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Clustering broiler farmers based on their behavioural differences towards biosecurity to prevent highly pathogenic avian influenza

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ABSTRACT

Highly pathogenic avian influenza (HPAI) is an important zoonotic disease. The study aims to identify farmer behaviour types to inform the design of behaviour change programmes for mitigating the transmission of HPAI. Therefore, the study utilised multivariate statistical analysis for gaining a better understanding of the relationships among farmers' 30 biosecurity behaviours, the risk of HPAI infection, and distinct features of commercial broiler farmers, which is different from using simple and few binary biosecurity measures. Convenience sampling was used to collect data from 303 Taiwan's farmers among which 40 farmers (13.2%) self-reported having had a HPAI outbreak in the study year while 16 farmers (5.3%) self-reported having had a HPAI outbreak in the past two years. Using categorical principal components analysis and a two-stage cluster analysis, four farmer clusters were identified with distinct features: 1)'Reserved' (4.6%) tended to choose 'No idea' for answering specific questions about HPAI; 2)'Secure' (76.3%) had a higher biosecurity status than the other farms; 3) 'Jeopardised' (16.8%) had a lower biosecurity status than the other farms; 4) 'No-response' (2.3%) tended to skip specific questions about HPAI. The biosecurity status of the 'Reserved' and 'No-response' clusters was undetermined, placing these farms at risk of HPAI infection. Compared to the 'Secure' cluster, the 'Jeopardised' cluster exhibited higher odds of self-reported HPAI in the study year (OR: 2.61, 95% CI: 1.22–5.58) and in the past two years (OR: 4.28, 95% CI: 1.39–13.19). Additionally, the 'Jeopardised' cluster showed increased odds of HPAI recurrence (OR: 4.01, 95% CI: 1.41–11.43). Our study demonstrates that inadequate biosecurity practices can elevate the occurrence or recurrence of HPAI outbreaks. The findings underscore the importance of distinguishing between these clusters to accurately assess the risk of HPAI infection across farms. Furthermore, understanding farmers' behaviours can inform the development of strategies aimed at behaviour change among farmers.

1. Introduction

Biosecurity-related research in farm animals has significantly increased in recent years, focusing on the identification of drivers in relation to on-farm biosecurity practices such as farmers' knowledge, attitudes, and personality [1–4]. However, studies have revealed that the implementation of on-farm biosecurity is usually low and varied [5–9].

On-farm biosecurity includes a variety of farm management practices such as workers wearing appropriate clothing, wash-down routines, and regular hygiene inspections, some of which are daily or repeated practices [10]. Although the concepts of biosecurity have been widely discussed, it is challenging to find consistent definitions of biosecurity [10–13]. The selection of the biosecurity measures to be implemented on a particular farm is usually up to the individual farmer. Given that each farmer has their own priorities, it is difficult to induce

Abbreviations: HPAI, highly pathogenic avian influenza; LDCC, local disease control centre.

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and maintain farmers' biosecurity practices with a 'one size fits all' approach [10,14]. Therefore, it is essential to apply appropriate and specified behavioural change interventions that are tailored to different groups of farmers [15,16].

'One Health' aims to achieve optimal health for people, animals, and the environment [17]. The 'One Health 'approach can play an important role in raising awareness and preventing zoonotic disease outbreaks [8,18]. Within the 'One Health' framework, the health of both commercial broiler chickens and farmers related to zoonotic HPAI can be jeopardised by incorrect human behaviours around those broiler chickens [19–22]. Farmers are the frontline for the prevention of HPAI for the health of chickens and human beings [23]. Using the 'One Health' approach to target behavioural change strategies for different farmers' biosecurity behaviours can not only secure animal health but also public health. Taking Taiwan's broiler farmers as an example, although biosecurity procedures for avian influenza have been established at the farm level over two decades, there have been several highly pathogenic avian influenza (HPAI) outbreaks in Taiwan over the past decade. The adoption rate of on-farm biosecurity measures in Taiwan's commercial broiler farms is usually low and variable [9].

Recent studies have revealed that identifying clusters of different farmer behaviour types can help reduce disease risk [24] and improve the adoption of better farming practices [25,26] by providing policymakers with a better understanding of the diversity of behaviours in the farming community. The current study aims to identify farmer behaviour types that will then allow the development of tailored evidence-based behaviour change programmes and policy recommendations.

2. Materials and methods

This study was the second part of a two-tier research initiative that examined the associations between farmers' biosecurity attitudes and behaviours in Taiwan's commercial broiler farms [27]. In this study, we first used data reduction methods to condense the fairly large number of biosecurity behaviour variables to a smaller number of principal components, which are more concise and uncorrelated with one another. Then, we developed clusters of the farmers based on their behavioural differences in relation to biosecurity. Tailored target strategies were further developed based on the behavioural traits identified within each cluster. In addition, the chi-square test of independence was used to determine whether there is an association between the farmer clusters and the occurrence / the re-occurrence of HPAI.

2.1. The development of a questionnaire survey

Data were collected on chicken farms throughout Taiwan via a survey of commercial broiler farm owners over a four-month period. Convenience sampling had to be used since farmers were reluctant to participate in the study due to HPAI outbreaks in waterfowl during the data collection period. The questionnaire collected background data about farms and farmers, including flock size, batch size, chicken type, individual farmer's age, and farming experience. Current behaviours in relation to on-farm biosecurity measures were also surveyed. In Oriental society, if the respondents are forced to choose an answer, the validity of the information may be seriously affected [28]. As such, in this study, the options of 'Neutral' and 'No idea' were provided to prevent bias when respondents do not want to answer the questions or do not know the answers [29–32].

Potential participants were invited by local disease control centres (LDCCs) and given a detailed explanation of the study's purpose. Participants were assured that participation in the study was entirely voluntary, all data would be anonymous and stored securely, and any participant was free to withdraw from the research at any time without prejudice. The survey was approved by the Ethics and Welfare Committee of the Royal Veterinary College, University of London, the United Kingdom(Approval # URN 2015 0125H).

2.2. Identification of farmer clusters

Categorical principal components analysis (CATPCA) and a two-stage cluster analysis were used to identify target clusters of the farmers who shared similar biosecurity behaviours. CATPCA was used for data dimensionality reduction [32]. Any variable with a mean coordinate of <0.1 [33] was excluded from further analysis. In addition, as recommended by Theunissen et al. [34], adding an extra category for missing values to separate them from other categories was chosen to obtain the most variation of the data [35].

Object scores retrieved from CATPCA were further used to perform a two-stage cluster analysis for the identification of potential clusters. A hierarchical clustering method pre-clustered the objects and identified appropriate sub-cluster numbers in this study [36]. Then, the K-means clustering method was applied to assign objects to their nearest cluster based on the number of clusters determined by the hierarchical clustering method [37]. After objects had been assigned to their specific clusters, the identified clusters were interpreted and accordingly, descriptive names were given to each cluster based on the selected characteristics that were statistically significant in a chi-squared test ($p \leq .05$). Distinct features of each cluster were identified based on farmers' social backgrounds and farms' production types.

2.3. The associations between the farmer clusters and the occurrence / the re-occurrence of HPAI

As this study aimed to examine if the differences in biosecurity behaviours are associated with the occurrence / the re-occurrence of HPAI, the following hypothesis was proposed:

- Null hypothesis (H0): the differences in biosecurity behaviours are not associated with the occurrence / the re-occurrence of HPAI.
- Alternative hypothesis (Ha): the differences in biosecurity behaviours are associated with the occurrence / the re-occurrence of HPAI.

The statistical analyses were based upon two-way contingency tests (Fisher's exact test if expected cell frequencies <5) using the Crosstabs procedures to test the associations between the farmer clusters (representing the differences in biosecurity behaviours) and the occurrence / the re-occurrence of HPAI.

3. Results

Survey data were collected from 303 commercial broiler farm owners who voluntarily participated in the study: 156 white-chicken broiler farmers (51.5%), 144 indigenous chicken farmers (47.5%), and three farmers without the identification of which kind of broiler farms they owned (1%). Although some of the participants in this research were hired workers, they all engaged with their farms' day-to-day practices. The general characteristics of the research participants are shown in Supplementary Information (S.I.; Table S.1). Table 1 provides a list of variables and their abbreviations used in this study.

By using 30 behaviour variables in relation to on-farm biosecurity, four clusters were identified: 'Reserved' (4.6%), 'Secure' (76.3%), 'Jeopardised' (16.8%), and 'No-response' (2.3%). The case number of each object was labelled in Fig. S.1. The designated cluster number of each object was labelled in Fig. 1b. The comparisons of the four clusters with statistically significant differences were presented in Table S.2, and names were chosen for the clusters based on the major differences in their biosecurity behaviours. The 'Secure' cluster had a higher biosecurity status than the other farms while the 'Jeopardised' cluster had a lower one. On the other hand, the 'Reserved' cluster tended to choose 'No idea' while the 'No-response' cluster tended to skip the questions in relation to biosecurity behaviours. The biosecurity status of the 'Reserved' and 'No-response' clusters was undefined.

We directly examined the associations between the farmer clusters

Table 1
The variables and their abbreviations used in this study.

Code	Items	Abbreviations of variables	Category
B1	Disinfectant, gloves, shoe covers or take baths with farm-specific shoes/clothes 'strictly 'used for the cleaning and disinfection of personnel upon arrival	DisinfectedPersonnelEntrance	Yes/No/No idea/Missing
B2	Cleaning and disinfection of vehicles upon arrival at the farm	DisinfectedVehicle	Yes/No/No idea/Missing
B3	A transition zone in the farm	TransitionZone	Yes/No/No idea/Missing
B4	The frequency at which vehicles enter the farm for the shipping of dead animals, feed, manure, and chicks	FrequencyVehicleShippingCarcass	<3 times per week/4–9 times per week/ >10 times per week/No idea/Missing
B5	The frequency at which vehicles enter the farm for the shipping of broilers for sale	FrequencyVehicleShippingBroiler	<3 times per week/4–9 times per week/ >10 times per week/No idea/Missing
B6	Shipping cages and collection buckets always empty upon arrival at the farm	CageEmptyArrival	Always empty/Sometimes empty/Never/ No idea/Missing
B7	Cleaning and disinfection of shipping cages and buckets upon arrival at the farm	CageDisinfectedArrival	Yes/No/No idea/Missing
B8	Cleaning and disinfection of shipping cages and buckets upon before entering animal housing	CageDisinfectedEnter	Yes/No/No idea/Missing
B9	Carcass storage area	CarcassStorage	Yes/No/No idea/Missing
B10	Carcass or litter accessible to animals	CarcassAccessedAnimal	Never/Sometimes/Always/No idea/ Missing
B11	The frequency at which dead chickens will be removed from poultry houses	FrequencyChickDisposal	>3 times per day/2 times per day/I time or <1 time per day/No idea/Missing
B12	Chicks originate from fixed suppliers	ChickFixedSupply	Always/Sometimes /Never/No idea/ Missing
B13	The quality of feed checked by bacteriological analysis	FeedQuality	Always/Sometimes /Never/No idea/ Missing
B14	The quality of chickens' drinking water checked by bacteriological analysis	WaterQuality	Always/Sometimes /Never/No idea/ Missing
B15	Disinfection measures taken for equipment before entering the farm	DisinfectedEquipment	Always/Sometimes /Never/No idea/ Missing
B16	Equipment presents on the farm that is used on at least a different poultry farm	EquipmentShare	Never/Sometimes/Always/No idea/ Missing
B17	Rodents present in the farm	Rodent	Yes/No/No idea/Missing
B18	Anti-bird nets placed for the poultry houses	BirdNetting	Always/Partial facilities or sometimes/ Never/No idea/Missing
B19	Wild birds present in the farm	BirdPresent	Never/Depending on the seasons/ AlwaysNo idea/Missing
B20	Broilers return to the poultry houses after being on transport vehicle for selling	ReturnFromVehicle	Never/Sometimes/Always/No idea/ Missing
B21	'All-in- all-out' management strictly implemented in the farm	AllInAllOut	Yes/No/No idea/Missing
B22	The disinfection of equipment after use strictly conducted	DisinfectedEquipmentAfterUse	Always/Sometimes /Never/No idea/ Missing
B23	The disinfection of equipment strictly conducted while moving between different poultry houses	DisinfectedEquipmentBetweenChickHouse	Always/Sometimes /Never/No idea/ Missing
B24	New needles or disinfect needles while vaccinating chicks between different poultry houses	DisinfectedNeedleBetweenChickHouse	Always/Sometimes /Never/No idea/ Missing
B25	Poultry house completely disinfected after each production round	DisinfectedChickHouseAfterRound	Always/Sometimes /Never/No idea/ Missing
B26	A sanitary transition period after each production round	SanitaryPeriod	Yes/No/No idea/Missing
B27	The frequency of the disinfection of individual poultry house	FrequencyDisinfectedChickHouse	Daily/Weekly or biweekly/Only after each batch out/No idea/Missing
B28	Cleaning and disinfection of poultry houses	DisinfectedChickHouse	Yes/No/No idea/Missing
B29	Diseased animals isolated from healthy ones	DiseasedChickIsolation	Always/Sometimes /Never/No idea/ Missing
B30	Diseased animals always handled after the healthy ones	DiseasedChickAfterHealth	Always/Sometimes /Never/No idea/ Missing

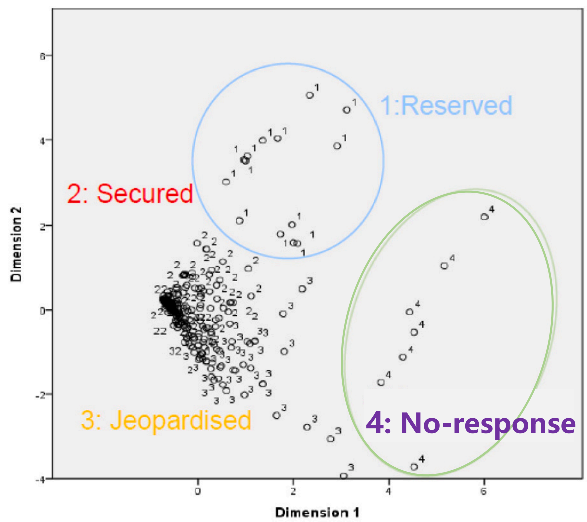
and their farms' disease situation of HPAI. Contingency tables described the associations between the farmer clusters and the occurrence / the re-occurrence of HPAI, and the statistical associations were listed in Table 2 and Table 3. A high proportion of missing values in relation to the questions about the disease situation of HPAI was noticed for the 'Reserved' (71.4%) and 'No-response' clusters (57.1%). The results of two-way contingency tests revealed that, at the 5% significance level, there is an association between the biosecurity level and the occurrence / the re-occurrence of HPAI. As such, we rejected the null hypothesis at the 5% significant level.

To be more specific, as compared to the 'Secure' cluster, the 'Jeopardised' cluster had higher odds of self-reported HPAI in the study year (OR: 2.61, 95% CI: 1.22–5.58) and in the past two years (OR: 4.28, 95% CI: 1.39–13.19). In addition, the 'Jeopardised' cluster had higher odds of HPAI recurrence (OR: 4.01, 95% CI: 1.41–11.43). For the two clusters, their different biosecurity behaviours are demonstrated to be significantly associated with the occurrence / the re-occurrence of HPAI.

We further integrated the 'Jeopardised' and 'Reserved' clusters with the 'No-response' cluster (as the 'Integrated' cluster). Compared to the 'Secure' cluster, the 'Integrated' cluster exhibited higher odds of self-reported HPAI in the study year (OR: 2.1, 95% CI: 1.00–4.42) and in the past 2 years (OR: 3.31, 95% CI: 1.17–9.36). Additionally, the 'Integrated' cluster showed increased odds of HPAI re-occurrence (OR: 3.4, 95% CI: 1.12–10.37). However, all these odds for the 'Integrated' cluster were lower than those observed for the 'Jeopardised' cluster.

Cluster descriptors were then formulated from the distinct features of each cluster using simple descriptions for each profile rather than quantitative information. Table 4 presents the distinct features of each cluster and recommended target strategies for developing evidence-based behaviour change programmes:

- 'Reserved' (4.6%): Indigenous chicken farms with the fewest batches per year and the fewest evaporative cooling chicken houses. A substantial majority of these farms were located in South Taiwan. The



	Frequency	Percentage
1	14	4.6
2	231	76.3
3	51	16.8
4	7	2.3
Total	303	100.0

Fig. 1. Identification of the clusters based on biosecurity behaviours.
By the application of CATPCA and two-stage cluster analysis, the clusters based on the differences in farmers' biosecurity behaviours were identified. Names were chosen for the clusters based on the major differences in their biosecurity behaviours.

Table 2
The associations between the clusters and the occurrence/ re-occurrence of HPAI.

		No		Yes		Missing		
	Category[a]	n	%	n	%	n	%	P[b]
The occurrence of HAPI in the study year	No response	2	28.6	0	0.0	5	71.4	0.0000
	Jeopardised	33	64.7	13	25.5	5	9.8	
	Reserved[c]	6	42.9	0	0.0	8	57.1	
	Secured	179	77.5	27	11.7	25	10.8	
The occurrence of HAPI in the previous two years	No response	2	28.6	0	0.0	5	71.4	0.0000
	Jeopardised	22	43.1	23	45.1	6	11.8	
	Reserved[d]	6	42.9	0	0.0	8	57.1	
	Secured	115	49.8	90	39.0	26	11.2	
Re-occurrence of HPAI in the study year	No response	2	28.6	0	0.0	5	71.4	0.0004
	Jeopardised	31	60.8	6	11.8	14	27.4	
	Reserved[e]	6	42.9	0	0.0	8	57.1	
	Secured	177	76.6	8	3.5	46	19.9	

Null hypothesis (H0): the differences in biosecurity behaviours are not demonstrated to be associated with the occurrence / the re-occurrence of HPAI.
Alternative hypothesis (Ha): the differences in biosecurity behaviours are demonstrated to be associated with the occurrence / the re-occurrence of HPAI.
[a] Reference cluster: 'Secure' cluster.
[b] Computed from Fisher exact test.
[c] OR: 2.61, 95% CI: 1.22–5.58
[d] OR: 4.28, 95% CI: 1.39–13.19.
[e] OR: 4.01, 95% CI: 1.41–11.43.

Table 3
The comparison between the 'Secured' cluster and the other clusters in terms of the occurrence/ re-occurrence of HPAI.

		No		Yes		Missing		
	Category[a]	n	%	n	%	n	%	P[f]
The occurrence of HAPI in the study year	Combined[b,c]	41	56.9	13	18.1	18	25	0.0021
	Secured	179	77.5	27	11.7	25	10.8	
The occurrence of HAPI in the previous two years	Combined[d]	30	41.7	23	31.9	19	26.4	0.0112
	Secured	115	49.8	90	39.0	26	11.2	
Re-occurrence of HPAI in the study year	Combined[e]	39	54.2	6	8.3	27	37.5	0.0010
	Secured	177	76.6	8	3.5	46	19.9	

Null hypothesis (H0): the differences in biosecurity behaviours are not demonstrated to be associated with the occurrence / the re-occurrence of HPAI.
Alternative hypothesis (Ha): the differences in biosecurity behaviours are demonstrated to be associated with the occurrence / the re-occurrence of HPAI.
Statistical at the level of significance ($\alpha <= 0.05$).
[a] Reference cluster: 'Secure' cluster.
[b] Combined cluster = 'Jeopardised' +'No response' + 'Reserved' clusters.
[c] OR: 2.1, 95% CI: 1.00–4.42.
[d] OR: 3.31, 95% CI: 1.17–9.36.
[e] OR: 3.4, 95% CI:1.12–10.37.
[f] Computed from Fisher exact test.

Table 4
Summary of the profiles of the behaviour clusters.

Item	'Reserved' Cluster (4.6%)	'Secure' Cluster (76.3%)	'Jeopardised' Cluster (16.8%)	'No-response' Cluster (2.3%)
Biosecurity behaviours	Undefined biosecurity status (with 'Don't know' responses)	The highest biosecurity status	The lowest biosecurity status	Undefined biosecurity status (with missing responses)
Farms' characteristics[a]				
Chicken type $\boldsymbol{p}$ =**.002**	**A substantial majority with indigenous chicken farms (92.9%)**	A moderate majority with white-chicken broiler farms (56.1%)	A moderate majority with indigenous chicken farms (54.9%)	A moderate majority with white-chicken broiler farms (57.1%)
Batch numbers per year $\boldsymbol{p}$ =**.001**	**A substantial majority with less than four batches (100.0%)**	A moderate majority with more than four batches (48.2%)	A moderate majority with two to four batches (61.3%)	A moderate majority with two to four batches (60.0%)
Farm location $\boldsymbol{p}$ =**.000**	**A substantial majority in South Taiwan (78.6%)**	A moderate majority in South Taiwan (46.8%)	A moderate majority in South Taiwan (58.8%)	**A substantial majority in Central Taiwan (100%)**
Poultry house types $\boldsymbol{p}$ =**.022**	**A substantial minority with evaporative cooling systems (7.2%)**	A moderate majority with evaporative cooling systems (41.2%)	A moderate majority with evaporative cooling systems (35.3%)	A moderate majority with evaporative cooling systems (50%)
Recommended target strategies for developing behaviour change programmes	Continuous communication to understand their situations. While necessary, knowledge delivery and resource supply together with policy instruments and enforcement.	Positive rewards. While necessary, resource supply.	Resource supply together with policy instruments and enforcement activities. Knowledge delivery may be necessary to change the farmers' attitudes before changing their behaviours.	Underlying problems need to be identified before further strategy development. While necessary, knowledge delivery and resource supply together with policy instruments and enforcement.

[a] Statistically significant differences.

respondents, as outliers, tended to choose 'No idea' for answering specific questions such as 'DisinfectedNeedleBetweenChickHouse'. Continuous communication is required to understand their situations. While necessary, knowledge delivery and resource supply together with policy instruments and enforcement can be considered.

- 'Secure' (76.3%): White-chicken broiler farms with more than four batches per year. A moderate majority of the farms were located in South Taiwan. This cluster represented the majority of the respondents. The cluster had a relatively higher biosecurity status. The farmers conducted biosecurity measures at acceptable levels; therefore, positive rewards to acknowledge their behaviours are suggested. While necessary, resource supply can be applied.
- 'Jeopardised' (16.8%): A moderate majority of the farms were located in South Taiwan. They owned indigenous chicken farms and had the most disease outbreaks during the previous year. This cluster represented the second-largest cluster. The biosecurity status of the cluster was relatively lower. Resource supply together with policy instruments and enforcement activities can be used to change the farmers' behaviours.
- 'No-response' (2.3%): A substantial majority in Central Taiwan (100%) were located in central Taiwan. They owned white-chicken broiler farms. The respondents, as outliers, tended to skip specific questions, such as 'CageEmptyArrival'. Since there is missing information (the answer of 'No idea'), underlying problems need to be identified before further strategy development.

4. Discussion

Recent studies have clustered farmers by sets of variables including socio-psychological factors and disease control practices to understand farmers' decision-making processes such as network interactions, risk perceptions, or the adoption of biosecurity practices [3,26]. Given that on-farm biosecurity involves a variety of measures [10], we focused on utilizing 30 biosecurity behaviour variables to distinguish clusters of farmers and subsequently develop evidence-based strategies for preventing HPAI.

In this study, distinct clusters were identified based on how farmers implemented crucial biosecurity measures [38]. To offer comprehensive insights, comparisons were made regarding the social backgrounds of clustered farmers and the production types of clustered farms. Notably, distinctions were observed in these characteristics; for instance, the 'Jeopardised' cluster predominantly comprised farmers producing indigenous chicken breeds, whereas the 'Secure' cluster mainly consisted of large-scale broiler farmers raising white chickens. This finding aligns with existing literature indicating that large-scale chicken farms generally exhibit higher biosecurity standards [39,40].

Our study demonstrates that inadequate biosecurity practices can increase the occurrence or recurrence of HPAI outbreaks. Compared to the 'Secure' cluster, the 'Jeopardised' cluster exhibited higher odds of self-reported HPAI in both the study year and the past two years. The latter also showed higher odds of HPAI recurrence. Reasons that can be explained, with examples: unlike the former, the latter is less likely to disinfect chicken houses at the end of each production cycle, despite evidence showing significant reductions in the risk of introducing avian influenza viruses [41].

On the other hand, 6.9% of the farmers (belonging to the 'Reserved' and 'No-response' clusters) preferred to answer 'No idea' or refused to answer the question regarding their implementation of biosecurity. Since those questions related to the HPAI disease situation are also susceptible to a 'social desirability response' [42–45], it is not surprising that those farmers tended to avoid answering questions regarding the HPAI disease situation. Considering that the risk of HPAI infection on farms in these clusters was undefined, these farms were susceptible to HPAI infection. We consolidated the 'Reserved' and 'No-response' clusters into the 'Integrated' cluster. Compared to the 'Jeopardised' cluster, the 'Integrated' cluster showed lower odds of self-reported HPAI in the current study year and the past two years. Moreover, the 'Integrated' cluster exhibited reduced odds of HPAI recurrence. These findings underscore the importance of considering distinct behavioural characteristics within the 'No-response' and 'Reserved' clusters. Failing to distinguish these clusters may lead to inaccuracies in estimating the risk of HPAI infection across farms associated with the 'No-response', 'Reserved', and 'Jeopardised' clusters.

The findings highlight the importance of targeting strategy for the diversity of behaviours in the farming community. There are examples of using target marketing and social marketing in agricultural production systems [46–48]. Table 5 shows the similarity between social marketing and the advocacy of on-farm biosecurity. Advocating for on-farm biosecurity aims to promote behaviour change among farmers at the farm level to enhance the prevention and control of infectious animal diseases. The effort to improve biosecurity can be viewed as a form of social marketing [49].

A large-scale survey would be beneficial for comprehensively understanding how commercial broiler farmers implement biosecurity measures and exploring correlations between specific biosecurity practices and the occurrence of HPAI. Future research should aim to analyse why different clusters exhibit distinct characteristics related to farmers' social backgrounds and farm production types. Furthermore, active risk communication can be conducted to illustrate the practical application of crucial biosecurity measures on a daily basis [50], ensuring farmers understand their responsibilities in biosecurity.

There is an increasing number of veterinary studies using multivariate statistical analysis (MSAs) for the evaluation of livestock management and biosecurity practices, for example, factor analysis, principal component analysis, and correspondence analysis [51–55]. In this study, CATPCA was chosen for data dimensionality reduction [32] to discover the meaning behind the data [34] since we focused on the benefits that CATPCA does not require the assumptions of linear relationships between variables [56] and the normal distribution for each input variable [57,58].

The limitations of the study are rooted in self-reported measures for the occurrence of HPAI in both the study year and the past two years. The reliability of self-reported HPAI statuses could not be confirmed through laboratory testing due to the large sample size. Given that farmers may be reluctant to accurately report HPAI occurrences, the survey results might underestimate the actual occurrence of HPAI. Additionally, this study did not conduct on-site observations to validate the implementation of biosecurity measures by farmers, potentially introducing errors as participants may have had motives to misreport their practices. However, biases in social desirability responses were likely mitigated by the longstanding relationships between the LDCC officials and the participants.

Overall, this study contributes to differentiating farmers based on their behavioural variations towards biosecurity, generating insights that can inform strategies aimed at changing farmer behaviour. As biosecurity encompasses numerous daily or recurring practices, our findings underscore the significance of including a diverse array of biosecurity-related behavioural variables to enhance the adoption of recommended on-farm disease management measures. Moreover, the study highlights the importance of differentiating between these clusters to accurately assess the risk of HPAI infection across farms. The cluster analysis results serve as empirical evidence, offering an opportunity to implement targeted HPAI interventions effectively.

Table 5
The comparison of social marketing and the advocacy of on-farm biosecurity.

Item	Social marketing	The advocacy of on-farm biosecurity
Type of products	Behaviour change	Biosecurity behaviours at the farm level which may change farmers' current behaviours of farm management
Motivation	For individual good and social good	For individual good and social good (such as the disease-free status of zoonotic disease)
Competition	Audiences' current or preferred behaviour and associated benefits	Farmers' current or preferred behaviours of farm management and associated profits
Drivers	Convince audiences that a particular behaviour is unhealthy/undesirable and to be willing to do something that they may not want to do (elicit voluntary, long-term behaviour changes in target populations)	Convince farmers that a set of on-farm biosecurity measures are beneficial and to be willing to conduct those measures which may change their current practices

Ethics statement

Verbal consent was obtained to reduce each participants' concerns in relation to anonymity with regard to social and cultural norms of Taiwan. The survey procedures were approved by the Royal Veterinary College, University of London, the United Kingdom(Approval # URN 2015 0125H).

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CRediT authorship contribution statement

Hai-ni Pao: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Elizabeth L. Jackson:** Supervision, Writing – review & editing. **Tsang-sung Yang:** Conceptualization, Data curation, Software, Writing – review & editing. **Jyan-syung Tsai:** Conceptualization, Formal analysis, Supervision, Writing – review & editing. **Yi-ting Hwang:** Conceptualization, Formal analysis, Writing – review & editing. **Watson H.T. Sung:** Data curation, Supervision, Writing – review & editing. **Dirk U. Pfeiffer:** Conceptualization, Supervision, Writing – review & editing, Formal analysis.

Declaration of competing interest

The authors declare that the research was conducted in absence of any commercial, financial, or other relationships that might be interpreted as representing a potential conflict of interest.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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