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Financial impact of low pathogenic avian influenza virus subtype H9N2 on commercial broiler chicken and egg layer production systems in Pakistan

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ABSTRACT

Low Pathogenic Avian Influenza (LPAI) subtype H9N2 is endemic in Pakistan and impacts poultry farming through disease related mortality, poor weight gain and reduced egg production. This study aims to estimate the farm-level financial impact of LPAI H9N2 infection on commercial broiler and layer production systems in Pakistan.

A questionnaire based cross-sectional survey of 138 broiler farms and 136 layer farms in Pakistan was conducted in 2019. Primary data collected by cross-sectional survey along with expert opinion and published literature were used to parameterize five stochastic production and gross margin models for three broiler and two layer production systems: fully integrated production (FIP), partially integrated production (PIP) and independent farming production (IP) systems. Partial budget analysis were then carried out to estimate the financial impact of LPAI H9N2.

Results indicate that in broiler production systems, starting with 35,000 day old chicks (DOC) per batch, the net cost of disease (million PKR/production cycle) was estimated at 4.10 (14,862 USD), 4.62 (16,747 USD) and 2.46 (8917 USD) for IP, PIP and FIP systems, respectively. The disease produced a negative gross margin (defined here as revenue minus replacement and variable costs) in IP (-53 PKR (-0.19 USD)/DOC bought) and PI (-25 PKR (-0.091 USD)/DOC bought) systems, while remained positive for FIP systems (87 PKR (0.32 USD)/DOC bought). For layer production systems, (mean flock size as 48,000 DOCs) the net cost (million PKR/production cycle) was 29.75 (107,095.21 USD) and 29.51 (106,223.45 USD) IP and PIP systems, respectively, and produced negative gross margin in both systems.

The outcomes of the study highlight the vulnerability of independent and partially integrated production systems to the disease. These findings also offer a decision-making tool to the farmers and policy makers to evaluate avian influenza surveillance systems and control interventions in Pakistan.

1. Introduction

Avian influenza (AI) outbreaks are capable of affecting all levels of poultry value chains (Rushton et al., 2005) and present a major challenge to poultry production operations across the globe (Otekunrin et al., 2018; Amin et al., 2022). Infectious diseases of animals like AI are not only a health problem but also cause major economic impact through production losses and additional resource used for prevention, surveillance and control measures (Rushton, 2009). Moreover, they can also affect humans leading to health losses and related expenditures (Gashaw, 2020). Avian influenza in its highly pathogenic form was found to disrupt poultry supply chains while creating a demand shift from poultry to other meat sources in countries like Egypt, Turkey and Indonesia (Govindaraj et al., 2018; Otekunrin et al., 2018; Gashaw, 2020; Pramuwidyatama et al., 2023). Household income of AI affected poultry producers in Indonesia was found to decrease by 38 % during outbreaks in 2009 (Basuno et al., 2010) while a recent study quoted a loss ranging from 1.2 to 62.7 million Indonesian Rupiah (75.8–396.1 USD) caused by highly pathogenic avian influenza (HPAI) (Pramuwidyatama et al., 2023). Producers in Vietnam and Thailand suffered substantial losses in 2003 and 2004 due to HPAI when almost 17.5 % and 14.5 %, respectively, of the total birds were destroyed

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(Gashaw, 2020). In India, the financial impact of HPAI during a six months' time period was estimated to be 453 USD per small-scale farm (with average 644 bird per batch) and 40 USD per backyard poultry holding (with an average 22 birds per batch) (Govindaraj et al., 2018; Otekunrin et al., 2018). In Turkey, producers suffered a 54 % decrease in the sale of poultry and a 32 % decrease in poultry prices due to HPAI outbreaks in 2005–2006 (Yalcin, 2006). While several studies investigated the financial and epidemiological impacts of HPAI on producers (Henning et al., 2019), there is a dearth of studies on the farm-level financial impact of low pathogenic AI (LPAI) (McLeod et al., 2005) especially subtype H9N2. Among LPAI viruses, the subtype H9N2 is widespread in poultry populations in Asia, especially in Pakistan and since 1998 it is endemic in the country with yearly outbreaks reported (Ahad et al., 2013; Ali et al., 2024). A recent study conducted in the Punjab province of Pakistan estimated that out of 6.3 % of sample pools positive for AIV, 73.9 % were found to be positive for LPAI H9N2 (Ali et al., 2024). Given its high prevalence, the quantitative information on direct and indirect economic impacts of AIV in Pakistan is currently lacking. Such information is important to inform decisions on infectious disease control (Lyons et al., 2015). This presents a major knowledge gap in countries where LPAI H9N2 is endemic and hinders evidence-based decisions on resource allocation for animal disease control. In Pakistan, many producers suffer outbreaks of LPAI H9N2 each year that cause reduced weight gain, an increase in the production time in broilers, reduced egg production, malformed and misshaped eggs and a delayed onset of production in egg layers (Iqbal et al., 2009; Rafique et al., 2015; Umar et al., 2016). The resulting financial impacts are insufficiently documented, and producers have limited knowledge of the short-term and long-term costs of the disease on their production. Only one study so far estimated the impact of an outbreak of LPAI in general including H9N2 subtype in breeder flocks in Pakistan. This study was conducted in Mansehra district of Khyber Pakhtunkhwa province and the authors estimated an economic loss of 2.2 billion PKR per annum (7.9 million USD) with production losses of 40–80 % in broiler flocks in the province (Muhammad et al., 2010). No studies have yet been conducted on the financial impact of LPAI H9N2 in Punjab, the major poultry producing area of Pakistan (Bin Aslam et al., 2020). Control measures like biosecurity and vaccination are in place against AI but their practise is subject to variation (Bin Aslam, 2021). Moreover Due to the continuous evolution of H9N2 AI virus and lack of effective surveillance, current preventive measure have not proven to be effective in controlling infection, and losses due to mortality and decreased production continues (Umar et al., 2016).

Chicken production in Pakistan spans independent growers to integrated producers (Bin Aslam et al., 2020); the farm-level impact of AI is expected to vary across the various production systems. Estimation of the financial impact by production system can provide specific information for producers relevant for their context. Because husbandry practices, production types, and levels of integration vary by production system, the incidence and effects of AI infection are envisaged to cause variation in the financial impact of AI including LPAI. For example, the incidence of HPAI was reported to be low in large-scale commercial poultry settings of Indonesia with enough resources to ensure and adopt effective farm management practices (Otekunrin et al., 2018; Pramuwidyatama et al., 2023). Also, production systems and their profitability will determine the ability to respond when disease occurs. Chicken producers with high profit margins have more financial capacity to absorb losses during an AI outbreak compared to those operating on small margins (Gashaw, 2020). Moreover, because the chicken meat and egg export industries are increasing in the country (Bin Aslam et al., 2020), potential exporters are likely to have an interest in the quantification of financial impacts to inform their disease control strategies. Financial impact studies are important to understand where the major losses occur and help in formulation of control strategies, but also they generate the baseline information needed to assess the economic effectiveness of interventions and policies. The aim of this study therefore was to estimate the farm-level financial impact of LPAI subtype H9N2 in Pakistan for various broiler and layer production systems.

2. Materials and method

2.1. Overview of the approach

Various broiler and layer production systems in the Punjab province identified previously (Bin Aslam et al., 2020) were used to develop farm-level production models for each production system type. Gross margin models were then developed by allocating prices or values to input and output parameters. Lastly, the disease related parameters were added (e.g., increase in mortality, rate of production of poor-quality eggs, price of condemned eggs) in the models. Comparisons of models with and without disease were used to calculate the net value of LPAI H9N2 on the broiler and layer farms using partial budget analysis. Values for the model parameters were obtained from data collected in a large survey among farmers, scientific literature and expert opinion (Fig. 1). All monetary values were presented in Pakistani rupee (PKR) (1PKR = 0.0036 USD). All models were set up in Microsoft Excel 2016 version. The overall approach of this study is shown in Fig. 1.

2.2. Identification and characterisation of production systems

Chicken production systems operational in Pakistan were first identified and characterised in a qualitative study (Bin Aslam et al., 2020). For this study, the five pre-dominant production systems were considered, namely: 1) Fully integrated broiler production (FIBP), 2) Partially integrated broiler production (PIBP), 3) Independent broiler production (IBP), 4), Partially integrated layer production (PILP), and 5) Independent layer production (ILP). The fully integrated systems are characterised by single ownership of the major part of the value chain, including distribution of finished birds and products. The partially integrated system are composed of companies that own most of the farm processes up to distribution point (i.e. own parent stock farms, grower farms and feed mills). The independent production system mainly comprised of producers only involved in growing broilers or commercial egg production, with the inputs, and distribution of products depending upon traders and suppliers. Backyard birds were not included due to very low market share in chicken value chain (Bin Aslam et al., 2020).

2.3. Key assumptions

Several assumptions were made on general management practices and disease parameters (Table 1). Production models were developed to simulate one production cycle for each production system of broilers (38 days) and egg layers (700 days). For this study, only farms operating in an all-in all-out environmental control system were modelled, as this represents 97–98 % of all commercial farms in Pakistan as described by Bin Aslam et al. (2020).

2.4. Production models for broiler and layer farms

The production models depicted flows of various inputs, outputs and their quantity in relation to inputs consumed and outputs obtained. For broiler production, the models were divided into four different phases, namely downtime phase, brooding phase, growth phase and finisher phase (Fig. 2). Preparatory phase occurs during downtime where the farm is cleaned, washed, disinfected and prepared for the next cycle, followed by brooding phase (0th-14th days) in which the day-old chicks (DOC) are received and special environmental conditions (high in-house temperature 32–33 degree Celsius) are ensured for chick growth. Growth phase (15th-28th days) is the phase of rapid gain in the body weight and mass of the broiler with maximum efficiency in feed conversion ratio (FCR). The finisher phase (29th-38th) is the last phase in broiler production where the birds are fed in a way to attain target-

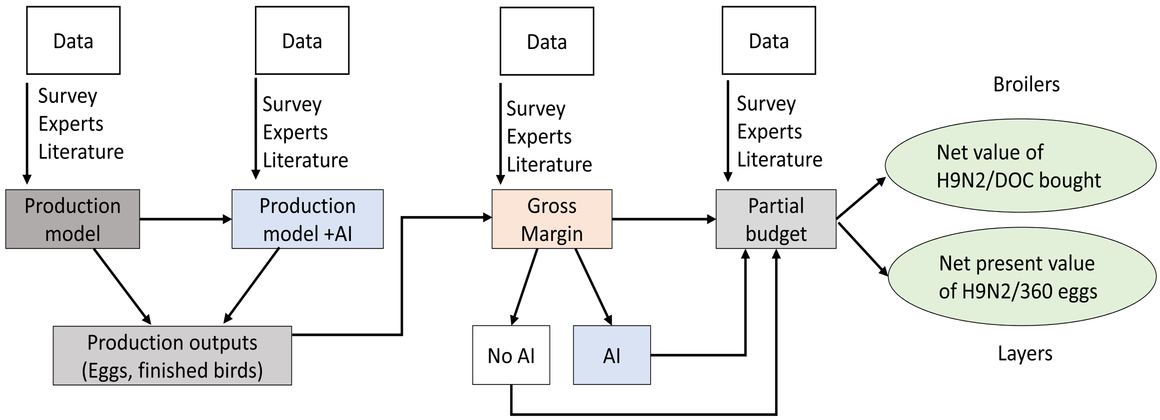

Fig. 1. Schematic presentation of the overall modelling approach to assess the financial impact of H9N2 avian influenza (AI) on chicken production in Pakistan. DOC=day-old-chicks.

Table 1
Key assumptions made on general management practices and disease parameters related to H9N2 AI infection in broiler and layer farms.

Key assumptions
• LPAI H9N2 associated mortality occurs in the middle of each phase (each poultry system is divided in several phases of production – see next section).
• Time duration of production cycle (i.e. 38 days for broiler and 700 days for egg layers) is fixed and will not change with the presence of disease. This implies farmers will sell some birds at lower weight (i.e. will not wait for these to achieve the normal average weight) as narrated by the survey participants. All birds and spent hens are sold once the production period is finished.
• The farms get affected with LPAI H9N2 during finishing and production phase of broiler and layer production, respectively. Justification: Given that some farms are affected earlier in the cycle and some later, the mid-point of production was used as the mean time of infection.
• In one production cycle birds that die consume half the amount of the feed consumed by birds that survive. This is because the mortality is assumed in the middle of each phase.
• In one production cycle egg layers that die produce half the quantity of eggs produced by the birds that survive as the mortality is assumed in the middle of production phase.
• Broilers and Layer birds that die due to LPAI H9N2 will not experience a reduction on the rate of feed consumption or egg production during their lifetime. These birds are assumed then to die shortly after infection occurs.

finishing weight according to the market requirements.

The layer models (Fig. 3) were structured into a rearing phase and a production phase. The rearing phase is subdivided into brooding phase (0th-14th days) and growth phase (15th-126th days) where the rapid growth of birds occur in order to attain the production weight. Once the production weight is attained the birds enter into the production phase (127th-700th days) marked by the onset of egg production until the time they are sold as spent hens.

Production models were initially developed for a situation without LPAI H9N2 on the farm. Production parameters, such as mortality, vaccination, feed consumption and weight gain were added to each phase. Only live birds at the end of a phase were allowed to enter the next phase. The number of finished birds sold at the end of one production cycle for broiler and layer production was calculated as:

$$Nb_{sold} = (N_{DOC} - N_{Dead}) = N_{DOC} - \sum_{p=1}^{3} (N_{dp}) \tag{1}$$

Where, Nb_{sold} is the number of birds sold (finished broilers or spent hens) at the end of production cycle, N_{DOC} is the number of DOCs bought in the beginning of cycle, N_{Dead} is the total number of dead birds per cycle, N_{dp} refers to the number of dead birds in each phase (p): brooding =1, growth =2, finisher or production =3. The number of dead birds in each phase was calculated as:

$$N_{d1} = N_{DOC} * m_1 \tag{2}$$

$$N_{d2} = (N_{DOC} - N_{d1}) * m_2 \tag{3}$$

$$N_{d3} = (N_{DOC} - N_{d1} - N_{d2}) * m_3 \tag{4}$$

Where m_1, m_2 and m_3 are the mortality rates in phase 1, 2 and 3. The values of m_1, m_2 and m_3 for layer production were calculated from the survey data (Bin Aslam, 2021) and are given in Table 2, while for broiler production these were calculated as follows:

$$m_1 = 0.65 * M; m_2 = 0.02 * M; m_3 = 0.33 * M \tag{5}$$

Where 0.65, 0.02 and 0.33 is the proportion of overall mortality rate (M) (Tabler et al., 2004). The number of live birds at the end of phase 1 (N_{l1}) and 2 (N_{l2}) of broiler and layer production were calculated as:

$$N_{l1} = N_{DOC} - N_{d1} \tag{6}$$

$$N_{l2} = N_{DOC} - N_{d1} - N_{d2} \tag{7}$$

For layer production, the calculation for number of eggs produced by the flock in one production cycle (N_{eggs}) was.

$$N_{eggs} = Nb_{sold} * n_{e3} + (n_{e3} * 0.5) * N_{d3} \tag{8}$$

Where, n_{e3} is the number of eggs produced by one bird in one production cycle and N_{d3} is the number of dead birds in the production phase of egg layers. Assuming that mortality occurs in the middle of the phase, the dead birds produced half the number of eggs.

The number of poor-quality eggs ($N_{pooreggs}$), out of total eggs produced, was calculated as:

$$N_{pooreggs} = (N_{eggs} * \alpha) \tag{9}$$

Where, α is rate of production of poor-quality eggs out of total eggs produced, with the rest representing normal eggs ($N_{normaleggs}$).

Eq. 10 shows the amount of feed (gm) consumed by the total flock per one production cycle (F_c).

$$F_c = \sum_{p=1}^{3} (N_{lp} * f_p + f_p * 0.5 * N_{dp}) \tag{10}$$

Where, f_p is the feed consumption (g) per bird in phase 1, 2 and 3 of production cycle. As the time of death is assumed to occur in the middle

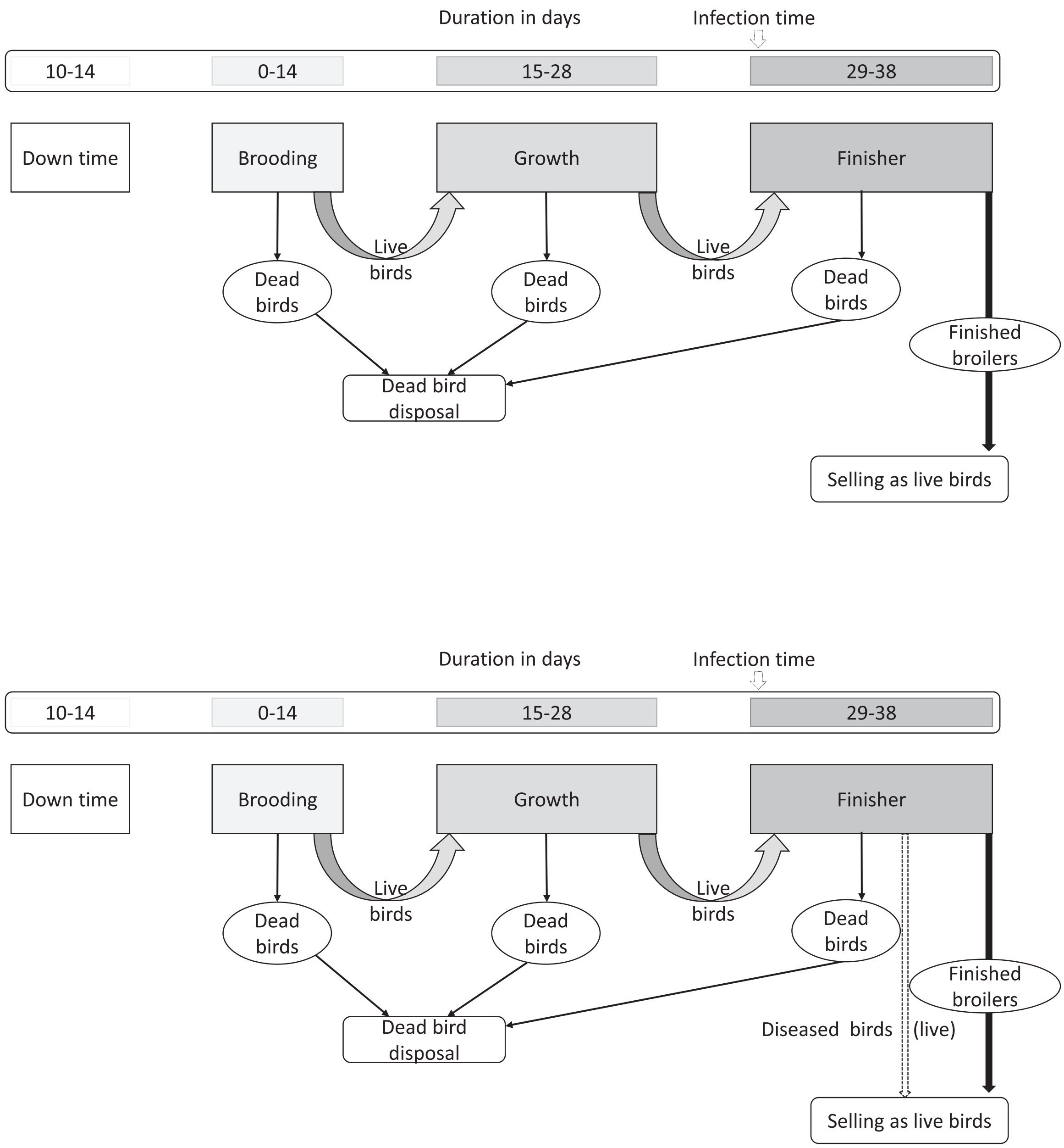

Fig. 2. The broiler production model simulating the flow of birds across the cycle. The dotted arrow indicates the shortening of production cycle length during LPAI H9N2 outbreak and early selling of birds.

of each phase, it was estimated that the dead birds consumed half of the normal feed of the corresponding phase. For broiler production f_p was calculated as:

$$f_1 = 0.114 * F; f_2 = 0.333 * F; f_3 = 0.553 * F \quad (11)$$

Where 0.114, 0.333 and 0.553 indicate the proportion of total feed (F) consumed over a bird's lifetime in the brooding, growth and finisher phase, respectively (Cobb-Vantress, 2018). Feed consumption for various phases of layer production was calculated as:

$$f_1 = 0.004 * F; f_2 = 0.078 * F; f_3 = 0.91 * F \quad (12)$$

Where 0.114, 0.333 and 0.553 indicated the proportion of total feed (F) consumed over a bird's lifetime in the brooding, growth and production phase, respectively (Hy-line, 2018).

The total number of feedbags used ($N_{feedbags}$) during one broiler and layer production cycle was calculated as:

$$N_{feedbags} = (F_c * 0.001)/50 \quad (13)$$

This accounts that each feedbag contains 50 kg of feed and that F_c is measured in grams

The live weight of the flock (Lw_{flock}) sold was only modelled for the broiler birds as these are normally sold on the base of live weight. Layer spent hens are valued on per spent bird unit and calculation of weight was not necessary. For broilers Lw_{flock} was calculated as:

$$Lw_{flock} = w * Nb_{sold} \quad (14)$$

Where, w is weight of the broiler bird in finisher phase.

The vaccine schedule for boilers and layer was obtained from the survey data (provided as supplementary material). Broiler and layer birds receive a total of 4 and 13 shots of vaccines (monovalent and polyvalent both) throughout the production cycle, respectively. While in production phase of layer, the birds are vaccinated against New castle

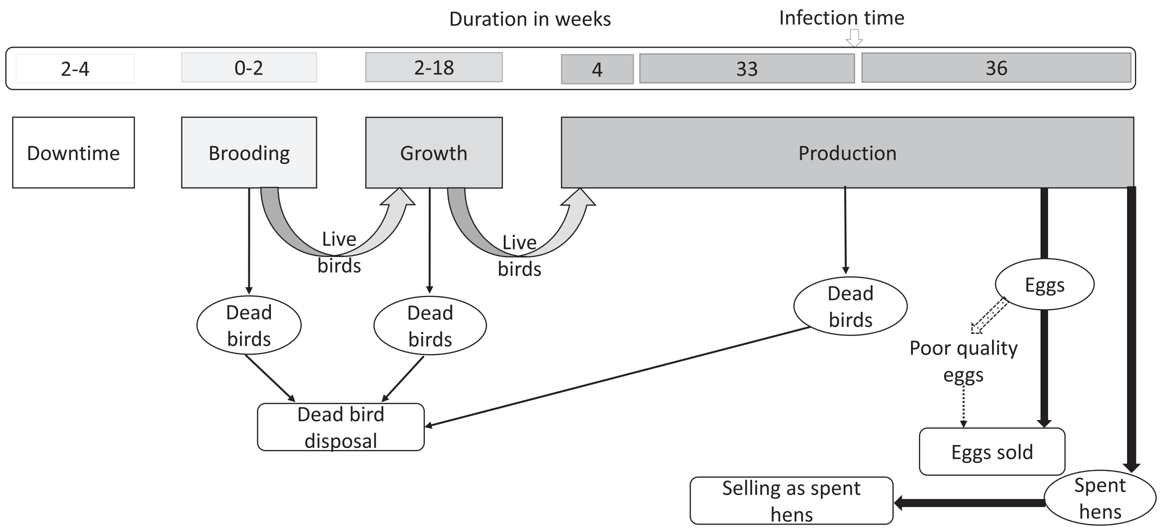

Fig. 3. The layer production model simulating the flow of birds across the cycle along with major outputs of layer production. The dotted arrow indicates separation of poor quality eggs (misshaped, thin-shelled or cracked eggs) from the normal eggs.

Table 2
Input variables and their values (expressed as FIXED and PERT distributions (minimum - most likely - maximum) used to parameterise the production models. Source: Cross-sectional survey (Bin Aslam, 2021).

Input parameters	Notation	Unit	Independent production	Partially integrated production	Fully integrated production
Broiler production					
Length of grow out time	-	Days	Fixed (39)	Fixed (38)	Fixed (34)
Number of DOC bought	N_{DOC}	Chicks	Fixed (35,000.00)	Fixed (35,000.00)	Fixed (35,000.00)
Total mortality per cycle	M	(%)	Pert (0.11–5.97–10.00)	Pert (1.40–2.04–2.74)	Pert (0.10–1.01–2.00)
Total feed consumption per cycle	F	(g)	Pert (2500.00–3450.00–4000.00)	Pert (3500.00–3608.00–3750.00)	Pert (2610.00–2900.00–3190.00)
Number of vaccine shots per cycle	n_{vac}	-	Fixed (4.00)	Fixed (4.00)	Fixed (4.00)
Weight of bird in finisher phase	w	(g)	Pert (1900.00–2270.00–2800.00)	Pert (2100.00–2350.00–2800.00)	Pert (1980.00–2200.00–2420.00)
Layer production					
Length of grow out time	-	Days	Fixed (697.00)	Fixed (700.00)	-
Number of DOC bought	N_{DOC}	Chicks	Fixed (48,000.00)	Fixed (48,000.00)	-
Mortality in brooding phase	m_1	(%)	Pert (0.13–1.70–4.20)	Pert (0.16–0.66–1.00)	-
Mortality in growth phase	m_2	(%)	Pert (0.001–1.75–3.50)	Pert (1.54–1.77–2.02)	-
Mortality in production phase	m_3	(%)	Pert (1.20–4.91–16.00)	Pert (2.00–5.16–13.00)	-
Feed consumption per bird per cycle	F	(g)	Pert (30,303.00–55,048.00–83,875.00)	Pert (45,000.00–54,000.00–63,000.00)	-
Number of vaccine shots per cycle *	n_{vac}	-	Fixed (14.00)	Fixed (14.00)	-
Number of eggs produced per bird	n_{e3}	-	Pert (150.00–400.00–650.00)	Pert (320.00–405.00–500.00)	-
Poor quality eggs produced	α	(%)	Pert (0.1–1.1–2.1)	Pert (0.6–1.85–3.1)	-

* It refers to the vaccines shots received by a bird during brooding and rearing phase before the onset of egg production (please see the production model description for details).

disease (ND) and infectious bronchitis (IB) in drinking water after every 75 days. As the time of routine mortality for various phases is assumed to occur in the middle of the phase, it was considered that a bird that died will have received half the number of vaccine shots or vials compared to a bird that lived through the cycle.

The total number of vaccine shots (N_{vac_shots}) used in the flock per cycle in broilers and for the brooding and rearing phase for egg layers was calculated as follows.

$$N_{vac\_shots} = \sum_{p=1}^{2} N_{lP} * n_{vac,\ p} + n_{vac,\ p} * 0.5 * N_{dP} \quad (15)$$

Where, $n_{vac,p}$ is the total number of vaccine shots received by a bird in phase p. For the production phase in egg layers, it was estimated that vaccine vials were given to birds in the drinking water every 75 days. Table 2 shows the production input parameters for the different broiler and layer systems.

2.5. Gross margin models

The production models developed in the previous step were used to estimate the total quantity of inputs consumed and outputs produced to calculate gross margin (PKR/DOC bought for broilers and egg layers). These quantities were multiplied by prices to estimate the expenditure of buying inputs and the revenue obtained by selling outputs per production cycle. Table 3 shows the prices (PKR) used to parameterise broiler and layer gross margin models.

The gross margins (GM) were calculated on the base of number of DOC bought per house by using following formula.

$$GM = \frac{(R - Cdoc - VC)}{N_{DOC}} \quad (16)$$

Where, R is the revenue obtained by selling outputs, $Cdoc$ is the cost of all day old chicks bought and is included as a part of replacement cost (Rushton, 2009) and, VC is the variable cost. Revenue obtained (R) for

Table 3
Values of outputs sold (PKR) expressed as PERT distribution (minimum- most likely- maximum) in different broiler and layer production systems. Source: Cross-sectional survey data (Bin Aslam, 2021).

Output prices	Notation	Independent production	Partially integrated production	Fully integrated production
Broiler production				
Selling price of finished bird per Kg live weight	p_{lw}	Pert (100.00–152.62–220.00)	Pert (135.00–154.00–186.00)	Pert (135.00–150.00–165.00)
Selling price of an empty feed bag	$p_{emptyfeedbag}$	Pert (4.00–9.08–20.00)	Pert (6.00–7.83–9.00)	Pert (9.90–11.00–12.10)
Layer production				
Selling price of normal quality eggs per crate	$p_{normaleggs}$	Pert (2100.00–2483.33–3300.00)	Pert (2200.00–2416.66–2700.00)	-
Selling price of poor-quality eggs per crate	$p_{pooreggs}$	Pert (650.00–1191.00–2500.00)	Pert (1000.00–1400.00–1800.00)	-
Selling price of one spent hen	$p_{spenthen}$	Pert (50.00–100.48–170.00)	Pert (80.00–100.00–120.00)	-
Selling price of an empty feed bag	$p_{emptyfeedbag}$	Pert (2.00–9.66–16.00)	Pert (2.00–7.33–8.00)	-

broiler production was calculated as:

$$R_{broilers} = Lw_{flock} * p_{lw} + N_{feedbags} * p_{emptyfeedbag} + Ls \quad (17)$$

Where, p_{lw} is the price of finished broiler per Kg live weight of bird; $p_{emptyfeedbag}$ is the price of one empty feed bag and Ls is the mean value of litter sold per house.

The R calculations for layer production are as follows:

$$R_{layers} = \left(N_{normaleggs} \middle/ 360\right) * p_{normaleggs} + \left(N_{pooreggs} \middle/ 360\right) * p_{pooreggs} + N_{sold} * p_{spenthen} + N_{feedbags} * p_{emptyfeedbag} + Ls \quad (18)$$

Where, $p_{normaleggs}$ is the price per crate of normal eggs (and where each crate contains 360 eggs); $p_{pooreggs}$ is the price per crate of poor quality eggs and $p_{spenthen}$ is the price of one spent hen as informed by the survey (Table 3). The value of flock for broiler and layer farms was calculated as follows:

Table 4
Values of inputs (PKR) expressed as PERT (minimum- most likely- maximum) and Fixed distributions used to parameterise broiler and layer financial models. Source: Cross-sectional survey data (Bin Aslam, 2021).

Economic parameters	Notation	Independent production	Partially integrated production	Fully integrated production
Broiler production				
Price per day old chick bought	p_{DOC}	Pert (40.00–69.4–98)	Pert (28.00–54.25–80.5)	Pert (8.00–32.50–57.00)
Bedding price per day old chick bought	c_{bed}	Pert (1.60–2.58–2.87)	Pert (1.08–1.78–2.57)	Pert (2.38–2.65–2.91)
Disinfection price per day old chick bought	c_{disin}	Pert (0.90–1.19–1.38)	Pert (0.51–0.74–0.9)	Pert (1.49–1.59–1.73)
Price of one vaccine shot	c_{vac}	Pert (0.75–1.92–3.50)	Pert (1.00–2.12–3.25)	Pert (1.25–1.50–1.75)
Price per feed bag	$p_{feedbag}$	Pert (2200.00–2584.33–2950.00)	Pert (2300.00–2444.66–2560.00)	Pert (1800.00–2000.00–2200.00)
Medicine expenditure per day old chick bought	c_{med}	Pert (0.44–9.42–19.90)	Pert (1.00–8.35–12.64)	Pert (2.862–3.18–3.49)
Disposal price per bird died	c_{disp}	Pert (0.1–0.45–1.03)	Pert (0.27–0.31–0.34)	Pert (0.47–0.53–0.58)
Price of one visit made by veterinarian	c_{visit}	Pert (4500.00–19,440.00–40,000.00)	Assumed as fixed cost	Assumed as fixed cost
Diagnostic expenditure per bird sampled	c_{diag}	Pert (227.00–1000.65–2000.00)	Pert (720.00–800.00–880.00)	Pert (1350.00–1500.00–1650.00)
Mean number of birds sampled	N_{diag}	Fixed (12)	Fixed (15)	Fixed (10)
Litter sold per house	Ls	Pert (2000.00–63,678.50–120,000.00)	Pert (3000.00–50,000.00–100,000.00)	Pert (50,400.00–56,000.00–61,600.00)
Layer production				
Price per day old chick bought	p_{DOC}	Pert (22.00–79.50–175.00)	Pert (60.00–78.00–88.00)	-
Bedding price per day old chick bought	c_{bed}	Pert (0.15–1.69–3.00)	Pert (0.80–0.90–1.20)	-
Disinfection price per day old chick bought	c_{disin}	Pert (0.13–1.19–1.26)	Pert (0.49–0.55–0.60)	-
Total cost of vaccination per DOC bought	v	Pert (4–40.9–101)	Pert (33–51.5–70)	-
Cost of a vaccine vial in production phase	C_{vacp3}	Fixed (7500)	Fixed (7500)	
Price per feed bag ***Self-produced bag**	$p_{feedbag}$	Pert (1800.50–2157.80–2400.00)	*Pert (2100.00–2150.00–2200.00)	-
Medicine expenditure per day old chick bought	c_{med}	Pert (0.33–20.88–75.00)	Pert (5.00–20.83–80.00)	-
Disposal price per bird died	c_{disp}	Pert (0.05–0.46–1.00)	Pert (0.27–0.30–0.33)	-
Price of one visit made by veterinarian[a]	c_{visit}	Pert (1000.00–11,146.66–25,000.00)	Assumed as fixed cost	-
Diagnostic expenditure per bird sampled	c_{diag}	Pert (187.50–2227.38–4000)	Pert (839.99–933.33–1026.66)	-
Mean number of birds sampled	N_{diag}	Fixed (25)	Fixed (29)	-
Litter sold per house	Ls	Pert (45,000.00–128,166.66–180,000.00)	Pert (30,000.00–87,000.00–144,000.00)	-

[a] Indicates visiting veterinarian hired by the independent layer farmers only, the PILP used permanent veterinarians and were regarded as fixed cost. Data source: Bin Aslam, H., 2021. Economic assessment of low pathogenic avian influenza virus subtype H9N2 and its vaccination in the commercial chicken production sector in Pakistan. Royal Veterinary College (University of London).

$$Cdoc = N_{DOC} * p_{DOC} \quad (19)$$

Here, p_{DOC} is the price of one layer or broiler DOC. The monetary values for various broiler and layer production parameters are given in Table 4.

The variable cost included the cost of feed, bedding, vaccine, disinfection, medicine and cost of disposing dead birds. Labour cost, fuel cost, kitchen cost for feeding labours, equipment and maintenance cost were considered as fixed costs. The variable cost for broiler production (VC) was calculated as:

$$VC = N_{feedbags} * p_{feedbag} + C_{vac} + N_{dead} * c_{disp} + N_{DOC} * c_{bed} + N_{DOC} * c_{disin} + C_{medflock} + Vet_{visit} * c_{visit} + N_{diag} * c_{diag} \quad (20)$$

Where, $p_{feedbag}$ is price of one full bag of feed (50Kg); c_{disp} is the expenditure on disposing dead birds; c_{disin} is the expenditure on disinfecting the house per DOC bought; c_{bed} is the bedding price per DOC bought; N_{diag} is the number of birds sampled for laboratory diagnosis per cycle and c_{diag} is the expenditure on laboratory diagnosis per bird sampled (Table 4). Vet_{visit} is the number of visits made by visiting veterinarian in independent production and c_{visit} is price per visit. Because hiring permanent veterinarians in fully and partially integrated production systems (Bin Aslam, H, 2021), the veterinary cost was considered as fixed cost, hence regarded as zero. C_{vac} is the cost of vaccination. To calculate this parameter, the data collected from farms were used to estimate the average total cost of vaccine expenditure per bird per farm for the whole cycle (v). Subsequently, the proportion of total vaccine expenditure incurred in the production stage ($PropExp\_vac_{vials}$) was estimated. For broiler, this proportion was set to 0, as all vaccinations are given in the brooding and rearing phase. For egg layers, this value was estimated as follow:

$$PropExp\_vac_{vials} = N_{l2} * (P_{vial} \;/\; 5000) * (573/75) \;/\; (v * N_{DOC}) \quad (21)$$

Where P_{vial} / 5000 indicates the price of vial per bird (as one vial can be used to vaccinate 5000 birds); and 573/75 is the number of times one layer bird will be vaccinated against ND and IB during the production cycle (573 being the length of the production phase and 75 is the intervals in days between vaccination). The cost for each vaccination shot in the brooding and rearing phase was calculated as:

$$C_{vaccine-shot} = \frac{v \; * (1 - PropExp_{vac\,vials})}{n_{vac,\quad p=1\&2}} \quad (22)$$

The cost of vaccination for each phase was then calculated as follow:

$$C_{vaccine,\quad p=1} = N_{l1} * \; C_{vaccine-shot} * n_{vac,\quad p=1} + N_{d1} * \; C_{vaccine-shot} * \; n_{vac,\quad p=1}/2 \quad (23)$$

$$C_{vaccine,\quad p=2} = N_{l2} * \; C_{vaccine-shot} * n_{vac,\quad p=2} + N_{d2} * \; C_{vaccine-shot} * n_{vac,\quad p=1}/2 \quad (24)$$

$$C_{vaccine,\quad p=3} = \; v * PropExp_{vac\,vials} * [Nb_{sold} \; + N_{d3}/2] \quad (25)$$

These calculations assume that half of the vaccine are given to dead animals in each phase. The total cost of vaccine was then the sum of all individual cost for each phase.

Total medicine expenses were derived from the survey data. This was obtained per house and then divided by the total number of birds in that house to get the final cost of medicine per bird per cycle; it was further divided into three equal parts assigned to each phase of broiler and layer production. Medicine cost per flock ($C_{medflock}$) was calculated as:

$$C_{medflock} = \sum_{P=1}^{3} (N_{LP} * c_{med} + c_{med} * 0.5 * N_{lP}) \quad (26)$$

Where, c_{med} is the expenditure on medicating a bird per phase.

2.6. Epidemiological parameters related to LPAI H9N2

Due to the scarcity of data on the time of occurrence of LPAI H9N2 outbreaks on farms, poultry stakeholders and experts were consulted. They were asked about the phase of production and time when most outbreaks occur in broiler and layer production in Pakistan. For broiler production, disease was said to occur commonly in the finisher phase. For egg layers, disease was said to occur commonly in the production phase. This information was used to model the phases affected by disease. Table 5 shows the disease-related parameters based on the survey results i.e., as described by farmer respondents (Bin Aslam, 2021) and used in the impact models.

All parameters affected due to AI were given subscript i for ease in understanding and differentiating it from the production parameters without AI. Hence, mortality in the production phase including LPAI H9N2 is denoted as m_{3i} and was calculated as follows:

$$m_{3i} = (M + m_i) - m_1 - m_2 \quad (27)$$

The value for mi is the increase in mortality due to LPAI H9N2. The mean value for mi was obtained during survey from the farms (Bin Aslam, 2021) that reported to have experienced an LPAI outbreak in the past.

The number of eggs produced during LPAI H9N2 outbreak on farm (N_{Eggsi}) was calculated by using the overall rate of reduction (Δ) in egg production at flock level and the rate of reduction in egg production per infected bird that survives (γ). It was assumed that all birds in the farm get infected by the virus (100 % morbidity), but that the animals that die will not suffer any reduction in egg production before they die. The overall rate of reduction (Δ) in egg production at flock level was obtained from the farm survey and its mean value was 38 % for both independent and partially integrated layer production systems. Since this overall reduction is a combination of the reduction in eggs production by infected birds that survive (γ) and also the lack of production of eggs by birds that died due to infection (Table 5). The following formula was used to estimate N_{eggsi}.

$$N_{eggsi} = (1 - \gamma) * n_{e3} * N_{l3i} + N_{d3i} * 0.5 * n_{e3} = Neggs * \Delta, where\ \Delta = 0.38 then\ \gamma = 0.362 \quad (28)$$

In this study, we assumed that birds that die due to LPAI H9N2 will not experience any reduction in eggs production while alive. Hence, the overall reduction in eggs production is a product of the reduction in egg production by infected birds that survive (γ) and the lack of eggs production by infected birds that die (a 100 % infection rate is assumed). The number of poor-quality eggs ($N_{pooreggsi}$) out of total eggs produced was calculated as:

$$N_{pooreggsi} = N_{eggsi} * (\alpha + \beta) \quad (29)$$

Where, β is the increase in the rate of production of poor-quality eggs due to AI (Table 5) out of total eggs produced by the flock while the number of normal eggs ($N_{normaleggsi}$) produced by the layer flock was obtained from subtracting N_{eggsi} from $N_{pooreggsi}$.

The feed consumed by the flock with LPAI (F_{ci}) was calculated using the overall reduction rate in feed consumption in the flock due to AI outbreak (δ), as shown in Eq. 25.

$$F_{ci} = F_c * (1 - \delta) \quad (30)$$

To estimate the feed consumed by infected birds that survive in the production or growth phase (f_{3i}), the following equation was used:

Table 5
Effects of H9N2 avian influenza (AI) outbreaks on production parameters in layer and broiler farms in Pakistan given as % change (increase or reduction) and expressed as PERT distributions (minimum - most likely - maximum). Source: Cross-sectional survey data (Bin Aslam, 2021).

Disease-related parameters	Notation	Independent production	Partially integrated production	Fully integrated production
Broiler production				
Increase in medicine expenditure per bird	μ	Pert (25–56.22–90.10)	Pert (45.83–47.91–50.00)	Pert (22.50–25.00–27.50)
Increase in disinfection expenditure per bird	θ	Pert (33.01–76.77–85.71)	Pert (49.72–64.77–82.25)	No increase
Increase in mortality	m_i	Pert (5.43–10.33–15.01)	Pert (26.25–30.78–35.25)	Pert (16.02–20.63–25.03)
Reduction in feed consumption	δ	Pert (11–15.5–20)	Pert (21–25.5–30)	Pert (21, 25.5, 30)
Reduction in weight of finished bird	ε	Pert (22.49–26.07–36.84)	Pert (21.42–23.80–26.18)	Pert (0.09–0.11–0.12)
Layer production				
Increase in medicine expenditure per bird	μ	Pert (53.85–59.84–65.82)	Pert (36.72–40.84–44.88)	-
Increase in disinfection expenditure per bird	θ	Pert (43.53–48.37–53.20)	Pert (44.67–49.64–54.60)	-
Increase in mortality	m_i	Pert (5–10–15)	Pert (5–10–15)	-
Reduction in feed consumption due to AI	δ	Pert (31–35.16–40)	Pert (41–45.50–50)	-
Increase in production of poor-quality eggs	β	Pert (1–3.05–5.1)	Pert (5–7.5–10)	-
Reduction in egg production	γ	Pert (34–36.2–38)	Pert (36–38–40)	-

$$f_{3i} = (F_c * (1 - \delta) - f_1 - f_2)/f_3 \tag{31}$$

The live weight of the whole finished broiler flock with LPAI (Lw_{flocki}) was calculated from Eq. 14, where w is replaced by w_i. The live weight of the finished bird after AI outbreak (w_i) was calculated by multiplying the reduction rate (ε) in the weight of bird in phase 3 with normal finished weight in phase 3 using following equation:

$$w_i = w * (1 - \varepsilon) \tag{32}$$

For broilers, it was considered that the disease had no impact on number of vaccinations, as the birds have already received all of the vaccines before the start of phase 3. For egg layers, animals that die due to the disease were assumed to have received half of the vaccination.

2.7. Gross margins with disease

In the same way as for the gross margin (PKR/DOC bought) without LPAI H9N2, the gross margin with LPAI H9N2 was calculated by estimating the inputs and outputs and multiplying them by value coefficients. Moreover, additional expenditures were included, namely an increase in disinfection cost for the next cycle:

$$C_{disini} = C_{disin} * (1 + \theta) \tag{33}$$

Where, θ is the increment rate of the disinfection cost as reported in the survey.

Moreover, additional expenditures were included for medicine cost that increased due to AI outbreak on the farm for the use of multivitamins, immune-boosters and antibiotics in drinking water to support bird's condition during illness. Medicine cost per flock ($C_{medflocki}$) for phase 3 (C_{3medi}) was calculated as:

$$c_{3medi} = c_{3med} * (1 + \mu) \tag{34}$$

Where, μ is the increment rate in the medicine cost due to LPAI H9N2.

Respondents reported no increase in the number of visits made by the veterinarian from the routine visits hence the veterinary cost remained same as it was without LPAI H9N2 outbreak on the farm.

2.8. Estimation of the net impact of LPAI H9N2

The production and gross margin models were run with and without disease and their differences between flocks with and without LPAI H9N2 outbreak was used to calculate the extra cost and extra benefits of the changes occurred due to disease using partial budget model. Non-monetary variables such as the extra time spent in selling birds due to disease, extra time in disinfecting houses and disposing dead birds were not considered as it was assumed that these are absorbed by the farmer without increase in actual expenditure. This assumption is based on the response from farmers to our survey, who reported to hire fixed labour and not to pay extra labour charges due to LPAI H9N2 outbreak. The equation below is showing the general expression for the calculation of net value PKR/production cycle) of LPAI H9N2 in broiler and layer farms.

$$NV_i = \frac{(CS_i) - (NC_i + RF_i)}{N_{DOC}} \tag{35}$$

Here, net value (NV_i) of LPAI H9N2 is the difference of the difference of cost saved (CS_i) due to LPAI H9N2 to the new costs (NC_i) incurred and revenue foregone (RF_i) due to LPAI H9N2. No new revenue was obtained in case of AI outbreak. The calculations for CS_i and NC_i are as follow:

$$CS_i = (N_{feedbagi} * p_{feedbag} - N_{feedbag} * p_{feedbag}) + (C_{vaci} - C_{vac}) \tag{36}$$

$$NC_i = (N_{DOC} * c_{disini} - N_{DOC} * c_{disin}) + (N_{Deadi} * c_{disp} - N_{dead} * c_{disp}) + (C_{medflocki} - C_{medflock}) \tag{37}$$

Revenue foregone (RF_i) due to AI in broiler production was calculated as:

$$RF_i = (Lw_{flock} * p_{lw} - Lw_{flocki} * P_{lw}) + (N_{feedbag} * p_{emptyfeedbag} - N_{feedbagi} * p_{emptyfeedbag}) \tag{38}$$

Revenue foregone (RF_i) due to AI in egg layer production was calculated as:

$$RF_i = \left(Nb_{sold} * p_{spenthen} - Nb_{soldi} * p_{spenthen}\right) + \left(N_{feedbag} * p_{emptyfeedbag} - N_{feedbagi} * p_{emptyfeedbag}\right) + (N_{normaleggs} * p_{normaleggs} - N_{normaleggsi} * p_{normaleggs}) + (N_{pooreggs} * p_{pooreggs} - N_{pooreggsi} * p_{pooreggs}) \tag{39}$$

In addition, the difference of gross margins with and without disease was also calculated to estimate the impact of LPAI H9N2 on the gross margins. For egg layers, all costs and benefits identified to occur in year 2 of the production cycle were discounted using a discount rate of 7 % (personal communication senior officials at Agricultural Development Bank of Pakistan).

2.9. Data collection on model parameters

Values for the model parameters were obtained by conducting a cross-sectional questionnaire based survey (conducted from January to July, 2019) on 138 broilers and 136 layer farms in the Punjab province; the biggest poultry producer in the country (Bin Aslam et al., 2020). The online software EPITOOLS epidemiological calculator (ESG, 2018) was used to calculate sample size (n = 278) assuming that 90 % (estimated proportion=0.9) of the broiler farms and 10 % (estimated proportion=0.1) of the layer farms in Punjab faced LPAI H9N2 outbreaks during the year 2019 (personal communication with senior official at Poultry Research Institute, Rawalpindi). The desired precision was set at 5 % (0.05) with a 95 % (0.95) confidence interval (CI) while considering an infinite population.

In order to locate farms, poultry census data (unpublished) was obtained from the Poultry Research Institute Rawalpindi, and farms were sampled using systematic random sampling where each 10th farm on the list was selected for the survey with 82 % of response rate. About 18 % of the farmers on the survey contact list could not be reached either due to wrong contact details, having left the farming business or failure to answer the call when contacted. In case of an unsuccessful contact, i.e. where the contact number/email was unavailable, was wrong, unanswered calls and unwillingness to participate, the next farm on the list was considered as a candidate farm. Questionnaires were administered among farm-level decision makers e.g., farm owners, farm veterinarians or farm managers, involved in commercial broiler and layer production. Data were collected on i) production and economic parameters related to chicken production, ii) experience with LPAI outbreaks, particularly LPAI (subtype H9N2), vaccination practices, and iii) changes in production and costs incurred as a result of a LPAI H9N2 outbreak on farm. The latter included changes in overall mortality, weight gain, feed consumption, egg production, disinfection and medicine and disposal costs (questionnaire available as supplementary material). The questionnaire was piloted prior to use with three broilers and two layer farmers and adjustments were made within the statements, units and answer options of the questions, where required. Once finalised, the questionnaire (English and Urdu versions) were coded in Microsoft Excel (Version 2016) to be used in Open Data Kit® software. Five enumerators were hired and trained to assist researcher in the field data collection using electronic tablets.

In the absence of official data on LPAI H9N2 outbreaks, effectiveness of its vaccines and time of LPAI H9N2 outbreaks during production cycle, expert consultation (n=5 experts) was obtained. These questions were removed during the piloting of questionnaire as per feedback obtained from the respondents. Five experts were selected based on their expertise regarding AI monitoring and surveillance, vaccine production and chicken production. Oral and written consent was obtained from the participants before data collection. Details regarding data cleaning and management and descriptive analysis could be found in the supplementary material given in the appendix.

2.10. Model validation, software, input values and sensitivity analysis

Deterministic models were initially developed to check the working of the models and to discuss computations with authors of this work and experienced farmers in a series of workshops conducted in December 2019. Next, stochastic simulation was introduced by applying distributions to uncertain parameters using @Risk add-in software (version 8.0; Ithaca NY, USA). PERT distribution was mostly used because the data was based on the subjective estimates of the respondents. The PERT distribution was assigned to uncertain variables using an in-built distribution function in Palisade @Risk, which estimated minimum, most likely and maximum value based the data collected. These values were then discussed with experts (focal persons in each production systems) and were also compared with existing literature estimates. In case our data showed deranged (figures very low or very high), values from experts or other studies were used. The impact of uncertain input values on the output of models (gross margin and net value) was done using the Palisade @Risk in-built sensitivity analysis tool that performed multivariate regression for values sampled from the defined distributions to calculate beta regression coefficients. Spearman correlation coefficients were obtained in @Risk after the sensitivity analysis and copulas were generated to account the inputs that were correlated. Using in built "define copulas" function in @Risk, Gaussian copula was fitted to the model as it accounts for the positive and negative correlations among input variables. The consistency of generated copulas was ensured in @Risk before running models (5000 iterations).

2.11. Ethics statement

Ethical approval was sought from and granted by the Social Sciences Research Ethical Review Board (SSERB) of the Royal Veterinary College, UK (project reference: URN SR2018–1739). Prior to survey, the objectives of the study, rights of participants, anonymity, data confidentiality and safety were carefully explained to the participants orally in local language Urdu. Written consent was obtained from all the respondents to participate in the study.

3. Results

3.1. Epidemiological parameters

Details of all input parameters as obtained from the cross-sectional survey (Bin Aslam, 2021) are given in Table 2, Table 3 and Table 4. Our survey results indicate that 63.8 % of broilers and 45.5 % of egg layers farms suffered LAPI outbreaks from January till June, 2019. Around 93.4 % of broiler farms used commercial feed while the rest used self-produced (3.6 %) or both commercial and self-produced (2.8 %). The share of commercial feed in layer farms was 61.7 %, self-produced 26.4 % and combined 11.7 %. For IBP 62 %, for PIBP75 % and for FIPB 100 % of the respondents reported LPAI H9N2 outbreaks on their farms in the past six months. The mean increment in bird's mortality due to LPAI H9N2 on the farm was 10 %, 31 % and 21 % for IBP, PIBP and FIBP, respectively. Mean reduction in feed consumption was 16 % for IBP, 26 % for PIBP and 26 % for FIBP. Reduction in the weight of finished broilers was 26 % for IBP, 24 % for PIBP, and 0.11 % for FIBP. All respondents in broiler production systems reported an increase in the expenditure of the medicines due to LPAI H9N2 outbreak on the farm with an increase of 56 %, 48 % and 25 % for IBP, PIBP and FIBP, respectively. A total of 76 % of respondents in IBP and 100 % in PIBP reported an increase in the disinfection cost due to H9N2 AI outbreak on the farm; no increase in the disinfection costs was reported by the FIBP respondents.

For ILP, 46 % and for PILP, 25 % of the respondents practising vaccination reported LPAI H9N2 outbreak on their farms in the past. Mean increase in the overall mortality was 10 % for farms in ILP and PILP systems. The PILP respondents reported a higher reduction (45 %) in feed consumption compared to ILP respondents (35 %). Reduction in egg production as reported by respondents in ILP and PILP was 38 % and the percentage of production of poor-quality eggs was 3 % and 8 % for ILP and PILP, respectively. Medicine expenditure increased by 60 % in ILP and by 41 % in PILP caused by an increased use of antibiotics and immune boosters. For ILP, 55.3 % participants reported not to practise extra disinfection with 44.6 % reported to perform aggressive disinfection that included disinfecting farm twice, deep cleaning and washing of the house resulting in increased disinfection cost for the next cycle. All PILP respondents reported to practise extra disinfection procedures in the case of an AI outbreak. For ILP and PILP respondents reported an increase of 48 % and 50 %, respectively, in the normal cost of disinfection.

3.2. Gross margin in broiler and layer production (without disease)

The gross margins for various broiler production systems are shown in Fig. 4. The mean gross margin for IBP without LPAI was 64 PKR (0.23 USD)/DOC bought (90 % central range (CR): −29–168 PKR/DOC bought) and for PIBP 103 PKR (0.37 USD)/DOC bought (90 % CR: 56–157 PKR/DOC bought). The highest mean gross margin was estimated for FIBP with 160 PKR (0.57 USD)/DOC bought (90 % CR: 127–196 PKR/DOC bought). The variable cost of raising DOC to the level of finished broiler was 267 PKR (0.936 USD)/DOC bought for IBP, 233 PKR (0.83 USD)/DOC bought for PIBP and 169 PKR (0.60 USD)/DOC bought for FIBP. The variable cost was mainly accrued from feed cost (64–71 %), vaccine cost (3–4 %) and medicine cost (2–4 %). The

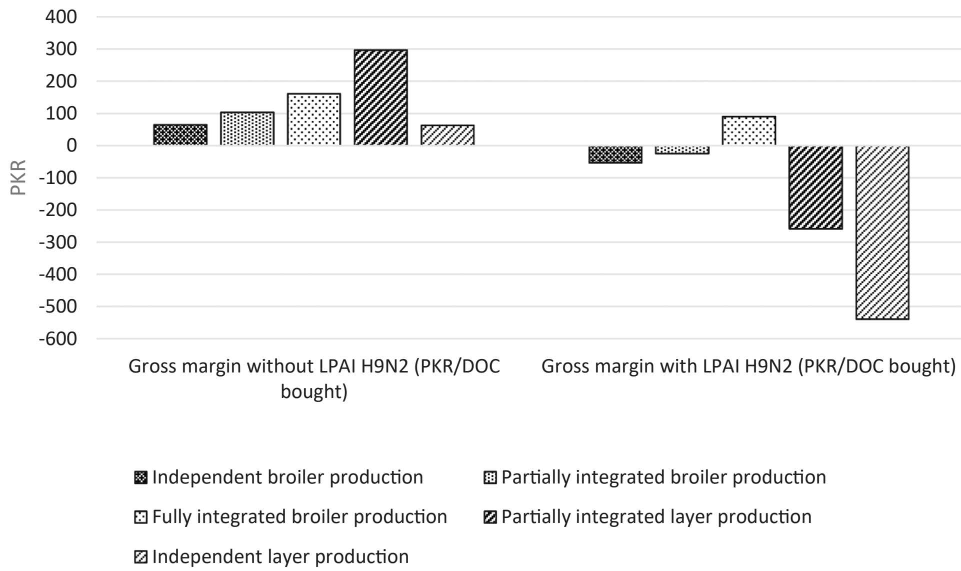

Fig. 4. Gross margins (PKR/DOC bought) without and with LPAI H9N2 in various broiler and layer production systems in Pakistan.

breakdown of the gross margin analysis is shown in supplementary material (S2).

Sensitivity analysis revealed that the price of broiler had the strongest positive effect on the mean gross margin in IBP with a regression coefficient of 0.83, followed by the weight of the finished broiler (0.41). The variables like price of DOC, mortality, expenditure on medicine, expenditure on vaccination and salary of visiting veterinarian had negative effects on the outcome with regression values of −0.31, −0.18, −0.15, −0.07, −0.06, −0.03 and −0.01, respectively. Similar trend was found for PIBP where the mean gross margin was most sensitive to the price and weight of finished broilers with regression values of 0.69 and 0.63, respectively. The other regression coefficients showed a negative effect on the mean gross margin in PIBP with −0.32 for price of DOC, −0.09 for price of feedbag, −0.07 for expenditure on medicine per bird, −0.06 for feed consumed by a bird and −0.05 for expenditure on vaccination. For FIBP, the weight and price of finished broiler had a positive influence on the mean gross margin with regression values of 0.60 for both. The other regression coefficients were negative with −0.45 for price of DOC, −0.21 for price of a feedbag and −0.21 for feed consumed per cycle.

The discounted gross margins for various layer production systems are shown in Fig. 4. Major outputs in layer production were the number of crates of eggs (360 eggs/crate) produced by ILP (51,419 crates) and PILP (52,828 crates). The mean baseline gross margin for ILP was 63 PKR (0.23 USD)/DOC bought (90 % CR: −1185 to 1317 PKR/DOC bought) and for PILP 297 PKR (1.07 USD)/DOC bought (90 % CR: −283–911 PKR/DOC bought), respectively. The discounted variable cost of producing one crate of eggs (360 eggs) in ILP was 2388 PKR (8.54 USD)/360 eggs and 1969 PKR (7.09 USD)/360 eggs in PILP. The variable cost mainly accrued from the expenditure on feed (94 %) and expenditure on vaccination (2 %). Sensitivity analysis for ILP showed that the number of eggs produced by a hen per cycle had the strongest positive influence on the mean gross margin, followed by the price per crate of eggs and the selling price of spent hens with regression coefficients of 0.76, 0.26 and 0.02, respectively. The other regression coefficients were negative with −0.52 for feed consumed by a bird, −0.09 for cost of a commercial feed bag, and −0.02 for the expenditure on vaccination, egg condemnation and medicine cost. Similar influences were found for PILP with the number of eggs produced by a hen, the price per crate of eggs and the selling price of spent hens having regression coefficients of 0.75, 0.39 and 0.02 respectively. The amount of feed consumed by a bird had the strongest negative effect on the gross margin in PILP with a regression coefficient of −0.55. The other variables like expenditure on medicine, egg condemnation, and DOC price had regression values ≤-0.1.

3.3. *Gross margin with disease (LPAI H9N2) in broiler and layer production*

The gross margins with H9N2 AI outbreak for various broiler and layer production systems are shown in Fig. 4. An H9N2 AI outbreak was estimated to cause a negative gross margin in IBP with −53 PKR (-0.19 USD)/DOC bought (90 % CR: −122–21 PKR/DOC bought) and PIBP with −25 PKR (-0.089 USD)/DOC bought (90 % CR: −52–5 PKR/DOC bought). The mean gross margin remained positive for FIBP but was reduced to 87 PKR (0.31 USD)/DOC bought (90 % CR: 66–114 PKR/DOC bought). An LPAI outbreak was estimated to cause a negative mean gross margin in both layer production systems with −539 PKR (-1.94 USD)/DOC bought (90 % CR: −1400–323 PKR/DOC bought) for ILP and −259 PKR (-0.93 USD)/DOC bought (90 % CR: −637–138 PKR/DOC bought) for PILP.

3.4. *Financial impact of LPAI H9N2 in broiler production*

The highest impact of H9N2 AI was estimated in PIBP system followed by IBP system and the lowest impact was calculated in FIBP (Table 6). In all broiler production systems, 98–99 % of the revenue foregone was accrued from selling a reduced number of birds with reduced finished weight. The sensitivity analysis for IBP revealed that reduction in weight gain due to LPAI H9N2 had the strongest negative impact on the mean net value with a regression value of −0.48 followed by the weight of finished birds, increase in mortality and increase in the medicine cost with regression values of −0.28, −0.19 and −0.02, respectively. For PIBP, the regression coefficient was −0.63 for weight of finished broiler, −0.28 for increase in mortality due to AI, −0.15 for reduction in weight due to AI and −0.01 for increase in the medicine cost. For FIBP, the increase in mortality had the strongest negative impact on the outcome of the model with a regression coefficient of −0.64 on the cost of AI, followed by the weight of finished broiler and reduction in weight due to AI having regression coefficients of −0.51 and −0.15, respectively. Reduction in feed consumption due to AI had a positive impact on model outcome in all production systems with regression coefficient of ≤ 0.1.

Table 6
Net value of the financial impact of a LPAI H9N2 outbreak per production cycle in three broiler and two layer production systems in Pakistan. All figures are mean values (PKR) for one house and one production cycle. For the net value, the central range (CR) is also given.

Costs	Independent production	Partially integrated production	Fully integrated production
Broilers			
New costs			
Disposal cost	1310.69	3220.33	3731.29
Medicine cost	53,436.04	24,505.57	4532.29
Disinfection cost	31,908.31	16,936.73	No increase
Revenue foregone			
Birds not sold	3909,024.52	5881,115.56	3325,285.28
Feed bags not sold	2389.26	3952.60	4047.78
Sum of costs	**3998,068.83**	**5929,730.80**	**3337,596.66**
Benefits			
Expenditure saved			
Feed cost	614,028.27	1059,633.73	735,960.20
Vaccination cost	0.00	0.00	0.00
New revenue	0.00	0.00	0.00
Sum of benefits	**614,028.27**	**1059,633.73**	**735,960.20**
Net value PKR (million)/ production cycle	**−4.10 (CR 90 %: −6.38 to −2.28)**	**−4.62 (CR 90 %: −5.58 to −3.78**	**−2.46 (CR 90 %: −2.94 to −1.99)**
Egg Layers			
New costs			-
Disposal cost	2028.49	1313.20	-
Medicine cost	336,461.26	158,315.02	-
Disinfection cost	94,579.43	49,973.83	-
Revenue foregone			-
Spent hens not sold	435,208.35	437,734.74	-
Eggs not sold	47,995,556.49	50,973,312.94	-
Feed bags not sold	79,470.55	76,104.80	-
Sum of costs	**48,943,304.00**	**51,696,754.56**	-
Benefits			-
Expenditure saved			-
Feed cost	19,182,548.25	22,312,545	-
Vaccine cost	4828.84	4880.19	-
New revenue	0.00	0.00	-
Sum of benefits	**19,187,377.15**	**22,317,425.54**	-
Net value PKR (million)/ production cycle	**−29.75 (90 % CR: −50.8.6 to −9.2)**	**−29.51 (90 % CR: −40.95 to −18.85)**	-

3.5. Financial impact of LPAI H9N2 in layer production

The results of the partial budget analysis for egg layers are shown in Table 6. The impact of H9N2 AI estimated in ILP was slightly higher compared to that of PILP system. For all production systems, the major costs mainly accrued from eggs not sold (98.0–98.5 % of the total additional expenditure and revenue forgone). The sensitivity analysis showed that the total number of eggs produced by a bird with disease had the strongest negative impact on the mean net value of AI per production cycle with a regression coefficient of −0.89. Other variables with negative impact on mean net value were the increment in poor quality egg production, increment in medicine cost and increment in medicine cost had regression values ≤0.1. The variable reduction in feed consumption had the strongest positive impact on the net value of H9N2 AI in ILP with a regression coefficient of 0.11. For PILP, the mean net value of AI was sensitive to the total number of eggs produced, increment in the production of poor-quality eggs, and reduction in feed consumption with regression coefficients of −0.83, −0.20, and 0.27, respectively. The variables increase in mortality due to AI and increase in the medicine cost due to AI had negative regression coefficients of ≤-0.1.

4. Discussion

This study is the first one to estimate the farm-level financial impact of LPAI subtype H9N2 in five distinct broiler and layer production systems in Punjab province in Pakistan. Using production models combined with gross margin and partial budget analysis populated with primary and secondary data, it was shown that the mean gross margin in different broiler and layer production systems increased with the increasing level of integration. The lowest gross margins were estimated for the IP systems and the highest gross margins were appraised for the FI production systems for broilers and PI production systems for egg layers. Outbreaks of LPAI H9N2 were estimated to have a negative financial impact on the broiler's and layer's farm profitability due to an increased mortality, decrease in finished bird weight and a drop in the number of eggs produced.

The gross margin without LPAI H9N2 outbreak was highest in the integrated broiler and layer production systems due to low variable costs per bird, as these production systems use self-produced feed and self-managed disease diagnostic laboratories cheaper than commercial feed and diagnostic services. Higher total cost was estimated in the PIBP compared to IBP and FIBP. This increment in the total cost is mainly attributed to the higher mortality in PIBP as reported by the respondents which might be due to better reporting and record keeping of production parameters in PIBP as compared to IBP. Feed was found to be the major contributor to the variable cost with feed price having a critical negative influence on gross margins in the sensitivity analysis. Such findings are in accordance with other studies conducted in Pakistan, India, Nepal, Indonesia and Nigeria where variable cost per bird varied in different production systems with expenditure on feed regarded as a major contributor to the variable cost in raising DOC to the level of finished bird (Afolayan et al., 2021; Khan and Afzal, 2018; Osti et al., 2016).

For this study, primary data collection via cross-sectional survey was conducted, because relevant data were not available in either the grey or scientific literature and secondary data was obtained from the published literature where available. The primary data collected allowed capturing different production practices that helped in estimating the burden of the disease under various production systems. Farm records would allow real-time monitoring of the whole production cycle and provide more accurate data. However, farmers refused access to these records. Following up on the respondents was previously found to increase the participation of the survey participants (Ponto, 2015). All enumerators hired were trained by the principal author before the survey to avoid misinterpretation of questions as also recommended by The World Bank (The World Bank, 2020). Most (60.5 % of the respondents) of the participants surveyed had bachelor or masters level education (Bin Aslam, 2021). Having some level of education in agriculture farming has proved to enhance the ability of farmers to acquire and process information more efficiently during surveys thus increasing the quality of collected data (Huffman, 2001). Due to a large sample size, electronic data collection was selected over paper based forms to simplify data collection, management and processing (Dickinson et al., 2019).

In this study, the farm-level financial impact of LPAI H9N2 was estimated. Farm-level assessments are a popular way to estimate the impact specific diseases have on farm business (Rushton, 2009). They provides information about the magnitude of the financial cost for producers, form a baseline for the assessment of control strategies and serve as a starting point for analyses that extend to the sector and country levels (Alarcon et al., 2014; Häsler et al., 2015). The production models developed to understand the population dynamics of a livestock enterprise not only allow estimating disease impact with more accuracy but also identifying the critical variables that determine the cost of a disease (Alarcon et al., 2014). Dividing the models into three major phases of broiler and layer production allowed understanding and quantifying the inputs for each phase and parameterizing them with the primary data gives context-specific and realistic gross margins and net disease impacts. Gross margin analysis has been used in the current study to identify profitability of various production systems, as it is recommended in lower-middle income countries settings to identify and assess livestock production dynamics and the best combinations of enterprise (Rushton, 2009). The systematic integration of production and financial models as done for example by Roy (2008) Alarcon et al. (2014), Häsler et al. (2015) and populating them with primary and secondary data allowed estimating the financial impact of LPAI H9N2 in the local farm-level settings of the Punjab poultry sector thereby providing valuable information for poultry farmers on their resource use. Insights were provided into various factors contributing to the losses incurred because of LPAI H9N2 outbreak on farm.

The outbreak was assumed to occur in the finisher and production phase of broiler and layer production, respectively; this assumption was made based on information received by survey respondents and experts. Consequently, its cascade effects on the other phases could not be estimated. The financial impact may be lower if the LPAI outbreak happens at the beginning rather than the end of the production cycle (Rushton et al., 2005). However, the models are flexible enough to cater for disease in growth phase of the production cycle leading to understand changes in the subsequent phases of the cycle and can be updated when more accurate data become available. In this study, the mortality was introduced in the middle of each phase to avoid an over or underestimation of the impact in the absence of data on the actual temporal occurrence of outbreaks and inaccessible farm records in Pakistan. In an ideal situation, the mortality incorporated based on real-time data could give a more detailed overview of the production dynamics. Better on-farm recording in the future potentially combined with centralised data collation systems may generate more accurate and reduce uncertainty in input parameters. Sensitivity analysis was incorporated into the models to account for uncertainty in input parameters. Sensitivity analysis has been used previously in a number of studies (Christopher Frey and Patil, 2002; Rushton, 2009; Alarcon et al., 2014; Häsler et al., 2015) based on economic modelling and has been considered as a prerequisite for corroboration, quality assurance and robustness of modelling estimates (Saltelli, 2002).Because H9N2 AI is low pathogenic, no impact assessments were available in Pakistan and in the south Asian region before this study was conducted. Thus, it fills a major knowledge gap on the financial impact of LPAI H9N2 at farm level and allows comparisons with other Asian countries. Assessment of LPAI H9N2 in its socio-economic context could be helpful in identifying global burden of animal diseases (GABDs) as the methodology used in this study is in agreement with the new approach proposed by World Organisation of Animal Health for estimating GBADs (Huntington et al., 2021). One of the main strengths of this study was the use of primary data on production, financial and disease parameters to populate the models. Thus, the models and (some) data could be used by other countries that have similar production systems and price structures like Pakistan. Because the study focused on the financial impact at the level of the farm, wider effects in the sector (e.g., ripple effects in the supply chain) or society (e.g., zoonotic transmission to humans) were not considered. It should be evident form the outcomes of this study that the impact of LPAI H9N2 on commercial chicken production is substantial and can affect the country's chicken production industry. Outbreaks of avian influenza are well known to disrupt country's economy, health system, trade and tourism and affect the export of chicken meat and eggs (Gashaw, 2020). These wider-reaching impacts of avian influenza were not studied in this study and remain open to further research.

Given the endemic status of LPAI H9N2 in Pakistan (Umar et al., 2016) and varying biosecurity levels among different production systems (Bin Aslam et al., 2020), elimination of the virus from susceptible populations might be challenging if not impossible. The high prevalence of the LPAI H9N2 in Pakistan (Channa et al., 2021) makes it one of the candidate viruses to be contained. Hence, future control strategies should focus on regional and farm-level interventions to prevent or reduce the incidence of disease and its spread down the chicken value chain given the zoonotic capability of the virus which cannot be ignored. With reference to the local socio-economic settings of Pakistan, culling of birds and compensation in case of disease outbreak is impractical and of low acceptance to the farmers. Hence, investment should be directed to increasing biosecurity measures at the regional and farm level, restricting birds' movement during the outbreak period, regulating inter-farm movement of personals and equipment, and designing novel disease control interventions like next-generation vaccines to control H9N2 LPAI infections. In our study, it was assumed that farmers will not extend the downtime period between batches. Such assumption was based on the survey done to farmers, who reported this infection to be common and not to pay any extra labour cost during outbreaks. Yet, ensuring longer downtime to allow for better decontamination of farms can be an effective option to reduce prevalence of LPAI H9N2 infection. Although such measure will increase cost of production, as it will delay the start of the next cycle, it can generate important benefits if future outbreaks are prevented. Such parameter should be considered in future research on long term analysis of control strategies of LPAI infection.

Interestingly, our survey revealed that the LPAI H9N2 outbreak did not trigger additional farm visits by veterinarians. Instead, farmers reported that feed manufacturing companies provide health consultancy services as part of their feed purchase agreements. These services include guidance on treatment options, such as antibiotics. This practice suggests that treatments, including antibiotics, may sometimes be administered without a prescription. Consequently, antibiotics may be purchased over the counter. Supporting this observation, a study by Habiba et al. (2023) involving 40 poultry farms found that 50 % of farmers used antibiotics without formal prescriptions (Habiba et al., 2023). Further research is needed to understand how farmers use antimicrobials during LPAI outbreaks and to help prevent potential misuse of these drugs.

A major limitation of this study is that no controlled field studies are available that would provide accurate data on the effects of LPAI H9N2 on production. Hence, the cross-sectional survey data set was a justifiable and feasible alternative given the context and time frame of the study. In fact, it is the first data set of its kind in Pakistan that provides useful insights into the financial, husbandry and disease parameters of the chicken industry of the country. The farm-level financial impact estimated in this study only give information on the commercial broiler and egg layer production systems as this was the main focus of this study. Whereas, the other aspects of value chain like impact of LPAI H9N2 on hatchery business, live bird markets and retail chicken outlets etc. remained unexplored and could be studied in future. The work presented in this study lays down a foundation for future work to estimate the impact of LPAI H9N2 on the consumers or prices of the chicken. The findings of the current study also encourage capitalising in designing a robust LPAI surveillance program in Pakistan. The financial consequences of LPAI H9N2 as found in this study give a signal to policymakers and other stakeholders to pay more attention to this endemic infection and consider the implementation of effective disease mitigation strategies. It is envisaged that decision makers (from farms to federal level) will consider the outcomes of this study to inform future decisions.

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CRediT authorship contribution statement

Pablo Alarcon: Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **Hassaan Bin Aslam:** Writing – review & editing, Writing – original draft, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Barbara Haesler:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Munir Iqbal:** Writing – review & editing, Validation, Supervision, Resources, Funding acquisition, Conceptualization. **Tahir Yaqub:** Writing – review & editing, Supervision, Resources, Project administration, Investigation, Funding acquisition.

Declaration of Competing Interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be constructed as a potential conflict of interest.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.prevetmed.2024.106346.

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