Aquaculture 584 (2024) 740664

Contents lists available at ScienceDirect

Aquaculture

journal homepage: www.elsevier.com/locate/aquaculture

Understanding aquaculture biosecurity to improve catfish disease management in Ogun and Delta states, Nigeria

Laura Khor [a,*], Olusola Ayodele Bodunde [b], Robert Wills [c], Larry Hanson [c], Olanike Kudirat Adeyemo [d], Oluwasanmi Olayinka Aina [d], Selim Adewale Alarape [d], Jérôme Delamare-Deboutteville [a], Vishnumurthy Mohan Chadag [a]

[a] WorldFish, Jalan Batu Maung, Batu Maung, Penang 11960, Malaysia
[b] International Institute of Tropical Agriculture, Oyo Road, Ibadan 200001, Oyo State, Nigeria
[c] Department of Comparative Biomedical Sciences, College of Veterinary Medicine, P.O. Box 6100, Mississippi State University, USA
[d] Fish and Wildlife Disease Laboratory, Department of Veterinary Public Health and Preventive Medicine, University of Ibadan, Nigeria

ARTICLE INFO

Keywords:
Epidemiology
Catfish (*Clarias* spp. & *Heterobranchus* spp.)
tilapia (*Oreochromis niloticus*)
Disease management

ABSTRACT

Nigeria is one of Africa's largest aquaculture producers with catfish and tilapia being dominantly farmed. However, the lack of biosecurity and an unclear aquatic animal health strategy have resulted in substantial disease-related production losses. This study aimed to better understand the existing biosecurity management practices and risk factors that could potentially lead to mortality in catfish production systems using Ogun and Delta States as study sites for a regional model. For this purpose, WorldFish and partners developed a Fish Epidemiology and Health Economics digital survey tool (version 1.13) to collect cross-sectional data from farms within the two states. Consenting farms were recruited from four Local Government Areas (LGAs) (Ijebu-Ode, Ikenne, Odogbolu and Shagamu) in Ogun State and five LGAs (Oshimili South, Udu, Ughelli North, Uvwie and Warri South) in Delta State, from which the data of 220 farms raising table-size catfish were analyzed. Descriptive statistics was used to classify findings by state identity and unusual level of mortality (abnormal losses with higher intensity or quantity) according to production systems, biosecurity measures, management practices, and other potential risk factors. Mixed model logistic regression was used to assess the association between high mortality occurrence and potential risk factors. No significant association between unusual farm mortality and state identity was detected ($p = 0.314$) but those were included as a random effect to account for them as a source of variation. Only 10.45% of farms experienced unusual fish mortality; however, those farms ($n = 23$) had higher baseline mortality ($p = 0.015$) at 15.08%, compared to 6.57% in farms without unusual mortality ($n = 197$). Only 14.55% of farms documented mortality on paper records, while other farms estimated losses from memory. Most farms (96.82%) did not implement biosecurity procedures at stocking. In that aspect, significantly more farms ($p = 0.045$) that introduced fish after main stocking reported unusual mortality (42.86%) compared to those that did not restock afterwards (9.39%). Farms using solely homemade feed had 5.1 and 18.2 times greater odds of unusual mortality compared to farms using only commercial feed and those depending on both commercial feed and other materials respectively ($p = 0.049$). Meanwhile, only 1.36% of farms reported using the services of a veterinarian. Findings from this study indicated plenty of room for biosecurity improvement in earthen pond systems rearing catfish in Ogun and Delta states. Risk factor analysis of industry data can inform the development of local biosecurity management plans and national aquatic health strategy guidelines for sustainable aquaculture.

1. Introduction

Nigeria is one of Africa's largest aquaculture fish producers, attaining an average of 12% growth per annum in the sector (WorldFish, 2018). The country produced 261,621 metric tonnes of farmed fish in 2020, supplying 11% of the total aquaculture production on the continent (Ajayi et al., 2022). Catfish (*Clarias* spp. and *Heterobranchus* spp.) and tilapia (*Oreochromis niloticus*) are the main farmed fish in the

* Corresponding author.
E-mail address: l.khor@cgiar.org (L. Khor).

https://doi.org/10.1016/j.aquaculture.2024.740664
Received 24 August 2023; Received in revised form 27 December 2023; Accepted 7 February 2024
Available online 8 February 2024

country (Adeleke et al., 2021; Kaleem et al., 2021), with catfish being the dominant species due to its resilience to harsh environmental conditions, good price, taste, acceptance by most tribes and ability to remain alive for extended periods during marketing (Anetekhai, 2017). However, the aquaculture industry faces a significant supply-demand discrepancy. The current supply of fish is not enough to meet the per capita of fish consumption of 13.3 kg per annum, with an annual deficit of over 800,000 metric tons sourced through fish importation (WorldFish, 2018).

The gap in local supply and demand can be bridged by increasing aquaculture growth. The industry's potential however, is constrained by multiple factors, among which are high input costs (Abe and Agbugui, 2023; USAID-Nigeria mission, 2012), disease infestation (Dauda et al., 2015) and lack of its control (Subasinghe et al., 2021), quality seed supply (Adewumi and Olaleye, 2011), use of unimproved breeds, feed quality and cost (Abe and Agbugui, 2023), lack of capital, availability of technical expertise, markets and water quality (Dauda et al., 2015). Among those factors, farmers have the most direct control over the health management of their fish. However, little information is available on the cause of fish health problems and their causes in Nigerian aquaculture, although opinions from farmers and experts point toward poor genetic stocks, limited access to quality inputs, problematic water quality and inappropriate health management practices at the farm. There is also poor understanding of existing biosecurity practices, if any, being implemented in local production systems. Although disease losses are widely reported, there is insufficient aquatic animal health management capacity within the veterinary system (Subasinghe et al., 2021) and a lack of an effective aquatic animal health strategy to manage risk factors in aquaculture production, for which a clear understanding of local health challenges is required.

With the lack of awareness on farm biosecurity and contingency planning, the aquaculture industry is challenged by both endemic and exotic (transboundary) diseases at the hatchery and grow-out levels (Subasinghe et al., 2021; Subasinghe and Bondad-Reantaso, 2008). There is a need for management of diseases through the implementation of adequate best management practices (BMPs) formed within the context of Nigerian aquaculture. However, the planning of BMPs requires baseline information on the existing production systems, farm management practices, observations of disease and mortality events from dominant culture systems within the country. In Nigeria, there are currently no known national surveillance programs on fish diseases being carried out on Small and Medium Enterprises (SMEs) and smallholder farms. Hardly any reports of mortalities or requests for professional fish health advice are made by farmers due to the absence of a functional extension network, while aquatic veterinary services are not engaged by most farms.

The objective of the current study was to better understand the existing risk factors that could potentially lead to mortality and production losses in table-size catfish production systems within a regional model using Ogun and Delta States. This model can be used for further refinement and replication with national competent authorities (CAs) and partners for scaling to state and national schemes. Using information gathered from surveyed farms, the study would collect information on the current biosecurity management practices being implemented in farms within both states, which form the hub of Aquaculture activities in the country and with Delta State being one of the USAID-FtF Zones of Influence (ZOI). Fulfilment of the objective would help toward the design of recommended BMPs contextualized for local production systems, by identifying and addressing the biosecurity risks present in those systems; and provide the foundation toward developing a baseline database for data-driven decision-making by policymakers at the national level.

2. Materials and methods

2.1. Study area and farm selection

Farms were selected for the survey based on their willingness to participate after meetings were held with cluster leaders to brief farmers on the purpose and benefits of the study. A total of 399 farms within farm clusters in selected Local Government Areas (LGAs) of Delta and Ogun states were picked for this study. Within Delta state, farms culturing catfish in Oshimili South, Udu, Ughelli North, Uvwie and Warri South of Delta State were selected, while in Ogun state, farms in Ijebu-Ode, Ikenne, Odogbolu and Shagamu were recruited. The geographic distribution of farms surveyed in the study is shown in Fig. 1, which was generated using QGIS (2020).

2.2. Questionnaire design and field team preparation

The questionnaire used for the study was originally developed by WorldFish in collaboration with the Norwegian Veterinary Institute (NVI) (Khor et al., 2021). Prior to deployment, the questionnaire was contextualized to be used for local production systems in Nigeria, covering information on a range of subjects (Table 1). Before the field survey, fourteen data enumerators were trained on how to carry out interviews with farmers, to use the Open Data Kit (ODK) Collect mobile application to collect data offline on mobile tablets while at the farm and to upload farm data to the KoboToolbox platform through internet connection points. ODK Collect and KoboToolbox are both free and open-source tools originally developed by the University of Washington (Brunette and Hartung, 2023) and the Harvard Humanitarian Initiative (https://hhi.harvard.edu/kobotoolbox; Harvard Humanitarian Initiative: KoBoToolbox, 2023) respectively for collection and management of field data.

2.3. Survey implementation

Informed consent was obtained from farmers to be interviewed for a cross-sectional survey on Fish Epidemiology and Health Economics (FEHE). Using the contextualized questionnaire within the Fish Epidemiology and Health Economics (FEHE) survey tool (version 1.13) that was deployed through the ODK Collect mobile application, 399 randomly selected consenting farms within selected LGAs were surveyed from 17th June-16th July 2021. Data were collected for the last completed production cycle of all-in all-out production or the last calendar year of continuous production. Data on baseline mortality was collected for all farms, whereas data on unusual mortality was collected only from respondents who answered 'yes' to the question of whether they encountered unusual mortality (abnormal losses of fish that were out of the ordinary, hence were determined as unusual mortality cases). Upon completion, questionnaire submissions were collated and downloaded through the KoboToolbox online platform and raw data were exported in CSV format.

2.4. Data analysis

Data from the FEHE Survey Tool Nigeria v1.13 was downloaded from KoboToolbox as a XLS spreadsheet, reviewed and prepared for initial analysis. Personally identifiable information in the dataset was anonymized to maintain confidentiality of the respondents. Data on the education level of the respondent were regrouped into three larger categories of none or some primary, secondary (includes junior and senior secondary) and post-secondary (includes vocational training, technical college, and university). Age data were categorized broadly into two major groups of 'older than 40' or '40 or younger'. Data on water source were re-grouped and differentiated based on farms using a single source of ground water only (via bore) versus a group comprising single and combined use of other water bodies, including surface water

Fig. 1. Locations of sites surveyed using the Fish Epidemiology and Health Economics tool (version 1.13) in Ogun and Delta states, Nigeria.

Table 1
Topics in the survey questionnaire.

Subject	Details
Farm respondent information	Gender, age, education level, years of farming, role at the farm, number of male and female workers
Production system information	Type of farm, number of production units, farm size, water spread area, farming intensity, life stage of farmed fish, all-in all-out/continuous farm practice, source of farm water, water exchange rate GPS location
Stocking practices	Type of culture system, type of fish group and species stocked, cost of stocking, stocking size, restocking practices, stocking density, presence of predators/prey, presence of vegetation
Feeding practices	Type of feed, feed source, feed quantity used, feed cost, ingredients, feed conversion ratio (FCR) (if any), feed freshness, feed storage, use of seafood offals
Biosecurity practices	Biosecurity during stocking, biosecurity between production cycles, internal biosecurity, altered biosecurity after outbreaks, fallowing period, sharing of equipment, service providers
Mortalities	Baseline mortality, mortality records, dead fish disposal

(municipal town water), irrigation canals, brackish water, nearby farms, rivers, rain, lakes, and others.

Before analyses, data were re-categorized according to the life stage of the farmed fish to provide more uniformity among the production systems being evaluated. Farms were grouped by life stage as opposed to production size as there was interest to examine the possible epidemiological risk factors with regards to outdoor systems that would have higher frequency of contact with visitors, feed inputs, predators and environmental fluctuations. With a focus on 220 farms raising table-sized catfish only, descriptive statistics were classified by state identity and unusual level of farm mortality using the tabulate procedure in SAS for Windows v9.4 (SAS Institute, Inc., Cary, NC, USA). Variables evaluated included production system, biosecurity, management, and other potential risk factors. For categorical variables that describe a farm characteristic, the number (percentage) of farms that experienced either the presence or absence of unusual farm mortality was determined for each level of the variable. For continuous numerical variables that described a farm characteristic, the mean, standard deviation, minimum, maximum, and number of observations were determined for each level of the variable. Mixed model logistic regression, utilizing the glimmix procedure in SAS for Windows v9.4, was used to assess the association between the occurrence of high mortality and potential risk factors. Local government areas within state and state identity were included as a random effects except in a model with state as the independent variable. Only factors with a p-value of <0.05 were considered statistically significant.

3. Results

Farms were grouped based on respondents' answers to a specific question on whether unusual mortality occurred, which was defined to respondents as any observation of fish loss that is abnormal or increasing in intensity hence worrying the farmer. Farms having unusual fish mortality ($n = 23$) had a higher baseline mortality ($p = 0.015$) compared to farms without unusual fish mortality ($n = 197$), at 15.08% and 6.57% respectively (Table 2). Based on Table 3, 10.45% of overall farms experienced unusual fish mortality, whereby slightly more farms (12.90%) reported unusual mortality in Delta compared to Ogun state (only 8.66% of farms). No significant association between unusual farm

Table 2
Baseline mortalities associated with unusual mortalities at table-sized fish farms within Delta and Ogun states ($N = 220$).

Baseline Mortality Percentage	Unusual Farm Mortality											
	Yes					No						
	N	Mean	StdDev	Min	Max	N	Mean	StdDev	Min	Max	Odds Ratio	p-value
Delta	12	21.06	29.01	1	90	81	4.78	9.65	0	80		
Ogun	11	8.55	5.68	0	20	116	7.83	11.32	0	50		
Overall total	23	15.08	21.83	0	90	197	6.57	10.74	0	80	1.03	0.015

Table 3
Table-sized fish farm baseline mortality observation and management associated with unusual mortality occurrences (N = 220).

Baseline Mortality - Records	Overall Totals					Percent of Total		
	Unusual Farm Mortality							
	Yes		No					
	n	%	n	%	N		Odds Ratio	p-value
Baseline mortality	12	12.90	81	87.10	93	42.27		0.314
Delta							0.44	
Ogun	11	8.66	116	91.34	127	57.73	Referent	
Overall total	23	10.45	197	89.55	220	100.00		
Is this Baseline Mortality Concerning								<0.001
Yes	11	39.29	17	60.71	28	12.73	9.75	
No	12	6.25	180	93.75	192	87.27	Referent	
Type of Mortality Record Kept								<0.001
Paper records	11	34.38	21	65.63	32	14.55	8.63	
None-estimated from memory	12	6.38	176	93.62	188	85.45	Referent	
Frequency of Dead Fish Removal							Did not converge	
Daily/several times per day	7	15.56	38	84.44	45	20.45		
Every 2 to 3 days	.	.	2	100.00	2	0.91		
Monthly	1	20.00	4	80.00	5	2.27		
Never	2	10.00	18	90.00	20	9.09		
Occasionally	10	6.99	133	93.01	143	65.00		
Weekly	3	60.00	2	40.00	5	2.27		
Frequency of Dead Fish Removal-Dichotomous								0.005
Several times per day to weekly	10	19.23	42	80.77	52	23.64	4.33	
Occasionally, Monthly, or Never	13	7.74	155	92.26	168	76.36	Referent	

mortality and state identity was detected ($p = 0.314$).

3.1. Respondent and production system information

The demographics of survey respondents from 220 table-sized catfish farms consisted of 74.09% males and 25.91% females. More than half of those respondents (54.09%) were older than 40 years of age, while the remaining were 40 or younger. At least 61.36% of the respondents have post-secondary education, while 33.64% studied up to secondary level of education. A small number of respondents (5.00%) only received primary education or none at all.

The main cultured species in Delta state was the North African catfish (*Clarias gariepinus*), whereas the dominant species in Ogun state was the hybrid catfish (*Heteroclarias* spp.), with majority of farms (94.09%) practicing monoculture. Majority of farms (84.09%) were perennial (continued to farm fish all year long regardless of season) while 15.91% were seasonal. Of all the surveyed farms, 90.45% were earthen pond systems while the remaining farms (9.55%) mostly consisted of outdoor flow-through tanks, concrete ponds, and a combination of both. The farms were mostly commercial (98.18%) while 1.82% consisted of homestead ponds. A minority of the farms (4.09%) were extensive production systems while the remaining majority practiced semi-intensive production, based on the definition of aquaculture intensity described by Oddsson (2020).

About 78.64% of all the surveyed farms practiced all-in all-out animal batch system. More than half of the farms (58.64%) depended solely on groundwater for their production, while 60.45% exchanged or added water to their production units. Only 14.55% of the surveyed farms shared water bodies; a higher number of farms (18.75%) that shared water bodies reported unusual mortalities, compared to farms that did not share their water source (9.04%), but the difference was not significant ($p = 0.094$). The reported baseline mortalities of Delta and Ogun states were at 6.88% and 7.89% respectively. When farmers were asked if they were concerned about those baseline mortalities, the majority (87.27%) indicated that they were not worried (Table 3). In addition, 85.45% of farms also did not keep any paper records of their fish mortalities. Of that number, only 6.38% were aware of unusual mortality; whereas more farms (34.38%) who kept paper records reported unusual mortality. For those 32 farms which kept paper records, the odds were 8.6 times greater ($p < 0.001$) that they reported unusual mortality ($n = 11$, 34.38%) than those 188 farms that did not keep paper records ($n = 12$, 6.38%).

3.2. Stocking practices

Regarding stocking practices as shown in Table 4, most of the surveyed farms did not introduce additional fish after the main stocking event (96.82%) and did not mix new and existing stock of fish (98.18%). A higher proportion of farms (odds ratio = 3.2, $p = 0.045$) reported unusual mortality (42.86%) among those that introduced fish after main stocking compared to those that did not add new fish after first stocking (9.39%). In terms of biosecurity during the process of stocking the farm, it was found that most farms do not use tyre baths for fry transport vehicles (99.55%) and do not disinfect newly arrived fish (97.73%). Almost all farms (99.55%) do not dispose of transport water away from fish, while 96.82% do not follow any biosecurity measures at stocking.

Table 4
General baseline biosecurity practices and associations with unusual mortality occurrences (N = 220).

Internal Biosecurity	Overall Totals							
	Unusual Farm Mortality							
	Yes		No		N	Percent of Total		
	n	%	n	%			Odds Ratio	p-value
Internal farm biosecurity practices								
Disinfect Vehicle	23	10.45	197	89.55	220	100.00	Did not converge	
No								
Use Footbath	23	10.45	197	89.55	220	100.00	Did not converge	
No								
Disinfects Hands	.	.	3	100.00	3	1.36	Did not converge	
Yes								
No	23	10.60	194	89.40	217	98.64		
Disinfects Equipment	.	.	2	100.00	2	0.91	Did not converge	
Yes								
No	23	10.55	195	89.45	218	99.09		
Fed Seafood Offal	.	.	1	100.00	1	0.45		
Missing								
Yes	2	6.67	28	93.33	30	13.64	0.54	
No	21	11.11	168	88.89	189	85.91	Referent	
AIAO in Last 12 Months	23	11.33	180	88.67	203	92.27		
Yes							Did not converge	
No	.	.	17	100.00	17	7.73		
Does Not Use Internal Biosecurity Practices	23	10.70	192	89.30	215	97.73		
True							Did not converge	
False	.	.	5	100.00	5	2.27		
External farm practices								
Shared Water Body with Other Farms	6	18.75	26	81.25	32	14.55	2.62	0.094
Yes								
No	17	9.04	171	90.96	188	85.45	Referent	
Share Equipment/Staff	2	15.38	11	84.62	13	5.91		0.443
Yes - 1 farm							1.72	
Yes - 2 farms or more	8	16.00	42	84.00	50	22.73	1.85	
No	13	8.28	144	91.72	157	71.36	Referent	
Biosecurity measures during stocking								
Mixing of New and Old Stock	.	.	17	100.00	17	7.73		0.554
Missing								
Yes	1	25.00	3	75.00	4	1.82	2.08	
No	22	11.06	177	88.94	199	90.45	Referent	
Continuous Mixing of New and Old Stock	23	11.33	180	88.67	203	92.27	Did not converge	
Missing								
No	.	.	17	100.00	17	7.73		
Introduction of Fish after Main Stocking	3	42.86	4	57.14	7	3.18		0.045
Yes							5.27	
No	20	9.39	193	90.61	213	96.82		
Use Vehicle Tyre Bath at Stocking	.	.	1	100.00	1	0.45	Did not converge	
Yes								
No	23	10.50	196	89.50	219	99.55		
Fish Disinfection at Stocking	2	40.00	3	60.00	5	2.27		0.133
Yes							4.41	
No	21	9.77	194	90.23	215	97.73	Referent	
Transport Water Disposed Away from Fish at Stocking	.	.	1	100.00	1	0.45	Did not converge	
Yes								
No	23	10.50	196	89.50	219	99.55		
No Biosecurity Followed at Stocking	21	9.86	192	90.14	213	96.82		
True							0.34	0.34
False	2	28.57	5	71.43	7	3.18		
Biosecurity between production cycles								
Drying Ponds between Cycles	5	8.47	54	91.53	59	26.82		0.856
Yes							0.91	
No	18	11.18	143	88.82	161	73.18	Referent	
Liming Ponds between Cycles	14	13.33	91	86.67	105	47.73		0.196
Yes							1.91	
No	9	7.83	106	92.17	115	52.27	Referent	
Cleaning Nets between Cycles	.	.	26	100.00	26	11.82		
Yes							Did not converge	
No	23	11.86	171	88.14	194	88.18		
No Biosecurity between Cycles	5	7.35	63	92.65	68	30.91		0.290
True							0.56	
False	18	11.84	134	88.16	152	69.09	Referent	

(*continued on next page*)

Table 4 (*continued*)

Internal Biosecurity	Overall Totals							
	Unusual Farm Mortality							
	Yes		No		N	Percent of Total		
	n	%	n	%			Odds Ratio	p-value
Fallow Period between Cycles	6	10.34	52	89.66	58	26.36		0.525
1–2 weeks							1.09	
1–7 days	11	9.48	105	90.52	116	52.73	0.81	
3 or more weeks	3	18.75	13	81.25	16	7.27	2.75	
None	3	10.00	27	90.00	30	13.64	Referent	

No observation could be made regarding the supply of each fish species as no information was collected on the fry source. After removal of outliers, the average stocking density among farms across both states that did not report unusual mortality was 206 individuals/m^3, while farms with unusual mortality stocked 372 individuals/m^3 on average; however, a significant association between stocking density and unusual mortality was not detected ($p = 0.356$).

3.3. Feeding practices

With regards to feeding practices, majority of farms (79.09%) used purely commercial feed, whereas 16.82% used a mix of commercial and other feeds. Commercial feeds were mostly sourced from local manufacturers; however, up to 34.55% of farms used feeds sourced from overseas manufacturers, either fully or as part of their total feed combination. Only 3.64% of farms used homemade feed alone. In farms that only used homemade feed ($n = 8$) the odds of unusual mortality were 5.1 times greater compared to farms using only commercial feed ($n = 174$) and 18.2 times greater compared to farms (37) that used commercial feed plus other materials ($p = 0.049$). A small number of farms (13.64% overall) included seafood offal into fish feed, which is a biosecurity concern. In terms of freshness of commercial feed, most farms (71.82%) stored their feed for 2 weeks or less before usage, while another 23.64% kept their feed in storage for 2–4 weeks. A small number (3.18%) stored feed for 1–3 months; only one farm stored feed for longer periods. Many farms did not have information on feed conversion ratio (FCR); only 18.18% of farms declared FCRs that ranged between 1.0 and 3.0 after removal of outliers.

3.4. Biosecurity practices

3.4.1. Internal and interfarm biosecurity

In view of biosecurity within the surveyed farms as shown in Table 4, most did not apply internal biosecurity practices at all (97.73%). None of the surveyed farms carried out vehicle disinfection or used footbaths. Only 1.36% of the farms practiced hand disinfection, while most respondents (99.09%) did not disinfect equipment on a regular basis. In terms of inter-farm practices, the survey findings showed that 28.64% of all farms shared their equipment and staff with other farms; among these, there were a higher proportion of farms that reported unusual mortality (15.38% for farms sharing with 1 farm and 16% for farms that shared with 2 or more farms) compared to those that did not share (8.28% unusual mortality); however, the association between unusual mortality and sharing equipment and staff was not significant ($p = 0.443$).

3.4.2. Altered biosecurity following disease outbreak

In terms of clinical signs of disease observed during abnormal mortality events, 39.13% of farms that reported unusual mortality observed fish swimming at the water surface, while 30.43% of farms reported fish gasping. Fish lethargy and loss of appetite were seen in 26.09% of farms, while another 21.74% of farms reported fish swirling erratically in the water. The reported clinical signs could not be associated with water quality conditions as 96.77% of the farms that experienced unusual mortality did not analyze their water quality, while the remaining 3.23% that measured their water quality was unable to provide the data at the time of the survey. Only 34.78% of farms that observed unusual mortality collected samples from the farm for the purpose of lab diagnostics. Of those farms, only one-fourth were able to determine the cause of mortality as acute contamination and acute environmental shock, while the remaining farms were unable to obtain any confirmation on the cause of mortality.

With regards to measures to prevent animal and plant intrusion into farm systems following an outbreak of disease, Table 5 shows that a total of 86.36% of farms did not install fences to ward off predators and scavengers. Of the 63.64% of farms that reported seeing predators and scavengers at their premises, almost half observed unknown species of birds (48.18%), while frogs (18.64% of farms), water snakes (15.45%), monitor lizards (13.18%) and rodents (10.91%) were also reported. Meanwhile, another 16.36% of farms reported the presence of aquatic weeds in their production system. More farms (13.89%) with aquatic weeds reported unusual mortalities, however no significant association was seen ($p = 0.385$).

Once an outbreak was discovered, only 38.18% of farms removed sick & dead fish, while only 27.73% carried out an emergency harvest. After outbreaks, majority (97.27%) of respondents said their farms did not disinfect equipment or separate their equipment according to production zones. In terms of water management, it was found that 85.91% of farms did not treat their water before discharge, while 94.09% did not stop water inflow and outflow from infected units. Only 11.82% of farms isolated their affected ponds after high mortality or outbreak events, with no restriction on the movement of staff or visitors within most (98.18%) farms. The majority (97.73%) of farms did not cancel their fish sales following an outbreak. In terms of fish disposal methods as indicated in Table 6, more than half of the surveyed farms (61.36%) collected dead fish for discarding; however, another 18.18% of farms discarded the dead fish into the nearest water body, while only 3.64% burnt the dead fish. A smaller number (1.82%) used dead fish as feed for other animals.

As seen in Table 7, majority of farms did not engage veterinarians for the purpose of health management, with only 1.36% of them using their services. A small number of farms (14.55%) used harvester services, while 5.91% and 3.64% of farms depended on feed suppliers and pond excavators respectively. None of the 220 farms mentioned the Department of Fisheries officers as their service provider. Only 1.36% of farms that produced table-sized fish, which were commercial ponds in Delta state and did not declare any unusual mortality, received assistance from NGOs. Meanwhile, the services of university students/staff/researchers were engaged by only 1.82% of farms, which were commercial systems in Ogun state and also had no unusual mortality. The survey findings indicate that only 0.91% of farms used biosecurity measures on arrival or departure of service providers.

3.4.3. Biosecurity between production cycles

From the viewpoint of biosecurity measures in between production cycles shown in Table 4, only 26.82% of farms dried their ponds, while

Table 5
Biosecurity measures in response to disease outbreak and associations with unusual mortalities reported in table-sized fish farms (N = 220).

Biosecurity after Outbreak	Overall Totals					Percent of Total		
	Unusual Farm Mortality							
	Yes		No					
	n	%	n	%	N		Odds Ratio	p-value
Emergency Harvest after Outbreak	3	4.92	58	95.08	61	27.73		0.122
Yes							0.36	
No	20	12.58	139	87.42	159	72.27	Referent	
Isolate Ponds after Outbreak								0.690
Yes	4	15.38	22	84.62	26	11.82	1.29	
No	19	9.79	175	90.21	194	88.18	Referent	
Remove Sick/Dead Fish after Outbreak								0.581
Yes	10	11.90	74	88.10	84	38.18	1.30	
No	13	9.56	123	90.44	136	61.82	Referent	
Treat H2O before Discharge after Outbreak								0.821
Yes	2	6.45	29	93.55	31	14.09	0.83	
No	21	11.11	168	88.89	189	85.91	Referent	
Stop H2O Inflow/Outflow after Outbreak								0.003
Yes	5	38.46	8	61.54	13	5.91	7.72	
No	18	8.70	189	91.30	207	94.09	Referent	
Disinfect Equipment between Ponds after Outbreak							Did not converge	
Yes	.	.	6	100.00	6	2.73		
No	23	10.75	191	89.25	214	97.27		
Install Net/Fence for Predators after Outbreak							Did not converge	
Yes	.	.	30	100.00	30	13.64		
No	23	12.11	167	87.89	190	86.36		
Use Separate Nets/Equipment between Ponds after Outbreak							Did not converge	
Yes	.	.	6	100.00	6	2.73		
No	23	10.75	191	89.25	214	97.27		

Table 6
Dead fish disposal methods and associations with unusual mortality occurrences at table-sized fish farms (N = 220).

Fish disposal method	Overall Totals					Percent of Total		
	Unusual Farm Mortality							
	Yes		No					
	n	%	n	%	N		Odds Ratio	p-value
Dead Fish Burnt on Farm	23	10.45	197	89.55	220	100.00	Did not converge	
No								
Dead Fish Burnt off Farm	1	7.14	13	92.86	14	6.36		0.523
Yes							0.49	
No	22	10.68	184	89.32	206	93.64	Referent	
Dead Fish Burnt	.	.	8	100.00	8	3.64	Did not converge	
Yes								
No	23	10.85	189	89.15	212	96.36		
Dead Fish Collected for Discarding	16	11.85	119	88.15	135	61.36		0.465
Yes							1.43	
No	7	8.24	78	91.76	85	38.64	Referent	
Dead Fish Discarded in Waterbody	3	7.50	37	92.50	40	18.18		0.809
Yes							0.85	
No	20	11.11	160	88.89	180	81.82	Referent	
Dead Fish Sold	.	.	1	100.00	1	0.45	Did not converge	
Yes								
No	23	10.50	196	89.50	219	99.55		
Dead Fish Fed to Animals on Farm	1	25.00	3	75.00	4	1.82		0.299
Yes							3.65	
No	22	10.19	194	89.81	216	98.18	Referent	

close to half of all farms (47.73%) limed their ponds between production cycles. Among the farms that dried their ponds, there were lower reports of unusual mortality (8.47%) compared to those of farms that did not dry their ponds (11.18%), however the difference was not significant ($p = 0.856$). Only 11.82% of total farms cleaned their nets between cycles, while 30.91% of farms did not carry out any biosecurity practices between production cycles. About half of the surveyed farms (52.73%) carried out fallowing for 1–7 days only; another 26.36% had fallow periods of 1–2 weeks, while 7.27% spent 3 or more weeks for fallowing. However, a small minority of farms (13.64%) did not carry out fallowing at all between production cycles.

4. Discussion and recommendations

Here we consider our study findings, observations and lessons and have attempted to draw inferences and recommendations for improving farm level biosecurity for Nigerian catfish industry.

Many of the surveyed farms were located close to river systems to source water for farming. In areas where such water bodies are shared or surrounded by farm clusters, the management of effluents is important

Table 7
Associations between service providers used by table-sized fish farms and unusual mortality occurrences (N = 220).

Farm Service Providers	Overall Totals					Percent of Total	Odds Ratio	p-value
	Unusual Farm Mortality							
	Yes		No					
	n	%	n	%	N			
Harvester	7	21.88	25	78.13	32	14.55		0.024
Yes							3.38	
No	16	8.51	172	91.49	188	85.45	Referent	
Excavator	2	25.00	6	75.00	8	3.64		0.217
Yes							3.03	
No	21	9.91	191	90.09	212	96.36	Referent	
Feed Supplier	2	15.38	11	84.62	13	5.91		0.815
Yes							1.22	
No	21	10.14	186	89.86	207	94.09	Referent	
Veterinarian	.	.	3	100.00	3	1.36	Did not converge	
Yes								
No	23	10.60	194	89.40	217	98.64		
No Service Providers	13	7.56	159	92.44	172	78.18		0.022
True							0.33	
False	10	20.83	38	79.17	48	21.82	Referent	
No Biosecurity for Service Provider on Arrival	13	7.39	163	92.61	176	80.00	Did not converge	
Missing								
True	10	23.81	32	76.19	42	19.09		
False	.	.	2	100.00	2	0.91		
No Biosecurity for Service Provider at Departure	13	7.39	163	92.61	176	80.00	Did not converge	
Missing								
True	10	23.81	32	76.19	42	19.09		
False	.	.	2	100.00	2	0.91		

to prevent the discharged water from contaminating the aquatic environment surrounding the farm and affecting local fish populations. In a study on an effluent-receiving stream near Ijebu-Ode in Ogun state, by (Famoofo and Adeniyi, 2020), it was shown that effluent discharge from a medium-scale fish farm had significant negative impact on the stream's water quality in terms of ammonia, pH and heavy metals ($Fe2+$, $Mn2+$, $Zn2+$ and $Cu2+$), among other parameters.

The lack of record keeping in majority of farms as indicated by the survey findings likely suggests low awareness of the actual number of mortalities. Record keeping among farmers in the agribusiness sector in general has been poor as they have little understanding of its importance (Omotesho et al., 2021), hence the same finding in this study within the perspective of aquaculture farms was not surprising.

The main clinical signs observed by farms that reported unusual mortality were mostly abnormal fish behaviour instead of physical signs, namely swimming and gasping at the water surface, lethargy, loss of appetite and erratic swirling. However, it is important to note that the current findings on clinical signs may be limited due to the structure of the questionnaire that restricted data collection (of clinical signs and sampling) only to farms that declared unusual mortality ($N = 23$). To ensure timely and accurate reporting of outbreaks, farmers should be trained to regularly examine their fish to check for common clinical signs that may indicate economically important diseases affecting the dominant cultured species, which includes the North African catfish (*Clarias gariepinus*) in Delta and the hybrid catfish from *Clarias* x *Heterobranchus* (*Heteroclarias* spp.) in Ogun. Due to the lack of appropriately experienced personnel with specific skills for fish parasitology to cover a large area in this study, we did not attempt any observation on fish parasites from the surveyed farms. Moreover, information on parasitic, bacterial and fungal diseases of North African catfish farmed in pond systems in Nigeria had already been described in a previous study by Nwabueze (2012), whereby several catfish parasites including *Ichthyobodo*, *Trichodina*, *Tricophyra*, *Cryptobia*, *Chilodonella*, *Gyrodactylus*, *Nematode* (*Capillaria*), *Glochidium* and *Piscicola* were observed; In the same study, Flavobacterium (formerly known as Flexibacter) and Saprolegnia were also found in biological samples of catfish. The early detection and targeted treatment of common catfish parasites should however be considered a first important biosecurity step toward preventing more serious secondary bacterial infection(s), which will quickly deteriorate the health of the affected fish. In addition to studies on disease, there should also be focused genetics research on the breeding of those popular species to produce adequate numbers of quality fry for the industry.

For production systems established in more natural settings such as earthen ponds, farms should invest in setting up physical barriers to prevent the entry of the specific groups fish predators and scavengers reported by more than half of all surveyed farms. The investment in predator control infrastructure could both directly and indirectly improve the survival of fish, especially fingerlings which are the preferred prey size (Adelakun et al., 2016).

Some of the findings of this study on the prominent predators are similar to that of (Adelakun et al., 2016) done in Niger state in Nigeria, who also mentioned birds such as kingfishers (*Alcedo* sp.), frog (*Rana* sp.), water snake (*Grayia smithii*), and monitor lizard (*Varanus niloticus*) as fish predators. The same study by (Adelakun et al., 2016) indicated that physical prevention methods such as netting, fencing and security guards were more effective than application of biological and chemical control measures. Since birds of unknown species were the most reported predator group in our findings, affected farms should consider setting up protective barriers to reduce economic losses to birds, as was observed in Kenya where seasonal fish damage by birds amounted to 15% of projected farm production (Otieno, 2019). Field observations of catfish farms in the same study noted that the predator birds of catfish tended to include larger species such as cormorants, herons and egrets; larger birds may consume higher volumes of fish and may also act as mechanical vectors carrying disease when migrating between ponds. Farms that use hapas may consider the installation of protective netting at the surface to prevent loss of fish to bird predation, as demonstrated by Yong-Sulem et al. (2007) from the increased survival of fry by 23% in bird netted hapas. Pond farms could also consider reducing the density of trees and hedge growths around fish ponds where predator birds may rest in between foraging (Otieno, 2019).

In the event of disease outbreaks, farms that reported the presence of frogs should also consider the animals as a biosecurity risk as the animals may reside and breed in natural water bodies where fish are farmed and are able to move considerable distances between ponds. As evidenced by the study carried out by (De Villiers and Measey, 2017) on the overland movement of African clawed frogs, the amphibians were able to migrate up to 150 m away and reached distances of up to 2.4 km on land in <6 weeks from their original position, with peak movement in spring and early summer upon drying of temporary water bodies. To prevent the possible carryover of disease by amphibians from infected ponds and the loss of fish to predatory adult frogs, the setup of fencing around ponds should be adequate to prevent their entry, as read by Yong-Sulem et al. (2007) who reported increased fry survival by 28% after successfully preventing the entry of adult amphibians using fences.

Nwadukwe and Arimoro (2012) also found that their use of fine mesh plastic nylon fencing installed 1.2 m above ground increased the survival of catfish fingerlings by 22.16%, and suggested the use of agricultural lime on the pond bottom and sides during the pond preparation stage to discourage the presence of frogs and snakes that may make their habitat in holes around the pond area.

Although only one tenth of farms reported the presence of rodents, care should be taken to control their population, especially around feed stores, which may be a source of attraction for the animals. Rodents can cause concerning damage within a few weeks, not only impacting the quality of feed stocks in bitten feed bags but also contaminating other feed and inputs through their urine, faeces and carcasses, as observed by Dossou et al. (2020) in their study on the economic impact of rodents in food warehouses in a Benin seaport. Hence, farms that reported the presence of rodents may consider regularly setting up baited traps and proper sealing of opened feed bags in feed storage areas as part of its pest control strategy.

More than half of the surveyed farms depended solely on groundwater to operate, which is considered suitable for maintaining high health animals such as broodstock since groundwater is uncontaminated, free from susceptible animals populations and diseases of concern (Sub-Committee on Aquatic Animal Health, 2016). However, farms that draw groundwater from boreholes located close to rivers may also need to consider flood mitigation measures due to land subsidence (sinking of the ground due to removal of underground material such as water) especially during the rainy season, as well as the cost sustainability of using diesel to operate bore pumps due to frequent power cuts. In order to mitigate the impacts of climate change such as flooding, affected farms may look at short term solutions such as the building of dikes before the start of each production cycle to prevent floodwaters from inundating the farms, and also plan ahead for long term prevention of the problem, including siting of new farms away from flood-prone areas (Onyeneke et al., 2020) and exploring the possibility of using alternative water sources such as dechlorinated municipal water. When considering the use of other water resources at the surface, the supply should first be pumped through a fine filter and held in retention ponds for at least 21 days before use (Dimelu et al., 2018).

Since about half of the farms did not collect dead fish for discarding, with a small number of farms discarding fish directly into the water and a smaller minority carrying out fish disposal through burning, farmers should be made aware of the importance of proper fish disposal methods to avoid the contamination of water bodies that are shared and adjacent to multiple farms. Collection and proper disposal should be carried out quickly before the dead fish are exposed to bacterial deterioration which would subsequently increase the proliferation of bacteria and spread of infection (Agbeja and Obosi, 2015). Furthermore, fish carcasses that are left to decompose in the water also release nitrates (Zhou et al., 2020), ammonium and phosphate (Yu et al., 2021) that significantly deteriorate water quality, and can impact public health through pollution of ambient water bodies with noxious metabolites (Zhou et al., 2021).

Our study found that the majority of farms depended solely on commercial feeds, however no information was collected on whether those were floating or sinking feeds. In general, better feed conversion ratios (FCR) can be obtained in Nigerian catfish culture using extruded floating feeds which also have longer shelf life, however the cost of pelleted sinking feed is more affordable and hence may be more commonly used in catfish grow out ponds (Adewumi and Olaleye, 2011).The study also found that 15% of farmers also use commercial feeds in combination with homemade feeds during a single production cycle, possibly to lower their production expenses (Economic Development Research, 2014) due to the high cost of fish feed in Nigeria (Igoche et al., 2019).

The findings of this study indicated that more than a quarter of the surveyed farms stored feed longer than 2 weeks. One-fifth of farms used either homemade feed or a combination of commercial feed with other local feeds or animal scraps, possibly resulting in varying degrees of feed moisture content that could increase their susceptibility to spoilage. To ensure the freshness of feed and avoid contamination by moulds during storage, commercial feed moisture content should generally be within the range of 8–12% (Adedeji et al., 2020; Goddard, 2012). Commercial dry feeds produced with <10% final moisture content will inhibit bacterial activity and allow for better storage in comparison with moist feeds (Goddard, 2012). Feeds that do not contain antioxidants should be stored in suitable conditions such as low humidity (below 75%) and low temperature to prolong their shelf life up to 3 months after manufacture (Golez, 2002), and used on a first-in first-out basis. Meanwhile, storage areas with appropriate temperatures, such as chillers or freezer should be used to keep homemade feed and their raw ingredients, if not immediately used. Feed should be stored away from high humidity and temperatures to prevent the production of mycotoxins that can adversely impact the quality of feed and subsequently the health of animals and workers handling the feed (Bennett and Klich, 2003). Existing storage conditions of feed may require some improvement, as indicated by a study in East Africa by (Marijani et al., 2017) on a number of fungi isolated from fish feeds and ingredients, including *Aspergillus flavus*, *A. tamarii*, *Mucor* sp., *Phoma* sp., *A. niger*, *Eurotium rubrum* and *Penicillium chrysogenum*. The inclusion and use of seafood offals by more than one tenth of the surveyed farms is also concerning as this practice may lead to disease transmission from raw animal tissue to farm stock as well as the culture water and should also be avoided as far as possible.

Another finding where more than a quarter of the farms shared staff and equipment with other farms, indicates the need for strict internal and intra farm biosecurity practices, where the sharing of equipment across zones should be avoided by allocating adequate number of labelled equipment with storage structures for each production zone, setting up disinfection stations in between production areas of different sensitivity and health status, as well as providing complementary training to all operational staff on farm biosecurity.

As almost all farms do not restrict workers' movement across the farm even after outbreaks as indicated by this survey, farm workers and visitors moving in and out of premises should follow proper disinfection protocols at each entry point with guidance from clear signboards and regular drills. If movement cannot be avoided, only authorized workers should be allowed to move within those zones while following strict sanitary measures.

Most farms also did not isolate their infected ponds or shut down the inflow and outflow of water in their affected premises after outbreak. For controlling the spread of disease within the farm and to other farms sharing similar water sources, it is highly recommended that farms have mechanisms to control the flow of water to and from each production unit and quarantine infected stocks where possible. The continuation of fish sales by most farms even after outbreak occurrence implies that the entry and exit of fish transport and harvesting vehicles may not have been restricted, possibly facilitating pathogen spread between farm areas visited by the same vehicle. Sales of potentially infected stock also increases the possibility of spreading zoonotic pathogens with implications to public health, such as *Edwardsiella tarda* and *Aeromonas hydrophila* that have been isolated from *Clarias gariepinus* (Fowoyo and

Achimugu, 2019; Nantongo, 2019).

Improvements can be made in terms of disease outbreak management, whereby the fish, water and equipment affected by the outbreak should undergo appropriate treatment to stop the spread of disease to other ponds. Common products that may be used for the purpose of non-biological disinfection include quaternary ammonium compounds, formaldehyde, hydrogen peroxide, isopropyl alcohol, glucoprotamine, chlorine, iodine and iodophors (Assefa and Abunna, 2018). Additionally, scheduled training on basic farm biosecurity and preparation of a contingency plan to handle outbreaks will help farmers to prevent the problem from the early stages and respond appropriately to farm emergencies.

The number of table-sized fish farms that engaged services from NGOs and academic institutions were too small to derive any significant observations of improvement in mortality compared to farms that did not receive help from these organizations. Since most farms do not work with professional fish health specialists, there is a need for those farms to engage the services of resident veterinarians for proper detection and control of mortalities due to diseases in their production systems. Some of the challenges faced by catfish farmers as mentioned by (Onuche et al., 2020), including the lack of access to extension services, the need for government support as well as poor expertise (Ume et al., 2016), can be overcome through the use of networks serviced by local research institutions focusing on aquatic animal disease and existing licensed veterinarians, by providing them with the exposure and gradually acquired skills to work with farmed aquatic animals in proximity with farmers. An example of this would be the recently established eAquaHealth network (https://ohrg-unibadan.org/aquahealth/) in Delta and Ogun states of Nigeria (https://thefishsite.com/articles/improving-farmed-fish-health-in-nigeria) (The Fish Site, 2022). The existence of such a network can be used to create awareness of the available extension network closest to the farm vicinity, help local farmers to obtain the extension services of skilled aquatic veterinary professionals, (Feed the Future Innovation Lab for Fish (2023), and subsequently build a foundation for diagnostic support for fish disease at the national level. The establishment of a network between aquaculture farmers and diagnostic service providers will also contribute toward the development of diagnostic services and help the industry to determine the types of aquatic animal health products that are beneficial for local production systems, which may include autogenous vaccines, biologicals, probiotics, and appropriate therapeutics (Montgomery et al., 2022) that will help farmers to reduce mortalities and improve farm production.

Many of the surveyed farms were part of a larger farm cluster or village. Achoja (2019) found in their study conducted within Delta state that aquaculture business clusters were able to generate significant and positive economic effects and earned more income than farmers operating in isolation. Therefore in the interest of cost efficiency and sustainability, the surveyed farms could consider working together as a cluster to use their cooperative position and potential to negotiate better prices with quality feed and fry producers through aggregated purchase and sharing of transportation costs, provision of additional credit by input suppliers, production of cooperative feed, access to cooperative loans through channels such as the Anchor Borrowers' Programme (ABP), entry to better markets through pooled produce (Subasinghe et al., 2021) and provision of investment opportunities (Montgomery et al., 2022). Cluster farmers may also cooperate to take up farm insurance to indemnify their farms against climate change risks such as flooding; as it was found in a study by (Onyeneke et al., 2020), only 5% of farmers in the Niger Delta region adopted insurance as a climate change adaptation strategy. All the mentioned possibilities should be taken into consideration by cluster farms in order to overcome marketing challenges and inadequate credit access faced by Nigerian catfish farmers (Ume et al., 2016). Careful planning can also be done at the cluster level to schedule simultaneous stocking, fallowing and pond drying across all farms to break the life cycle of pathogens within each farm and within a shared water body where farms may discharge water containing pathogens.

The findings of this study were used to develop a set of suggested best management practices (BMPs) and draft action plan and outline for the national aquatic animal health strategy (NAAHS), which were shared with stakeholders through focused group discussions (FGDs) comprising the fish farming industry, veterinary service providers, government agencies and academic institutions. Communications and feedback with farmers who participated in the survey were maintained through a local farmer-veterinary network initiative (established as the e-AquaHealth Web Platform (The Fish Site, 2022)) to enable farmer consultations with resident veterinarians and to provide continuing education resources for aquatic veterinarians (Feed the Future Innovation Lab for Fish, 2023). The stages of survey data collection, compilation and application to the industry are shown in Fig. 2.

5. Conclusion

Future research should focus on the management of the main cultured species at Delta and Ogun states, which are the North African catfish (*C. gariepinus*) and hybrid catfish (Heteroclarias spp.) respectively. Thorough evaluation of farm biosecurity should be prioritized before moving on to future breeding of commercially important species, so as to minimize the risk of spreading disease not only within the facility but also to other farming sites that may receive the disseminated brood and seed (Basiita et al., 2022). Based on the results of the FEHE survey, it was shown that most of the surveyed farms in Delta and Ogun states did not practice basic internal and interfarm biosecurity, and had no methods to record farm mortalities, possibly creating low awareness of actual farm losses due to the current management practices. Majority of farms also did not practice proper biosecurity procedures in the event of an outbreak, highlighting the need to provide training to farmers on how to handle disease and high mortalities. It was revealed that most farms have not engaged the services of veterinarians, and so may not be aware of diseases present in their production systems due to the identified risks. Frequent reporting and sampling for diagnostic purposes will help to contribute to Nigeria's baseline database of endemic diseases or economic importance.

Since most farms were part of a cluster and were located close together around a natural water resource, a biosecurity plan is needed at the individual farm and cluster level for effective control of disease spread and sustainability of the industry. The findings of this study show that the biosecurity status of fish farms can be identified and improved using surveillance and risk factor analysis to better understand Nigeria's aquaculture industry. Those findings can be used to inform the development of interventions in the form of better management practices (BMPs) for farms and farm clusters, as well as guidelines for national aquatic health strategies (NAAHs) for the improvement of catfish farming systems in Nigeria. Using information from each state or farm cluster, contextualized cluster-level biosecurity practices can be planned for better impact on farms around the same vicinity/water source and aim to achieve similar goals in better fish health management, lower mortalities, cost efficiency, supplier cooperation, food security and consumer confidence.

Author statement

Prior to each interview carried out in the cross-sectional survey on Fish Epidemiology and Health Economics (FEHE), informed consent was obtained from farmers by reading the consent form to each respondent, after which the interview would only proceed with the agreement of the respondent. Data collected from survey participants were kept confidential and private information anonymized where necessary. No experimentation with human subjects was carried out in this survey.

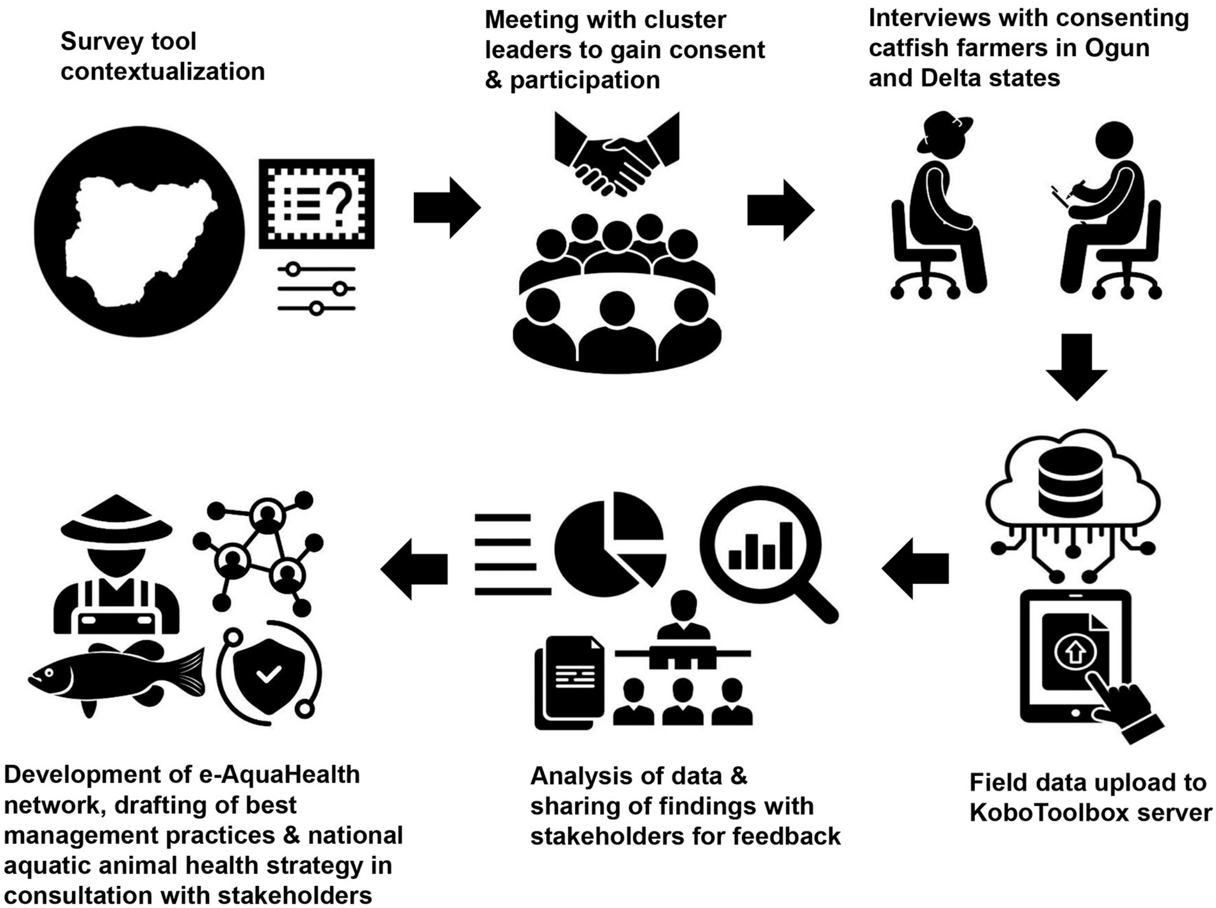

Fig. 2. Stages of survey tool contextualization, data collection and stakeholder consultation for development of best management practices and action plan for the national aquatic animal health strategy in Nigeria.

Dataset

Khor, L., Delamare-Deboutteville, J., Mohan, C·V, Adeyemo, O., Alarape, S., Oluwasanmi, A., Hanson, L., & Wills, R., 2022, "Dataset of fish epidemiology and health economics in Ogun and Delta States", Harvard Dataverse, V2, 2023, https://doi.org/10.7910/DVN/RGG7OW.

CRediT authorship contribution statement

Laura Khor: Data curation, Software, Writing – original draft, Writing – review & editing. **Olusola Ayodele Bodunde:** Methodology. **Robert Wills:** Formal analysis, Software, Writing – review & editing, Methodology. **Larry Hanson:** Funding acquisition, Project administration, Validation, Writing – review & editing. **Olanike Kudirat Adeyemo:** Funding acquisition, Methodology, Project administration, Resources, Supervision, Writing – review & editing. **Oluwasanmi Olayinka Aina:** Methodology, Project administration. **Selim Adewale Alarape:** Methodology, Project administration. **Jérôme Delamare-Deboutteville:** Conceptualization, Investigation, Methodology, Project administration, Supervision, Writing – review & editing. **Vishnumurthy Mohan Chadag:** Conceptualization, Funding acquisition, Investigation, Project administration, Supervision, Writing – review & editing.

Declaration of competing interest

The authors of this paper have no identifiable financial conflicts of interests or personal relationships that might have a bearing on the research and findings presented in this paper.

Data availability

The link to the study data has been shared in the manuscript under the 'Dataset' section.

Acknowledgements

The study and the preparation of this article were mainly funded under a three-year project 'Improving Biosecurity: A Science-based Approach to Manage Fish Disease Risks and Increase the Socio-economic Contribution of the Nigerian Catfish and Tilapia Industries' by the USAID Feed the Future Innovation Lab for Fish (FIL) under Cooperative Agreement 7200AA18CA0030, with partial sponsorship from the Resilient Aquatic Food Systems (RAqFS) and the One Health initiatives under OneCGIAR. The survey tool used in the current study was originally developed in a previous version with funding from the Norwegian Agency for Development Cooperation (Norad) project: "Increased Sustainability in the Aquaculture Sector in sub-Saharan Africa, through Improved Aquatic Animal Health Management" and further contextualized before application in the current study. Coding for survey tool preparation and contextualization was supported by Saadiah Ghazali from WorldFish. The project was led by the WorldFish headquarters in Malaysia, together with its implementing partners Mississippi State University (MSU) and University of Ibadan (UI) in close collaboration with fish farmers and farm cluster leaders in Ogun and Delta states.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.aquaculture.2024.740664.

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