or permanent decline in poultry exports, income lost by farmers and communities during production interruptions, increased consumer costs from a decrease in the supply of poultry products, and losses from declines in consumer spending, can quickly multiply losses by five to ten times. An LPAI H7N1 avian influenza virus changed into an HPAI in northern Italy, killing over 16 million chickens and causing significant economic losses to industry (Monne *et al*., 2014). Since 2005, 389 million poultry have died or been culled due to 8534 outbreaks from H5 strains worldwide. Three waves of explosions have occurred due to the H5 strains of Avian Influenza. The first wave (2005-2010) was caused by H5N1, mainly in Asian countries, resulting in the loss of 55.2 million poultry. The second wave (2011-2019), which spanned worldwide (Asia, Europe, Africa, and North America), was responsible for the loss of 139.9 million poultry and was caused by multiple strains of AIV. The third wave, driven mainly by H5N1 and H5N8 strains of AIV, started in 2020 and has almost resulted in the loss of approximately 193.9 million poultry until November 2022 (Shi *et al*., 2023). In 2015, the United States experienced a severe loss of roughly 3 billion USD due to the outbreaks of H5N2 HPAI (Blagodatski *et al*., 2021). Currently, outbreaks by the H5N1 subtype of AIV have devastated the poultry industry worldwide, causing severe economic loss (Rehman *et al*., 2023). Furthermore, 106 outbreaks (2005-2022) of different H7 highly pathogenic avian influenza viruses resulted in over 33 million poultry losses worldwide. Out of the total outbreaks, 77 were caused by H7N3 viruses, losing more than 29 million birds (Woah-Wahis, 2023).

Problems of avian influenza in low and middle-income countries (LMICs): The incidence of AI is spiraling in most parts of the world but poses a threat to LMICs such as Nigeria, Nepal, South Africa, and Ghana (Abolnik *et al*., 2022; Otekunrin *et al*., 2019; Shrestha *et al*., 2021; Subedi and Kaphle, 2019; Tasiame *et al*., 2020). Farmers in LMICs such as Nigeria, Nepal, and Ghana know AI etiology, clinical signs, and transmission (Asare *et al*., 2021; Oyadeyi *et al*., 2022; Timilsina and Mahat, 2018). Moreover, these factors also play an essential role in transmitting HPAI in the Indonesian poultry sector and among the human population (Wibawa *et al*., 2018). Developed countries like Australia and the USA are equipped to effectively handle an avian influenza outbreak, with comprehensive and thoroughly tested strategies established to address emergencies related to animal diseases. At the same time, LMICs often have limited resources and infrastructure to effectively respond to and control avian influenza outbreaks (Kuehne *et al*., 2019). They may lack well-equipped laboratories for quick and accurate diagnosis, insufficient healthcare facilities, and inadequate funding for preventive measures (Acheampong *et al*., 2021; Lasley *et al*., 2023). Surveillance systems for early detection and monitoring of avian influenza may be weak or non-existent in LMICs. This makes it challenging to identify outbreaks promptly, leading to delayed response and increased risk of the virus spreading further (Gwenzi *et al*., 2022). Underdeveloped countries such as Nigeria and South Africa may struggle to implement effective biosecurity measures to prevent the spread of avian influenza among poultry farms (Ijoma *et al*., 2020; Uwishema *et al*., 2021). Inadequate infrastructure, lack of knowledge, and limited resources can hinder the implementation of measures like proper waste management, restricted access to farms, and hygiene practices (Henry *et al*., 2006; Nicastro and Carillo, 2021; Sharma *et al*., 2020). Poultry farming plays a crucial role in the livelihoods and nutrition of many people in LMICs (Acharya and Behera, 2019). However, the close interaction between humans and poultry increases the risk of transmission of avian influenza to humans, potentially leading to outbreaks of highly pathogenic strains, such as the H5N1 or H7N9 subtypes (Yamaji *et al*., 2020). LMICs often face challenges in providing adequate healthcare access to their populations. This can hamper timely diagnosis, treatment, and containment efforts during avian influenza outbreaks, potentially leading to higher mortality rates (Kehlenbrink *et al*., 2019).

Addressing the avian influenza problem in LMICs requires international cooperation and support (Pannu and Barry, 2021). It involves strengthening surveillance systems, improving biosecurity measures, providing access to diagnostic tools and vaccines, and enhancing healthcare infrastructure and capacity (Torreele *et al*., 2023). Efforts should focus on building sustainable systems that can respond effectively to future outbreaks and mitigate the impact on human health and the economy (Afrin *et al.*, 2021). Avian influenza outbreaks often result in the culling of infected birds and the implementation of movement restrictions to contain the spread of the virus (Guinat *et al.*, 2020). These measures can severely disrupt the poultry industry, leading to a decline in production and a loss of income for farmers, traders, and other workers involved in the poultry value chain (Ijaz *et al.*, 2021).

Preventive measures to be adopted in low and middle-income countries (LMICs): Improved preventive measures such as vaccination and biosecurity would be more effective in LMICs (Parvin *et al.*, 2020). Adopting preventive measures in LMICs has consequential impacts on the economy, public health, food security, environment, and international trade, as shown in Fig. 2 (Bénard *et al.*, 2023). Avian influenza outbreaks can have significant economic consequences, including losing poultry stocks, reduced production, and market disruptions (Oduoye *et al.*, 2023). Preventive measures can help minimize the occurrence of outbreaks, reducing the economic losses associated with avian influenza. By investing in preventative measures, LMICs can protect farmers' livelihoods, maintain stability in the poultry industry, and ensure sustained economic growth. Globally, highly pathogenic avian influenza, particularly certain strains like H5N1 and H7N9, can pose an extreme risk to human health. Preventive measures, such as biosecurity practices and surveillance, help reduce the transmission of the virus from poultry to humans (Leung *et al.*, 2023). By focusing on prevention, LMICs can mitigate the public health risks associated with avian influenza, protecting their populations from potential outbreaks and the spread of the virus to humans (Alhaji *et al.*, 2023). Poultry products, such as eggs and poultry meat, are important sources of protein and essential nutrients, particularly for vulnerable populations in LMICs. Preventive measures aim to reduce the occurrence and impact of avian influenza outbreaks, ensuring a stable supply of safe poultry products for the population. This contributes to food security and helps safeguard the nutritional needs of communities (Chieloka, 2020). In countries like Bangladesh, AI outbreaks can result in the culling and disposal of infected birds, which can have environmental implications if not managed properly.

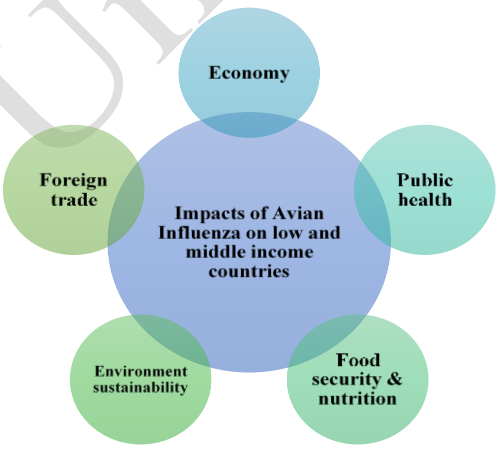

Fig. 2: Possible impacts of Avian Influenza outbreaks on LMICs.

Ultimately, preventive measures, such as improved biosecurity practices, disinfection, and waste management systems, help reduce the contamination environmental impact of avian influenza outbreaks (Islam *et al.*, 2023). This contributes to sustainable agriculture and minimizes environmental contamination in LMICs (Kaneda *et al.*, 2023). LMICs often rely on international trade for their poultry products. Implementing robust preventive measures can enhance the safety and quality of poultry products, meet international standards, and facilitate trade (Zhou *et al.*, 2019). By demonstrating a commitment to preventive measures, LMICs can build trust and confidence in their poultry products, opening opportunities for export and economic growth (Aday and Aday, 2020; Skripnuk *et al.*, 2021).

Moreover, dynamic facilities of real-time diagnosis of H1, H2, H3, H5, H7, and H9 such as RT-PCR, quantum dot-based immunoassay, reverse transcription Loop-Mediated Isothermal Amplification (RT-LAMP), fluorescent-magnetic-catalytic nanospheres (FMCNs), Neuraminidase-Resistant Glycopolymer-Coated Microbeads are not fully available in LMICs (Li *et al.*, 2021; Peng *et al.*, 2019; Xiao *et al.*, 2019; Yan *et al.*, 2023; Yang *et al.*, 2022). The lack of such highly developed diagnostics facilities in low-income states affects farmers' economies in many ways (Devi *et al.*, 2021). Preventive measures are more cost-effective than diagnostics facilities to work on surveillance of any outbreak (Peeling *et al.*, 2022).

Economic Consequences of Avian Influenza Outbreaks: The poultry sector contributes 4% to the national GDP of Nepal (Gompo *et al.*, 2020), 1.4-1.6% to the national GDP of Bangladesh, 6-8% to the national GDP of Nigeria (Anon, 2020), 20% of the agricultural GDP of South Africa (Makoma, 2022), 14% to national GDP of Ghana (Bagbara, 2021). Western Java in Indonesia contains the highest poultry population (60%), and most broiler farms are smallholder farms. In reaction to an AI outbreak, the early selling of poultry birds to the market leads to economic losses that small-scale farmers cannot bear (Pramuwidyatama *et al.*, 2023). Likewise, both large- and small-scale poultry farmers have suffered massive financial losses in Bangladesh due to HPAI H5N1 outbreaks (Rimi *et al.*, 2019). In Nigeria, having suffered a huge loss due to HPAI outbreaks in the past few years, 43% of farmers were discouraged and never returned to poultry farming (Agri *et al.*, 2020). The following support policies are necessary to control Avian influenza epidemics effectively.

Supportive government policies: Avian influenza outbreaks can devastate farmer's livelihoods, particularly in LMICs, where poultry farming is a significant source of income (Cousins *et al.*, 2022). Government support can help protect farmers from economic losses by providing financial assistance, compensation for culled birds, and access to alternative income-generation opportunities (Hazell and Varangis, 2020; Moore *et al.*, 2021). In countries like Nigeria and Ghana, government support is essential in promoting and facilitating the implementation of effective biosecurity measures in the poultry sector (Oyadeyi *et al.*, 2022). This includes providing public health guidance, training, and resources to help farmers improve hygiene practices, secure poultry farms, and prevent the spread of avian influenza. Financial assistance can also be provided to farmers to upgrade their infrastructure and invest in biosecurity equipment (Pramuwidyatama *et al*., 2020). In developing countries like Nepal, government stakeholders can establish or strengthen surveillance systems to enable early detection of avian influenza outbreaks (Lambrou *et al*., 2020). This involves supporting veterinary services, laboratories, and field surveillance activities to quickly identify and respond to potential cases. Timely detection is crucial in containing the spread of the virus and minimizing its impact on human and animal health (Krammer and Schultz-Cherry, 2023). The government should support capacity-building programs and educational initiatives to enhance farmers' practices and skills in avian influenza prevention, control, and biosecurity practices, as poultry farmers and workers play a significant role in chain transmission (Jha *et al*., 2021). Training programs can help farmers understand the risks, improve their farming techniques, and effectively respond to outbreaks (Bello *et al*., 2022).

Furthermore, governments can play a vital role in ensuring access to avian influenza vaccines for poultry populations in affected areas (Guyonnet and Peters, 2020). They can collaborate with international organizations, such as the World Organization for Animal Health (OIE), to facilitate the availability and distribution of vaccines. Additionally, governments can support veterinary services to provide timely diagnosis, treatment, and advice to farmers (Varshney and Prasanna, 2020).

Supportive insurance policies: Avian influenza outbreaks pose significant financial risks to farmers, including losing poultry stock, decreased production, and market disruptions (Koh *et al*., 2022). Insurance companies can provide risk mitigation tools, such as avian influenza insurance policies, to help farmers recover from these losses (Richter and Wilson, 2020). Insurance coverage can provide financial compensation and support farmers in rebuilding their businesses after an outbreak (Obayelu *et al*., 2021; Pan *et al*., 2020). Avian influenza outbreaks can lead to significant economic losses for farmers, potentially pushing them into financial distress (Høg *et al*., 2021). Insurance coverage can provide a safety net, ensuring financial stability for farmers and protecting them from severe economic hardships. This stability allows farmers to continue their operations and mitigate the negative impacts on their livelihoods (Rasul *et al*., 2021). Access to insurance coverage for avian influenza can give farmers and investors greater confidence in the poultry sector. It encourages farmers to invest, expand their businesses, and adopt improved farming practices (Indrawan *et al*., 2020). Insurance coverage provides a level of security that can attract additional investments in the poultry industry, supporting its growth and development (Erdaw and Beyene, 2022). Insurance companies can contribute to capacity-building initiatives for farmers. They can provide training and resources on risk management, biosecurity practices, and preventive measures to reduce the likelihood and impact of avian influenza outbreaks (Bannor *et al*., 2023). This education can help farmers better understand their risks and take proactive measures to protect their flocks (Pao *et al*., 2023). Collaboration between insurance companies, governments, and other stakeholders can lead to innovative insurance products tailored to the needs of farmers in LMICs. Public-private partnerships can help address farmers' AI outbreak challenges and ensure that insurance solutions are affordable, accessible, and practical (Mayburd, 2021).

Conclusion: Avian influenza outbreaks in low- and middle-income countries (LMICs) can trigger major economic crises with wide-ranging repercussions. The poultry industry, a prime target, suffers immense losses due to production disruptions and supply chain halts. This scarcity leads to price hikes, impacting consumers, especially those in LMICs who rely heavily on poultry for protein. Trade restrictions imposed by unaffected countries further devastate the economies of LMICs by limiting export opportunities and foreign exchange earnings. Moreover, food security concerns become paramount, as poultry scarcity and inflation make it difficult for vulnerable populations to afford this vital source of nutrition.

Governments struggle under the burden of managing outbreaks, allocating resources for surveillance, response measures, compensation to farmers, and public health campaigns. These substantial expenditures strain already limited budgets, diverting funds from crucial sectors like education and healthcare. LMICs' inherent vulnerabilities, such as weak agricultural systems, inadequate healthcare infrastructure, and high poverty rates, exacerbate the economic impact of these outbreaks. International cooperation is crucial to mitigate these crises. Financial aid, technical expertise, and capacity-building initiatives can bolster disease surveillance, control measures, and alternative livelihood opportunities for affected communities. Facilitating trade with appropriate safety measures can minimize the blow to the poultry industry. Furthermore, investments in strengthening healthcare systems, improving agricultural practices, and reducing poverty can bolster LMICs' resilience against future outbreaks. By acknowledging the intricate interplay between avian influenza outbreaks and economic crises in LMICs, policymakers, international organizations, and stakeholders can collaboratively implement multi-dimensional strategies that prioritize the well-being and livelihoods of affected communities while fostering sustainable and inclusive economic development.

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REFERENCES

Abolnik C, Phiri TP, van der Zel G, *et al.*, 2022. Wild Bird Surveillance in the Gauteng Province of South Africa during the High-Risk Period for Highly Pathogenic Avian Influenza Virus Introduction. Viruses 14(9), 2027. https://doi.org/10.3390/v14092027

Acharya S and Behera M, 2019. Backyard Poultry Rearing: An Effective Tool for Enhancement of Livelihood of Farm Family. Journal of Krishi Vigyan 7(2), 32. https://doi.org/10.5958/2349-4433.2019.00006.0

Acheampong G, Owusu M, Nkrumah B, *et al.,* 2021. Laboratory capacity in COVID-19 diagnosis and the need to enhance molecular testing in Ghana. Global Security: Health, Science and Policy 6(1), 10–17. https://doi.org/10.1080/23779497.2021.1908157

Aday S and Aday MS, 2020. Impact of COVID-19 on the food supply chain. Food Quality and Safety 4(4), 167–180. https://doi.org/10.1093/fqsafe/fyaa024

Afrin S, Chowdhury FJ and Rahman MM, 2021. COVID-19 Pandemic: Rethinking Strategies for Resilient Urban Design, Perceptions, and Planning. Frontiers in Sustainable Cities 3. https://doi.org/10.3389/frsc.2021.668263

Agri B, Sotonye OI and Sunday EO, 2020. Socio-economic Effect of High Pathogenic Avian Influenza on Poultry Farmers in Rivers State, Nigeria. Black Sea Journal of Agriculture 3(4), 286–289. https://dergipark.org.tr/en/pub/bsagriculture/issue/56447/709543

Alders R, Awuni JA, Bagnol B, *et al.,* 2013. Impact of Avian Influenza on Village Poultry Production Globally. EcoHealth https://doi.org/10.1007/s10393-013-0867-x

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

Alhaji NB, Adeiza AM, Godwin EA, *et al*., 2023. An assessment of the highly pathogenic avian influenza resurgence at human-poultry-environment interface in North-central Nigeria: Sociocultural determinants and One Health implications. One Health 16, 100574. https://doi.org/10.1016/j.onehlt.2023.100574

An S-H, Son S-E, Song J-H, Hong S-M, *et al*., 2022. Selection of an Optimal Recombinant Egyptian H9N2 Avian Influenza Vaccine Strain for Poultry with High Antigenicity and Safety. Vaccines 10(2), 162. https://doi.org/10.3390/vaccines10020162

Anon, 2020. POULTRY SECTOR STUDY NIGERIA Commissioned by the Netherlands Enterprise Agency. Netherlands Enterprise Agency. https://www.rvo.nl/sites/default/files/2020/10/Poultry-Sector-Study-Nigeria.pdf

Apaliya MT, Kwaw E, Osae R, *et al.,* 2022. The Impact of COVID-19 on Food Security: Ghana in Review. Journal of Food Technology Research 9(3), 160–175. https://doi.org/10.18488/jftr.v9i3.3228

Asare RB, Folitse RD, Burimuah VD, *et al.,* 2021. Knowledge, Attitudes, and Practices Relating to Avian Influenza Among Poultry Workers in Ejisu-Juaben Municipality of Ashanti Region, Ghana. PAMJ - One Health 4. https://doi.org/10.11604/pamj-oh.2021.4.1.25797

Bagbara T, 2021. Revamping the Poultry Sector in Ghana. https://mofa.gov.gh/site/media-centre/agricultural-articles/321-revamping-the-poultry-sector-in-ghana

Bannor RK, Oppong-Kyeremeh H, Amfo B, *et al.,* 2023. Agricultural insurance and risk management among poultry farmers in Ghana: An application of discrete choice experiment. Journal of Agriculture and Food Research 11, 100492. https://doi.org/10.1016/j.jafr.2022.100492

Bello OG, Abdul rahaman OL, Kayode AO, *et al.,* 2022. Awareness of poultry farmers on biosafety practices against infectious diseases in Kano State, Nigeria. Journal of Agricultural Extension 26(2), 1–10. https://doi.org/10.4314/jae.v26i2.1

Bénard É, Drolet M, Laprise J-F, *et al.,* 2023. Potential benefit of extended dose schedules of human papillomavirus vaccination in the context of scarce resources and COVID-19 disruptions in low-income and middle-income countries: a mathematical modelling analysis. The Lancet Global Health 11(1), e48–e58. https://doi.org/10.1016/S2214-109X(22)00475-2

Blagodatski A, Trutneva K, Glazova O, *et al.,* 2021. Avian Influenza in Wild Birds and Poultry: Dissemination Pathways, Monitoring Methods, and Virus Ecology. Pathogens 10(5), 630. https://doi.org/10.3390/pathogens10050630

Brown I, Mulatti P, Smietanka K, *et al.,* 2017. Avian influenza overview October 2016–August 2017. EFSA Journal 15(10). https://doi.org/10.2903/j.efsa.2017.5018

Capua I and Alexander DJ, 2006. The challenge of avian influenza to the veterinary community. Avian Pathology 35(3), 189–205. https://doi.org/10.1080/03079450600717174

Chan PKS, 2002. Outbreak of Avian Influenza A(H5N1) Virus Infection in Hong Kong in 1997. Clinical Infectious Diseases 34 (Supplement_2), S58–S64. https://doi.org/10.1086/338820

Chand A, 2021. Rules of the avian influenza game. Nature Food 2(2), 76–76. https://doi.org/10.1038/s43016-021-00235-7

Chattu VK, Singh B, Kaur J, *et al.,* 2021. COVID-19 Vaccine, TRIPS, and Global Health Diplomacy: India's Role at the WTO Platform. BioMed Research International 2021, 1–8. https://doi.org/10.1155/2021/6658070

Chieloka OS, 2020. Serosurveillance for Avian Influenza in Local Chickens in Households and Live Bird Markets in Enugu State, Nigeria. East African Journal of Agriculture and Biotechnology 1(1), 24–34. https://doi.org/10.37284/eajab.1.1.52

Chowdhury H, Hossain G, Rahman B, *et al.,* 2019. The Pattern of Highly Pathogenic Avian Influenza H5N1 Outbreaks in South Asia. Tropical Medicine and Infectious Disease 4(4), 138. https://doi.org/10.3390/tropicalmed4040138

Cousins T, Pentecost M and Van Helden L, 2022. Containment and conversion. American Ethnologist 49(3), 413–426. https://doi.org/10.1111/amet.13083

Devi S, Sharma N, Ahmed T, *et al.,* 2021. Aptamer-based diagnostic and therapeutic approaches in animals: Current potential and challenges. Saudi Journal of Biological Sciences 28(9), 5081–5093. https://doi.org/10.1016/j.sjbs.2021.05.031

Dhingra MS, Artois J, Dellicour S, Lemey P, *et al.,* 2018. Geographical and Historical Patterns in the Emergences of Novel Highly Pathogenic Avian Influenza (HPAI) H5 and H7 Viruses in Poultry. Frontiers in Veterinary Science 5. https://doi.org/10.3389/fvets.2018.00084

Donadeu M, Nwankpa N, Abela-Ridder B, *et al.,* 2019. Strategies to increase adoption of animal vaccines by smallholder farmers with focus on neglected diseases and marginalized populations. PLOS Neglected Tropical Diseases 13(2), e0006989. https://doi.org/10.1371/journal.pntd.0006989

Erdaw MM and Beyene WT, 2022. Trends, prospects and the socio-economic contribution of poultry production in sub-Saharan Africa: a review. World's Poultry Science Journal 78(3), 835–852. https://doi.org/10.1080/00439339.2022.2092437

Feng Y, Le X and Wu S, 2021. Pathogenesis and Pathological Changes of Avian Influenza in Humans. In *Avian Influenza in Human* (pp. 29–40). Springer Singapore. https://doi.org/10.1007/978-981-16-1429-3_4

Ghedin E, Fitch A, Boyne A, *et al.,* 2009. Mixed Infection and the Genesis of Influenza Virus Diversity. Journal of Virology 83(17), 8832–8841. https://doi.org/10.1128/JVI.00773-09

Gompo TR, Shah BR, Karki S, *et al.,* 2020. Risk factors associated with Avian Influenza subtype H9 outbreaks in poultry farms in Kathmandu Valley, Nepal. PLOS ONE, 15(4), e0223550. https://doi.org/10.1371/journal.pone.0223550

Gong B, Zhang S, Yuan L, *et al.,* 2020. A balance act: minimizing economic loss while controlling novel coronavirus pneumonia. Journal of Chinese Governance 5(2), 249–268. https://doi.org/10.1080/23812346.2020.1741940

Guilloux A, 2007. Arthur Kleinman and James L. Watson (eds), SARS in China. China Perspectives 2007(2). https://doi.org/10.4000/chinaperspectives.1923

Guinat C, Comin A, Kratzer G, *et al.,* 2020. Biosecurity risk factors for highly pathogenic avian influenza (H5N8) virus infection in duck farms, France. Transboundary and Emerging Diseases 67(6), 2961–2970. https://doi.org/10.1111/tbed.13672

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

Gwenzi W, Skirmuntt EC, Musvuugwa T, *et al.,* 2022. Grappling with (re)-emerging infectious zoonoses: Risk assessment, mitigation framework, and future directions. International Journal of Disaster Risk Reduction 82, 103350. https://doi.org/10.1016/j.ijdrr.2022.103350

Haider M, Nahar AS and Leslie T, 2008. Challenges for Bangladesh to conquer avian influenza. International Journal of Pharmaceutical and Healthcare Marketing 2(4), 273–283. https://doi.org/10.1108/17506120810922321

Hazell P and Varangis P, 2020. Best practices for subsidizing agricultural insurance. Global Food Security 25, 100326. https://doi.org/10.1016/j.gfs.2019.100326

Henry RK, Yongsheng Z and Jun D, 2006. Municipal solid waste management challenges in developing countries – Kenyan case study. Waste Management 26(1), 92–100. https://doi.org/10.1016/j.wasman.2005.03.007

Høg E, Fournié G, Hoque MA, *et al.,* 2021. Avian Influenza Risk Environment: Live Bird Commodity Chains in Chattogram, Bangladesh. Frontiers in Veterinary Science 8. https://doi.org/10.3389/fvets.2021.694753

Huang K-YA, Rijal P, Schimanski L, *et al.,* 2015. Focused antibody response to influenza linked to antigenic drift. Journal of Clinical Investigation 125(7), 2631–2645. https://doi.org/10.1172/JCI81104

Hunter P, 2022. Europe's worst ever bird flu outbreak. EMBO Reports 23(10). https://doi.org/10.15252/embr.202256048

Ijaz M, Yar MK, Badar IH, *et al.,* 2021. Meat Production and Supply Chain Under COVID-19 Scenario: Current Trends and Future Prospects. Frontiers in Veterinary Science 8. https://doi.org/10.3389/fvets.2021.660736

Ijoma SI, Agusi ER, Ifende VI, *et al.,* 2020. Biosecurity challenges in the control of avian influenza in Nigeria. Sokoto Journal of Veterinary Sciences 18(3), 150–157. https://doi.org/10.4314/sokjvs.v18i3.5

Indrawan D, Stegeman A, Daryanto A, *et al.,* 2020. A Push and Pull Intervention to Control Avian Influenza: A Lesson Learned from the Western Java Poultry Sector. Jurnal Manajemen Dan Agribisnis. https://doi.org/10.17358/jma.16.3.179

Islam A, Islam S, Islam M, *et al.,* 2023. Prevalence and risk factors for avian influenza virus (H5 and H9) contamination in peri-urban and rural live bird markets in Bangladesh. Frontiers in Public Health 11. https://doi.org/10.3389/fpubh.2023.1148994

Jha SK, Thapa R, Gupta PK, *et al.,* 2021. Knowledge, attitude and practice related to Avian influenza among poultry workers of Kathmandu, Nepal. International Journal of Community Medicine and Public Health 9(1), 76. https://doi.org/10.18203/2394-6040.ijcmph20214984

Kaneda Y, Ozaki A, Gyeltshen T, *et al.,* 2023. The unprecedented avian influenza crisis in Japan: Strategies for prevention and response. New Microbes and New Infections 53, 101130. https://doi.org/10.1016/j.nmni.2023.101130

Kehlenbrink S, Smith J, Ansbro É, *et al.,* 2019. The burden of diabetes and use of diabetes care in humanitarian crises in low-income and middle-income countries. The Lancet Diabetes & Endocrinology 7(8), 638–647. https://doi.org/10.1016/S2213-8587(19)30082-8

Keogh-Brown MR, Jensen HT, Edmunds WJ, *et al.,* 2020. The impact of Covid-19, associated behaviours and policies on the UK economy: A computable general equilibrium model. SSM - Population Health 12, 100651. https://doi.org/10.1016/j.ssmph.2020.100651

Kim S-H, 2018. Challenge for One Health: Co-Circulation of Zoonotic H5N1 and H9N2 Avian Influenza Viruses in Egypt. Viruses 10(3), 121. https://doi.org/10.3390/v10030121

Koh K-Y, Ahmad S, Lee J, *et al.,* 2022. Hierarchical Clustering on Principal Components Analysis to Detect Clusters of Highly Pathogenic Avian Influenza Subtype H5N6 Epidemic across South Korean Poultry Farms. Symmetry 14(3), 598. https://doi.org/10.3390/sym14030598

Krammer F and Schultz-Cherry S, 2023. We need to keep an eye on avian influenza. Nature Reviews Immunology 23(5), 267–268. https://doi.org/10.1038/s41577-023-00868-8

Kuehne A, Keating P, Polonsky J, *et al.,* 2019. Event-based surveillance at health facilities and community level in low-income and middle-income countries: a systematic review. BMJ Global Health 4(6), e001878. https://doi.org/10.1136/bmjgh-2019-001878

Lambrou AS, Luitel H, Bhattarai RK, Basnet HB, *et al.,* 2020. Informing influenza pandemic preparedness using commercial poultry farmer knowledge, attitudes, and practices (KAP) surrounding biosecurity and self-reported avian influenza outbreaks in Nepal. One Health 11, 100189. https://doi.org/10.1016/j.onehlt.2020.100189

Lane MA, Walawender M, Carter J, *et al.,* 2022. Climate change and influenza: A scoping review. The Journal of Climate Change and Health 5, 100084. https://doi.org/10.1016/j.joclim.2021.100084

Lasley JN, Appiah EO, Kojima K *et al.,* 2023. Global Veterinary Diagnostic Laboratory Equipment Management and Sustainability and Implications for Pandemic Preparedness Priorities1. Emerging Infectious Diseases 29(4), 1–12. https://doi.org/10.3201/eid2904.220778

Le TH and Nguyen NTB, 2014. Evolutionary dynamics of highly pathogenic avian influenza A/H5N1 HA clades and vaccine implementation in Vietnam. Clinical and Experimental Vaccine Research 3(2), 117. https://doi.org/10.7774/cevr.2014.3.2.117

Leight J, Awonon J, Pedehombga A, *et al.,* 2022. The impact of an integrated value chain intervention on household poultry production in Burkina Faso: evidence from a randomized controlled trial. Journal of Development Effectiveness 14(2), 108–124. https://doi.org/10.1080/19439342.2021.1968932

Leung K, Lam TTY and Wu JT, 2023. Controlling avian influenza. BMJ p560. https://doi.org/10.1136/bmj.p560

Li G, Ma W, Mo J, *et al.,* 2021. Influenza Virus Precision Diagnosis and Continuous Purification Enabled by Neuraminidase-Resistant Glycopolymer-Coated Microbeads. ACS Applied Materials & Interfaces 13(39), 46260–46269. https://doi.org/10.1021/acsami.1c11561

Liu S, Zhuang Q, Wang S, *et al.,* 2020. Control of avian influenza in China: Strategies and lessons. Transboundary and Emerging Diseases 67(4), 1463–1471. https://doi.org/10.1111/tbed.13515

Lone NA, Spackman E and Kapczynski D, 2017. Immunologic evaluation of 10 different adjuvants for use in vaccines for chickens against highly pathogenic avian influenza virus. Vaccine 35(26), 3401–3408. https://doi.org/10.1016/j.vaccine.2017.05.010

Lupiani B and Reddy SM, 2009. The history of avian influenza. Comparative Immunology, Microbiology and Infectious Diseases 32(4), 311–323. https://doi.org/10.1016/j.cimid.2008.01.004

Lycett SJ, Duchatel F and Digard P, 2019. A brief history of bird flu. Philosophical Transactions of the Royal Society B: Biological Sciences 374(1775), 20180257. https://doi.org/10.1098/rstb.2018.0257

Magouras I, Brookes VJ, Jori F, *et al.,* 2020. Emerging Zoonotic Diseases: Should We Rethink the Animal–Human Interface? Frontiers in Veterinary Science 7. https://doi.org/10.3389/fvets.2020.582743

Mahase E, 2023. H5N1: Do we need to worry about the latest bird flu outbreaks? BMJ p401. https://doi.org/10.1136/bmj.p401

Makoma MAC, 2022. Poultry and Products Annual. https://apps.fas.usda.gov/newgainapi/api/Report/DownloadReportByFileName?fileName=Poultry%20and%20Products%20Annual_Pretoria_South%20Africa%20-%20Republic%20of_SF2022-0024.pdf

Mayburd A, 2021. A public-private partnership for the express development of antiviral leads: a perspective view. Expert Opinion on Drug Discovery 16(1), 23–38. https://doi.org/10.1080/17460441.2020.1811676

Medina RA and García-Sastre A, 2011. Influenza A viruses: new research developments. Nature Reviews Microbiology 9(8), 590–603. https://doi.org/10.1038/nrmicro2613

Monne I, Fusaro A, Nelson MI, *et al.,* 2014. Emergence of a Highly Pathogenic Avian Influenza Virus from a Low-Pathogenic Progenitor. Journal of Virology 88(8), 4375–4388. https://doi.org/10.1128/JVI.03181-13

Moore TC, Fong J, Rosa HAM and Pogreba-Brown K, 2021. CAFOs, novel influenza, and the need for One Health approaches. One Health 13, 100246. https://doi.org/10.1016/j.onehlt.2021.100246

Naguib MM, Verhagen JH, Samy A, *et al.,* 2019. Avian influenza viruses at the wild–domestic bird interface in Egypt. Infection Ecology & Epidemiology 9(1), 1575687. https://doi.org/10.1080/20008686.2019.1575687

Nicastro R and Carillo P, 2021. Food Loss and Waste Prevention Strategies from Farm to Fork. Sustainability 13(10), 5443. https://doi.org/10.3390/su13105443

Ninyio NN, Ho KL, Omar AR, *et al.,* 2020. Virus-like Particle Vaccines: A Prospective Panacea Against an Avian Influenza Panzootic. Vaccines 8(4), 694. https://doi.org/10.3390/vaccines8040694

Obayelu AE, Obayelu OA, Bolarinwa KK, *et al.,* 2021. Assessment of the Immediate and Potential Long-Term Effects of COVID-19 Outbreak on Socioeconomics, Agriculture, Security of Food and Dietary Intake in Nigeria. Food Ethics 6(1), 5. https://doi.org/10.1007/s41055-021-00085-w

Oduoye MO, Akilimali A, Nazir A, *et al.,* 2023. Highly pathogenic avian influenza (HPAI A H5N1) outbreak in Spain: its mitigation through the One Health approach – a short communication. Annals of Medicine & Surgery 85(4), 1352–1355. https://doi.org/10.1097/MS9.0000000000000399

Oidtman RJ, Arevalo P, Bi Q, *et al.,* 2021. Influenza immune escape under heterogeneous host immune histories. Trends in Microbiology 29(12), 1072–1082. https://doi.org/10.1016/j.tim.2021.05.009

Otekunrin OA, Otekunrin OA, Momoh S, *et al.,* 2019. How far has Africa gone in achieving the zero-hunger target? Evidence from Nigeria. Global Food Security 22, 1–12. https://doi.org/10.1016/j.gfs.2019.08.001

Oyadeyi OA, Jegede AS, Oluwayelu DO, *et al*., 2022. Exposure to avian influenza in poultry farms and access to veterinary healthcare services in Nigeria and Ghana. Nigerian Journal of Parasitology 43(2), 369–380. https://doi.org/10.4314/njpar.v43i2.20

Pan D, Yang J, Zhou G, *et al.,* 2020. The influence of COVID-19 on agricultural economy and emergency mitigation measures in China: A text mining analysis. PLOS ONE 15(10), e0241167. https://doi.org/10.1371/journal.pone.0241167

Pannu J and Barry M, 2021. The state inoculates: vaccines as soft power. The Lancet Global Health 9(6), e744–e745. https://doi.org/10.1016/S2214-109X(21)00091-7

Pantin-Jackwood MJ, Costa-Hurtado M, Bertran K, *et al.,* 2017. Infectivity, transmission and pathogenicity of H5 highly pathogenic avian influenza clade 2.3.4.4 (H5N8 and H5N2) United States index viruses in Pekin ducks and Chinese geese. Veterinary Research 48(1), 33. https://doi.org/10.1186/s13567-017-0435-4

Pao H, Jackson E, Yang T, *et al.,* 2023. The attitude-behaviour gap in biosecurity: Applying social theories to understand the relationships between commercial chicken farmers' attitudes and behaviours. Frontiers in Veterinary Science 10. https://doi.org/10.3389/fvets.2023.1070482

Parvin R, Nooruzzaman M, Kabiraj CK, *et al.,* 2020. Controlling Avian Influenza Virus in Bangladesh: Challenges and Recommendations. Viruses 12(7), 751. https://doi.org/10.3390/v12070751

Peeling RW, Heymann DL, Teo Y-Y, *et al*., 2022. Diagnostics for COVID-19: moving from pandemic response to control. The Lancet 399(10326), 757–768. https://doi.org/10.1016/S0140-6736(21)02346-1

Peng X, Luo G, Wu Z, *et al.,* 2019. Fluorescent-Magnetic-Catalytic Nanospheres for Dual-Modality Detection of H9N2 Avian Influenza Virus. ACS Applied Materials & Interfaces 11(44), 41148–41156. https://doi.org/10.1021/acsami.9b16718

Philippon DAM, Wu P, Cowling BJ, *et al*., 2020. Avian Influenza Human Infections at the Human-Animal Interface. The Journal of Infectious Diseases 222(4), 528–537. https://doi.org/10.1093/infdis/jiaa105

Poovorawan Y, Pyungporn S, Prachayangprecha S, *et al.,* 2013. Global alert to avian influenza virus infection: From H5N1 to H7N9. Pathogens and Global Health 107(5), 217–223. https://doi.org/10.1179/2047773213Y.0000000103

Pramuwidyatama MG, Hogeveen H and Saatkamp HW, 2020. Understanding the Motivation of Western Java Smallholder Broiler Farmers to Uptake Measures Against Highly Pathogenic Avian Influenza (HPAI). Frontiers in Veterinary Science 7. https://doi.org/10.3389/fvets.2020.00362

Pramuwidyatama MG, Indrawan D, Boeters M, *et al.,* 2023. Economic impact of highly pathogenic avian influenza outbreaks in Western Java smallholder broiler farms. Preventive Veterinary Medicine 212, 105833. https://doi.org/10.1016/j.prevetmed.2022.105833

Rasul G, Nepal AK, Hussain A, *et al.,* 2021. Socio-Economic Implications of COVID-19 Pandemic in South Asia: Emerging Risks and Growing Challenges. Frontiers in Sociology 6. https://doi.org/10.3389/fsoc.2021.629693

Rebel JMJ, Peeters B, Fijten H, *et al.,* 2011. Highly pathogenic or low pathogenic avian influenza virus subtype H7N1 infection in chicken lungs: small differences in general acute responses. Veterinary Research 42(1), 10. https://doi.org/10.1186/1297-9716-42-10

Rehman S, Effendi MH, Witaningruma AM, *et al.,* 2023. Avian influenza (H5N1) virus, epidemiology and its effects on backyard poultry in Indonesia: a review. F1000Research 11, 1321. https://doi.org/10.12688/f1000research.125878.2

Richter A and Wilson TC, 2020. Covid-19: implications for insurer risk management and the insurability of pandemic risk. The Geneva Risk and Insurance Review 45(2), 171–199. https://doi.org/10.1057/s10713-020-00054-z

Rimi H, Sultana CR, Debnath B, *et al.,* 2019. A Decade of Avian Influenza in Bangladesh: Where Are We Now? Tropical Medicine and Infectious Disease 4(3), 119. https://doi.org/10.3390/tropicalmed4030119

Saito T, Tanikawa T, Uchida Y, *et al.,* 2015. Intracontinental and intercontinental dissemination of Asian H5 highly pathogenic avian influenza virus (clade 2.3.4.4) in the winter of 2014-2015. Reviews in Medical Virology 25(6), 388–405. https://doi.org/10.1002/rmv.1857

Sharma HB, Vanapalli KR, Cheela VS, *et al.,* 2020. Challenges, opportunities, and innovations for effective solid waste management during and post COVID-19 pandemic. Resources, Conservation and Recycling 162, 105052. https://doi.org/10.1016/j.resconrec.2020.105052

Shi J, Zeng X, Cui P, *et al.,* 2023. Alarming situation of emerging H5 and H7 avian influenza and effective control strategies. Emerging Microbes & Infections 12(1). https://doi.org/10.1080/22221751.2022.2155072

Shrestha D, Bhattachan B, Parajuli H *et al.,* 2021. Avian/Bird flu: A review: H5N1 outbreaks in Nepal. Nepal Journal of Biotechnology 9(1), 24–41. https://doi.org/10.3126/njb.v9i1.38647

Silva CAT, Kamen AA and Henry O, 2021. Recent advances and current challenges in process intensification of cell culture-based influenza virus vaccine manufacturing. The Canadian Journal of Chemical Engineering 99(11), 2525–2535. https://doi.org/10.1002/cjce.24197

Sims LD and Swayne DE, 2016. Avian influenza control strategies. In *Animal Influenza* (pp. 363–377). John Wiley & Sons, Inc. https://doi.org/10.1002/9781118924341.ch14

Varshney SKV and Prasanna NKP, 2020. Vaccine Diplomacy: Exploring the Benefits of International Collaboration. Current Trends in Biotechnology and Pharmacy 15(1), 110–114. https://doi.org/10.5530/ctbp.2021.1.12

Skripnuk DF, Davydenko VA, Romashkina GF, *et al.,* 2021. Consumer Trust in Quality and Safety of Food Products in Western Siberia. Agronomy 11(2), 257. https://doi.org/10.3390/agronomy11020257

Spackman E, 2008. A Brief Introduction to the Avian Influenza Virus. In *Avian Influenza Virus* (pp. 1–6). Humana Press. https://doi.org/10.1007/978-1-59745-279-3_1

Subedi D, Phuyal P, Bhandari S, *et al.,* 2022. Risk Factors Associated with Avian Influenza Subtype H9 Outbreaks in Poultry Farms of Central Lowland Nepal. Infectious Disease Reports 14(4), 525–536. https://doi.org/10.3390/IDR14040056/S1

Subedi D and Kaphle K, 2019. Highly Pathogenic Avian Influenza in Nepal. International Journal of Graduate Research and Review 5(3), 194–203.

Sun Y, Zhang T, Zhao X, *et al.,* 2023. High activity levels of avian influenza upwards 2018–2022: A global epidemiological overview of fowl and human infections. One Health 16, 100511. https://doi.org/10.1016/j.onehlt.2023.100511

Sun Z, Wang Q, Li G, *et al.,* 2021. Development of an Inactivated H7N9 Subtype Avian Influenza Serological DIVA Vaccine Using the Chimeric HA Epitope Approach. Microbiology Spectrum 9(2). https://doi.org/10.1128/Spectrum.00687-21

Tasiame W, Johnson S, Burimuah V, *et al.,* 2020. Outbreak of highly pathogenic avian influenza in Ghana, 2015: degree of losses and outcomes of time-course outbreak management. Epidemiology and Infection 148, e45. https://doi.org/10.1017/S095026882000045X

Thompson JM, Pendell DL, Boyer T, *et al.,* 2019. Economic Impacts of Business Continuity on an Outbreak of Highly Pathogenic Avian Influenza in Minnesota Egg Laying Operations. Journal of Agricultural and Applied Economics 51(02), 235–248. https://doi.org/10.1017/aae.2018.37

Timilsina A and Mahat S, 2018. Knowledge and Practices towards Avian Influenza among Poultry Workers in Pokhara. Janapriya Journal of Interdisciplinary Studies 7(1), 26–34. https://doi.org/10.3126/jjis.v7i1.23047

Torreele E, McNab C, Adeyi O, *et al.,* 2023. It is time for ambitious, transformational change to the epidemic countermeasure's ecosystem. The Lancet 401(10381), 978–982. https://doi.org/10.1016/S0140-6736(23)00526-3

Uwishema O, Adriano LF, Chalhoub E, *et al.,* 2021. Bird flu outbreak amidst COVID-19 pandemic in South Africa: Efforts and challenges at hand. Journal of Medical Virology 93(10), 5676–5679. https://doi.org/10.1002/jmv.27124

Uyeki TM and Peiris M, 2019. Novel Avian Influenza A Virus Infections of Humans. Infectious Disease Clinics of North America 33(4), 907–932. https://doi.org/10.1016/j.idc.2019.07.003

Vandegrift KJ, Sokolow SH, Daszak P, *et al.,* 2010. Ecology of avian influenza viruses in a changing world. Annals of the New York Academy of Sciences 1195(1), 113–128. https://doi.org/10.1111/j.1749-6632.2010.05451.x

Webster RG and Govorkova EA, 2014. Continuing challenges in influenza. Annals of the New York Academy of Sciences 1323(1), 115–139. https://doi.org/10.1111/nyas.12462

Wibawa H, Karo-Karo D, Pribadi ES, *et al.,* 2018. Exploring contacts facilitating transmission of influenza A(H5N1) virus between poultry farms in West Java, Indonesia: A major role for backyard farms? Preventive Veterinary Medicine 156, 8–15. https://doi.org/10.1016/j.prevetmed.2018.04.008

Wille M and Barr IG, 2022. Resurgence of avian influenza virus. Science, 376(6592), 459–460. https://doi.org/10.1126/science.abo1232

WOAH-WAHIS, 2023. *WAHIS: World Animal Health Information System*. The World Organisation for Animal Health (WOAH, Founded as OIE).

Xiao M, Huang L, Dong X, *et al.,* 2019. Integration of a 3D-printed read-out platform with a quantum dot-based immunoassay for detection of the avian influenza A (H7N9) virus. The Analyst 144(8), 2594–2603. https://doi.org/10.1039/C8AN02336K

Yamaji R, Saad MD, Davis CT, *et al.,* 2020. Pandemic potential of highly pathogenic avian influenza clade 2.3.4.4 A(H5) viruses. Reviews in Medical Virology 30(3). https://doi.org/10.1002/rmv.2099

Yan S, Yang F, Yao H, Dong D, *et al.,* 2023. A multiplex real-time RT-PCR assay for the detection of H1, H2 and H3 subtype avian influenza viruses. Virus Genes 59(2), 333–337. https://doi.org/10.1007/s11262-022-01963-z

Yang F, Dong D, Wu D, *et al.,* 2022. A multiplex real-time RT-PCR method for detecting H5, H7 and H9 subtype avian influenza viruses in field and clinical samples. Virus Research 309, 198669. https://doi.org/10.1016/j.virusres.2021.198669

Yang R, Sun H, Gao F, *et al.,* 2022. Human infection of avian influenza A H3N8 virus and the viral origins: a descriptive study. The Lancet Microbe 3(11), e824–e834. https://doi.org/10.1016/S2666-5247(22)00192-6

Zhou L, Li L and Lei L, 2019. Avian influenza, non-tariff measures and the poultry exports of China. Australian Journal of Agricultural and Resource Economics 63(1), 72–94. https://doi.org/10.1111/1467-8489.12285