ORIGINAL RESEARCH

Biosecurity protocols and fish health management in Kenyan fish hatcheries: a key to sustainable production of quality fish seed

Fredrick Juma Syanya[1, 3, *], Harikrishnan Mahadevan[1], A. R. Nikhila Khanna[1], Wilson Munala Mathia[2], Paul Mumina[3], Joel Anyula Litabas[2] and Caleb Sifuna[4]

[1]School of Industrial Fisheries, Cochin University of Science and Technology, India. [2]Government of Kenya Ministry of Mining Blue Economy and Maritime Affairs, Vihiga County Government, Kenya. [3]Government of Kenya Ministry of Mining Blue Economy and Maritime Affairs, Kenya Fisheries Service, Kenya. [4]Department of Land Use Management, Masinde Muliro University of Science and Technology, Kenya. mahadevhari@cusat.ac.in (HM); nikhilakhanna.nk@gmail.com (ARNK); willymunala@yahoo.com (WMM); palmumiki@yahoo.com (PM); liatbasanyla@yahoo.com (JAL); calebsifuna022@gmail.com (CS). ORCID *Fredrick Juma Syanya* https://orcid.org/0000-0001-8728-8614, *Harikrishnan Mahadevan* https://orcid.org/0000-0003-1766-8560, *A. R. Nikhila Khanna* https://orcid.org/0009-0006-9433-4643, *Wilson Munala Mathia* https://orcid.org/0000-0002-3986-6384, *Paul Mumina* https://orcid.org/0009-0002-7024-7191, *Joel Anyula Litabas* https://orcid.org/0009-0007-5633-0577, *Caleb Sifuna* https://orcid.org/0009-0008-4226-1723

ABSTRACT. Aquaculture, or aquafarming, is increasingly becoming a vital farming activity globally to meet exponentially high demand for fish and reduce pressure on global capture fisheries. In Kenya, aquaculture growth has led to concerns over the supply of quality fish seed, with farmers often reporting involving fingerling adulteration and mislabelling where frog tadpoles are packed and supplied as *Clarias gariepinus* fingerlings and mixed-sex *Oreochromis niloticus* fingerlings are falsely sold to fish farmers as sex-reversed monosex Nile tilapia. This study aims to identify strategies to enhance the quality of fish seed production in the country. Primary data were collected via questionnaires and interviews using the Kobo toolbox. Respondents were selected through purposive and random sampling. The SPSS software was used for the analysis. Findings showed moderate reliance on specific reporting offices for fish disease cases and significant variation in disease types and bio security measures. Fish disease treatment and management practices were more engaged by hatchery operators than disease reporting. No significant differences were found between disease treatment and management, type of fish diseases encountered at the hatchery, and the nature of fingerlings produced ($p > 0.05$). However, there was a significant difference between the source of broodstock, biosecurity measures, type of fish diseases encountered, and the Disease Case Reporting Office ($p < 0.05$). No significant difference was found between biosecurity measures and the period when the hatchery was established ($p > 0.05$). Lack of financial support, inexperienced workforce, and a lack of knowledge in fish disease identification and treatment were the major problems affecting the sustainability of hatchery operations in the country. Aquaculture policymakers should establish financial support for hatcheries, implement disease management training, promote research collaborations for disease surveillance, and incentivize biosecurity measures among hatchery managers and farmers to improve aquaculture sustainability in Kenya. Further research should explore treatment methods and long-term sustainability to mitigate disease risks.

Key words: Fish health, biosecurity measures, fish hatchery operations, fish disease management, aquaculture health practices.

Marine and Fishery Sciences MAFIS

OPEN ACCESS

*Correspondence:
juma.syanya@cusat.ac.in

Received: 30 May 2024
Accepted: 28 June 2024

ISSN 2683-7595 (print)
ISSN 2683-7951 (online)

https://ojs.inidep.edu.ar

Journal of the Instituto Nacional de Investigación y Desarrollo Pesquero (INIDEP)

Protocolos de bioseguridad y gestión de la salud de los peces en los criaderos de Kenia: una clave para la producción sostenible de semillas de peces de calidad

RESUMEN. La acuicultura se está convirtiendo cada vez más en una actividad agrícola vital a nivel mundial para satisfacer la demanda exponencialmente alta de pescado y reducir la presión sobre la pesca de captura mundial. En Kenia, el crecimiento de la acuicultura ha generado preocupaciones por el suministro de semillas de peces de calidad, y los agricultores a menudo informan de casos relacionados con la adulteración de alevines y el etiquetado incorrecto en los que renacuajos de rana se empaquetan y suministran como alevines de *Clarias gariepinus*, y alevines de *Oreochromis niloticus* de sexos mezclados se venden falsamente a los piscicultores como tilapia del Nilo monosexo de sexo invertido. Este estudio tiene como objetivo identificar estrategias para mejorar la producción de semilla de peces de calidad en el país. Los datos primarios se recopilaron mediante cuestionarios y entrevistas utilizando la caja de herramientas de Kobo. Los encuestados se seleccionaron mediante muestreo intencional y aleatorio. El análisis utilizó el software SPSS. Los hallazgos mostraron una dependencia moderada de oficinas de notificación específicas para casos de enfermedades de peces y una variación significativa en los tipos de enfermedades y medidas de bioseguridad. Los operadores de los criaderos participaron más en las prácticas de tratamiento y gestión de enfermedades de los peces que en la notificación de enfermedades. No se encontraron diferencias significativas entre el tratamiento y el manejo de enfermedades, el tipo de enfermedades encontradas en los peces de criadero y la naturaleza de los alevines producidos ($p > 0,05$). Sin embargo, hubo una diferencia significativa entre la fuente de reproductores, las medidas de bioseguridad, el tipo de enfermedades encontradas en los peces y la Oficina de Notificación de Casos de Enfermedades ($p < 0,05$). No se encontraron diferencias significativas entre las medidas de bioseguridad y el período en que se estableció el criadero ($p > 0,05$). La falta de apoyo financiero, una fuerza laboral sin experiencia y la falta de conocimiento en la identificación y tratamiento de enfermedades de peces fueron los principales problemas que afectaron la sostenibilidad de las operaciones de los criaderos en el país. Los formuladores de políticas de acuicultura deben establecer apoyo financiero para los criaderos, implementar capacitación sobre manejo de enfermedades, promover colaboraciones de investigación para la vigilancia de enfermedades e incentivar medidas de bioseguridad entre los administradores de los criaderos y los piscicultores para mejorar la sostenibilidad de la acuicultura en Kenia. Se deberían realizar más investigaciones para explorar métodos de tratamiento y sostenibilidad a largo plazo para mitigar los riesgos de enfermedades.

Palabras clave: Salud piscícola, medidas de bioseguridad, operaciones de criaderos de peces, manejo de enfermedades de peces, prácticas de salud en acuicultura.

INTRODUCTION

Aquaculture, commonly known as aquafarming, has become a crucial solution to meet the rising global demand for food and fishery products, as well as to alleviate the pressure on capture fisheries. Notably, 3.3 billion people receive their micronutrients from aquatic organisms, either harvested or cultured within aquatic ecosystems. Nearly 600 million people worldwide depend on fish and aquaculture for their livelihoods, making the quest for high-quality fish seeds and breeds critically important (WorldFish 2024). However, this demand has often compromised the quality of fish seeds produced in many hatcheries globally. Breeding fish that grow faster and are more resilient to diseases can significantly mitigate the risks associated with securing food and nutrition as well as maintaining livelihoods. Similarly, Arumugam (2023) and Munguti et al. (2024) pointed out that the demand for fish seeds for both ornamental fishes and aquaculture has equally increased exponentially with the rise in aquaculture production and market demand for ornamental fishes. Kenya ranks fourth in aquaculture production in Africa and is among developing countries with a steady increase in aquaculture development, driven by a growing population and declining capture fisheries in major lakes such as Lake Victoria (Research and Markets 2023; Munguti et al. 2024; Syanya et al. 2024b). With the widespread increase in aquaculture activities in the country, uncertainty among fish farmers regarding the supply of quality fish seeds has been a significant challenge for most fish farmers in Kenya. According to Abwao et al. (2023) and Munguti et al. (2014), high-quality fish seed production and healthy broodstock are the foundations of a successful aquaculture industry in Kenya, ensuring the availability of healthy and disease-resistant fish for sustainable fish farming. Similarly, Otieno (2019) and Genschick et al. (2021) reported that achieving optimal fish seed quality involves a delicate interplay between effective hatchery management practices and robust biosecurity protocols. Biosecurity and safety in the hatchery are crucial for the production of healthy fingerlings. According to Uppanunchai et al. (2015) and Chaudhary et al. (2021), good fish hatchery management practices are a multifaceted process consisting of various aspects such as water quality management, fish feed nutrition, proper broodstock management, the adoption of advanced breeding programs, and disease prevention as witnessed among fish hatcheries in India. Similarly, Miller and Atanda (2011) observed that the efficiency of hatchery management significantly influences the growth, survival, and overall health of fish seeds in Nigeria. Therefore, poor-quality fish seed can hamper the growth of the aquaculture sector.

Efficient hatchery management significantly influences the growth, survival, and overall health of fish seeds (Kumar et al. 2022; Robledo et al. 2024). Suboptimal practices can lead to poor-quality fish seed, hampering aquaculture growth. Therefore, understanding and improving hatchery management techniques is crucial. Opiyo et al. (2018) and Syanya and Mathia (2023) also stated that biosecurity protocols are essential for safeguarding farmed fish against disease outbreaks and promote sustainability. Disease outbreaks, especially nutritional fish diseases, can cause massive economic losses and ecological imbalances, but the question of whether nutritional fish diseases are a health problem for consumers is still something for debate (Hossain et al. 2018; Syanya et al. 2023a). Effective biosecurity measures, including quarantine procedures and pathogen detection, can mitigate these risks (Assefa and Abunna 2018). Climate change also affects hatcheries causing economic losses due to diseases and environmental factors (Mohanty et al. 2017). Despite advancements, Kenyan aquaculture faces challenges such as a lack of awareness about modern fish breeding technologies and shortages of certified quality fingerlings and fish feed suppliers. Aquaculture in Kenya has been considered a hidden goldmine for the rural poor (Syanya et al. 2024a), as most fish farmers are based in rural areas and rely on fish farming for their nutritional needs as well as economic breakthroughs with smaller ponds being preferred over larger ones in terms of variable costs.

Although the Kenya Fisheries Service (KFS) and county governments monitor hatchery activities in Kenya, limited actions have been taken to improve the quality fingerlings. Farmers frequently report fingerling product adulteration where amphibian tadpoles are packed and supplied as African catfish (*Clarias gariepinus*) fingerlings, under-packaging of fingerlings, and the supply of mixed-sex Nile tilapia (*Oreochromis niloticus*) fingerlings falsely sold as mono sex. These issues persist due to inadequate inspection, certification and regulation by the KFS. Although hatcheries produce large quantities of fingerlings, quality concerns remain a big issue among fish farmers.

Nutritional and other fish diseases have also been reported among the broodstock supplied to fish farmers with complaints of twisted bodies, spinal deformities, stunted growth and susceptibility to illness, indicating early infection (Hossain et al. 2018; Roh et al. 2020; Syanya et al. 2023a). Similar problems were reported in Indian fish hatcheries (Jayasankar 2018; Singh 2021), highlighting the need for research on fish health management and hatchery biosecurity not only in the Kenyan aquaculture sector but from a global perspective.

Most hatchery operators in Kenya are unfamiliar with the health and disease issues affecting their operations, a problem also observed among fish farmers in Uganda and Egypt (Mehrim and Refaey 2023; Mutyaba et al. 2024). The absence of a fish health certification system and diagnostic laboratories prevents the verification of disease-free broodstock and fingerlings. Establishing clear fish health and biosecurity measures is crucial to prevent disease transmission within and between facilities (Pathak et al. 2000; Li et al. 2009; Arumugam et al. 2023). Understanding aquaculture systems and disease transmission concepts is key to creating effective hatchery biosecurity. Even though in biosecurity fish hatcheries still lags behind the poultry sector, integrated poultry-fish farming in particular has successfully implemented biosecurity measures (Brummett and Williams 2000; Ahmed et al. 2019).

Although many fish hatcheries exist in Kenya, some fish farmers still purchase fingerlings from neighboring farmers after their harvest. These locally sourced and unauthenticated hatchery fingerlings are often stunted and unsuitable, especially for Nile tilapia fingerlings in terms of their growth performance (Kaliba et al. 2007; Opiyo et al. 2021).

Fish farmers prioritize quick growth and high survival rates as indicators of good-quality fish seeds. The increasing number of hatcheries necessitates proper broodstock management and quality control for high-quality fingerling production (Dewanggani et al. 2021; Otoh et al. 2024). Concerns about the quality and safety of the final fish product depend on hatchery practices (Rahman et al. 2021; Arumugam et al. 2023; Jiang et al. 2023; Syanya et al. 2023b). Inadequate practices and lack of biosecurity at the hatcheries cause seed quality issues, leading to poor quality fish produced through aquaculture species degradation. Despite the increasing demand for fingerlings due to the expansion of cage fish farming along Lake Victoria (Njiru et al. 2019; Syanya et al. 2023c), fingerling producers have not yet focused much on the best biosecurity and hatchery management practices in the country.

In Kenya, there exists a disparity gap between fish farmers and hatchery managers because the majority of fish farmers are semi-literate and struggle to identify hatcheries with required good management practices and biosecurity. This study aimed to address this gap and highlighted challenges to ensure high-quality fingerling production for local farmers and promoting sustainability in aquaculture, by examining years of hatchery operation and biosecurity measures, broodstock source and disease occurrence, fingerling characteristics, and the relationship between fish diseases encountered and fingerling characteristics.

MATERIALS AND METHODS

The research employed a descriptive approach across 24 counties in Kenya, targeting operational fish hatcheries supplying fingerlings to local farmers. Primary data were collected via questionnaires and interviews administered by fisheries officers through the Kobo data collection tool. The study focused on 96 authenticated hatcheries listed on the Kenya Fisheries Service website, with 60 hatchery owners/managers randomly selected. The questionnaire covered hatchery background, broodstock, management practices, disease issues, biosecurity, and health management. Pre-testing at Mwitoko Fish Hatchery ensured questionnaire validity, with adjustments based on feedback. A simple random sampling technique ensured a representative sample, providing insights into hatchery biosecurity practices across the 24 counties. To ensure transferability, purposive and random sampling techniques were employed. Credibility was enhanced through rigorous training of interviewers and clear questionnaire design. Validity was addressed by using established scales and validated questions. Data management involved secure storage on Kobo servers with regular backups, ensuring confidentiality and integrity. Limitations encountered during the study included potential respondent bias, logistical challenges in reaching remote areas, and variability in data quality due to different interviewer skill levels.

Data were analysed using Pearson correlation to assess the relationship between hatchery management status and biosecurity measures. The SPSS v.24 software was used for this analysis. The variability of different biosecurity parameters was determined at a significance level of $p < 0.05$. This approach identified significant associations between variables, emphasizing the effectiveness of adopted hatchery management practices and biosecurity measures. Findings were presented as mean ± SD of the biosecurity variables under comparison.

RESULTS

Nexus between hatchery operations and robust biosecurity measures in fish seed production

Results revealed that 38.3% of hatchery respondents prioritized biosecurity through practices like record keeping and limiting visitors, indicating awareness of the impact of external factors. Additionally, 16.7% focused on cleaning and maintaining hatchery hygiene, recognizing the importance of a clean environment in preventing the spread of pathogens and fish diseases through regular cleaning of tanks and equipment. Respondents prioritizing biosecurity by ensuring disease-free broodstock and promptly removing dead fry in order to prevent disease transmission along the fish seed production line reached 13.3%, while 11.7% used physical barriers like foot baths and protective clothing to mitigate the risks of external contaminants. A smaller group (10.0%) employed advanced biosecurity measures such as quarantine, vaccination, and disease monitoring, while another 10.0% focused on disinfecting equipment and managing water quality, highlighting the importance of maintaining a biosecure environment for sustainable aquaculture.

Regarding years of hatchery establishment, findings indicated that 45.0% of respondents established their hatcheries before 2016. Additionally, 33.3% of hatcheries were established between 2017 and 2019, reflecting a surge in aquaculture activities in Kenya during this period, potentially benefiting from modern infrastructure and support from the county government and the Department of Fisheries. The remaining 21.7% of hatcheries were established between 2020 and 2022, suggesting ongoing interest and investment in aquaculture.

Regarding the species of fingerlings produced at hatcheries across Kenya, findings showed that over half (53.3%) of respondents produced tilapia fingerlings. Similarly, 28.3% of respondents produced African catfish fingerlings, a widely farmed species known for their hardiness and consumer preference. Additionally, 10.0% of respondents were engaged in trout (*Oncorhynchus mykiss*) fingerlings production, a species typically farmed in colder water environments along the central regions of Mount Kenya. Furthermore, 8.3% of respondents produced common carp (*Cyprinus carpio*) fingerlings, a traditional species valued for its resilience. The diversity in fingerling production reflected various species cultured in Kenya, adapted to market demands, environmental conditions, and farmer preferences.

Surveillance and management of fish diseases in hatcheries as a biosecurity approach

Fish disease surveillance and management were critical aspects of biosecurity in fish farms and seed production centres. The highest percentage of respondents (38.3%) reported fish disease cases to their County Government Fisheries Office, 36.7% reported fish disease cases to Kenya Fisheries Service offices, and 18.3% reported to the Kenya Marine Fisheries Research Institute (KMFRI) offices. However, only 3.3% reported disease cases to local NGOs and an equal percentage (3.3%) did not report diseases at all, raising concerns about underreporting and the need for a more comprehensive disease-reporting system and awareness campaign among the hatcheries managers in the country.

Findings also highlighted the association between types of fish diseases encountered at hatcheries and corresponding treatment methods (Table 1). Fungal diseases were the second most commonly reported in most hatcheries after bacteria. No respondents used chloramphenicol, lime, or permanganate together for disease treatment for fungal diseases treatment. However, four respondents used lime and permanganate. The most common treatment was sanitizing the environment and using well-formulated feeds as reported by eight respondents. Multipurpose antibiotics oxytetracycline and erythromycin were also used particularly when clinical signs were contradictory but suspected to be fungal or bacterial infections, as per the opin-

Table 1. Fish diseases and disease treatment and management method.

Nature of disease	Disease treatment and management method: Chloramphenicol	Lime and permanganate	Sanitising the environment and using well-formulated feeds	Multipurpose antibiotic oxytetracycline and erythromycin	Total respondents
Fungal diseases	0	4	8	7	19
Nutritional disorders	3	2	11	0	16
Viral diseases	1	3	0	0	4
Bacterial diseases	3	8	3	7	21
Total responses	7	17	22	14	60

ion of the seven respondents. Nutritional disorders were the third most common infection (Table 1). The predominant treatment was sanitizing the environment and using well-formulated feeds. Viral disease cases were minimal, with only four cases reported across the country (Table 1). Bacterial diseases were the most common in most hatcheries. For fish treatment, respondents primarily used multipurpose antibiotics such as oxytetracycline and erythromycin as well, as lime and permanganate. Environmental sanitization with well-formulated feeds and chloramphenicol with lime and permanganate were also used as disease prevention measures. Sanitizing the environment and using well-formulated feeds emerged as a common treatment across all fish disease types.

Significant relationship among disease case reporting, type of fish disease treatment method and biosecurity

The disease case reporting had a 1.96 ± 1.007 and showed a moderate reliance on specific reporting offices for fish disease cases. The low standard deviation suggested consistency among hatchery owners, with a significant difference observed compared to the type of fish diseases encountered ($p = 0.004$). The type of fish diseases encountered had a 2.45 ± 1.267, indicating moderate diversity in the diseases encountered. A highly significant difference was noted compared to the Disease Case Reporting Office ($p < 0.05$) with types of fish diseases encountered at the hatchery.

Disease treatment method and management (2.72 ± 0.958) showed higher engagement of respondents in treatment and management practices compared to disease reporting. There were no significant differences between disease treatment and management and the type of fish diseases encountered at the hatchery, as well as the nature of fingerlings produced ($p > 0.05$). There was a significant difference between the source of broodstock, biosecurity measures in practice, type of fish diseases encountered at the hatchery, and Disease Case Reporting Office ($p < 0.05$). No significant difference was found between biosecurity measures in practice at the hatchery and the period when the hatchery was established ($p > 0.05$). These findings highlight variations in disease reporting, fish disease types encountered, broodstock sources, biosecurity measures, establishment periods, fingerling production, and disease treatment methods and management among hatcheries (Table 2).

Challenges to achieving effective biosecurity and good fish health management practices

The primary challenge reported was the lack of financial support for hatchery activities, identified by 43.3% of respondents. This indicated difficulties in securing adequate funds for fish hatchery operations, impacting infrastructure development, technological advancement, and input purchases. Additionally, an inexperienced workforce was highlighted by 18.3%. Furthermore, a smaller percentage (10.0%) identified a lack of knowledge in fish disease identification and treatment as a challenge. High mortalities during production were reported by 8.3% of respondents. Finally, 16.7% of those surveyed expressed a lack of training and hatchery infrastructure.

DISCUSSION

Hatcheries play a significant role as the initial stage in nearly every aquaculture fish production cycle, necessitating the implementation of robust best management practices in hatcheries. Broodstock management is the key indicator for the success of good fingerling production at the hatchery level. Infectious diseases among the broodstock present a substantial challenge in hatcheries and have the potential to cause extensive mortality (Prieto-Carolino et al. 2018; Santiago and Laron 2002; Kumar et al. 2022). Findings of this study offer a significant roadmap into the biosecurity measures practised at various hatcheries in Kenya, shedding light on the proactive approaches adopted by respondents.

The prioritization of biosecurity by the majority of respondents, involving practices like record-keeping and limiting visitors, aligns with the findings of Watanabe et al. (2002) who reported improved tilapia fingerling production in America due to advancements in hatchery biosecurity measures. This awareness of external factors impacting hatchery operations signifies a positive step towards realization of quality fish seed production required for sustainable aquaculture production. The focus on cleaning and maintaining hatchery hygiene as reported in the study indicates the use of cleanliness and hygiene as biosecurity tools among Kenyan hatcheries. Similar findings were reported by Bhatnagar and Budhalia (2023)

Table 2. Mean (± SD) of case reporting, type of fish disease and treatment methods for biosecurity.

Variables	Mean ± SD	P value
Disease case reporting office	1.96 ± 1.007^{a}	0.004
Type of fish diseases encountered at the hatchery	2.45 ± 1.267^{b}	0.000
Disease treatment method and management	2.72 ± 0.958^{b}	0.115
The nature of fingerlings produced	1.73 ± 0.95^{b}	0.128
Source of broodstock	1.48 ± 0.68^{c}	0.000
Biosecurity measure in practice	2.68 ± 1.75^{d}	0.032
Period of hatchery establishment	1.77 ± 0.79^{d}	0.160

Data are presented as mean values ± SD from three determinations. Different superscripts in the column indicate significant differences at ($p < 0.05$).

and Chaudhari et al. (2023) in India, highlighting the crucial role of a clean environment in disease prevention and pathogen control in aquaculture production systems.

Findings emphasizing on disease-free broodstock and prompt removal of dead fry among different hatcheries aligns with the findings of Pathak et al. (2000), Akoll and Mwanja (2012) and Dadar et al. (2017), who highlighted the significance of maintaining healthy broodstock to prevent bacterial disease transmission. This fact may drive the use of chemicals and vaccines in an aquaculture facility. This practice is essential for maintaining the health and quality of fish seed production. The use of physical barriers such as foot baths and limiting visitors to hatchery areas, as previously reported, is consistent with recommendations made by Quevedo Cascante et al. (2022) on the role played by externalities in the adoption of aquaculture in Colombian fish farming, where the role of barriers in preventing external contaminants and diseases is highlighted. This approach reflects a proactive stance towards mitigating potential risks, especially to broodstock and fingerlings, during production at the hatchery stage and associated aquaculture escapees cases that may result in the other part of the farm facility which may have associated effects on the aquatic ecosystem (Harikrishnan et al. 2024). The engagement in advanced biosecurity measures, such as quarantine, vaccination, and disease monitoring based on the findings of this study, reflects an understanding of the comprehensive nature of disease prevention and management. This aligns with the findings of Jia et al. (2017) on biosecurity attitudes and perceptions of fish farmers culturing yellow catfish (*Pelteobagrus fulvidraco*) in China. This mirrors evolving strategies for biosecurity in aquaculture in Kenya as well.

Based on the year of hatchery establishment, the majority of the hatcheries in the countries that were established before 2016 reflect experienced entities with potentially well-established aquaculture hatchery management practices which was as a result of an economic stimulus programme (ESP) an aquaculture government that necessitated the demand for fingerling in the country. These findings are in line with those of Syanya and Mathia (2023) indicating the positive correlation between experience and biosecurity practices in different aquaculture settings. Hatcheries established between 2017 and 2019 represent a growing interest and potential modernization, aligning with literature that associates newer establishments with technological advancements and best management practices. Hatcheries established between 2020 and 2022 as the most recent additions suggest continued interest and potential challenges faced during COVID-19. These hatcheries incorporated the latest technologies and the peak of the World Bank-funded Aquaculture Business Development Program (ABDP) through Kenya Fisheries Service, which has increased demand for fingerlings among fish farmers not only in counties under ABDP-funded project activities but also in other counties with potential for aquaculture.

Regarding the species of fingerlings produced at different hatcheries across Kenya, the dominance of tilapia fingerling production occurs across all hatcheries in the country. This finding is due to the available ready market for this fish in the country and its fast growth rate and resistance to diseases. A similar case reported by Liti et al. (2005), Kaliba et al. (2007), Opiyo et al. (2018) and Kaminski et al. (2024) highlights the production and popularity of tilapia driving a change in the Kenyan aquaculture sector. Tilapia is favoured for its adaptability, rapid growth, and high market demand as was witnessed also in China (Yuan et al. 2017; Zongli et al., 2017; Yongo et al. 2023). This study suggests a significant emphasis on tilapia production among the surveyed hatcheries, indicative of its economic importance and potential contribution to the food security of the country. A substantial proportion of hatchery facilities also producing African catfish fingerlings is consistent with widespread catfish farming in Kenya. Similar findings were reported by Miller and Atanda (2011), Munguti et al. (2014) and Otieno et al. (2021) highlighting the hardiness of this species and its consumer preference as a viable choice for aquaculture fisheries in Kenya and Nigeria. While not as prevalent as tilapia, the production of *C. gariepinus* found in this study indicates its continued importance in the aquaculture sector contributing to the diversity of cultured fish species. The 10.0% of respondents indicating trout (*O. mykiss*) fingerling production reflects a more specific and regional focus. Trout farming is associated with colder water environments (Munguti et al. 2014), and its presence in central Kenya suggests a targeted approach to aquaculture based on the local conditions of the central regions near Mount Kenya, known for being very cold. The inclusion of trout production in the surveyed hatcheries highlights the adaptability and diversification efforts within the aquaculture sector in the country. The report of 8.3% of respondents engaged in common carp fingerling production signifies the traditional and widespread culture of this fish species in the central part of Kenya. According to Munguti et al. (2014) and Syanya and Mathia (2023), the resilience of common carp in this region has contributed to its continued cultivation, although it may not dominate the study sample. This finding reinforces the importance of understanding and catering to regional preferences and conditions in aquaculture practices.

The high percentage of respondents reporting fish disease cases to county government fisheries offices suggests a reliance on local administrative bodies due to their proximity and accessibility. Similarly, the significant reporting to Kenya Fisheries Service offices indicates trust in national authorities, possibly due to their regulatory role and resources for disease management. The reporting to Kenya Marine Fisheries Research Institute offices reflects an acknowledgement of their expertise in fish health and disease research. A similar finding was reported in India where fish disease-related cased are reported to respective fisheries government institutions such as the Central Marine Fisheries Research Institute (CMFRI) (Aswathy and Imelda 2018).

The predominance of bacterial diseases, as reported across most hatcheries in the country reveals their prevalence and impact on fish hatchery operations. This aligns with the findings of Pathak et al. (2000), Novoslavskij et al. (2016) and Henriksson et al. (2018) highlighting bacterial diseases as common threats in aquaculture due to their ability to spread rapidly and cause significant losses. The use of multipurpose antibiotics like oxytetracycline and erythromycin as reported among the hatcheries reflects standard treatment protocols for bacterial infections, aiming to control pathogen growth and restore fish health. Similarly, the use of lime and permanganate suggests reliance on chemical interventions to combat bacterial diseases, consistent with biosecurity practices as was also witnessed in India (Pathak et al. 2000). The minimal reporting of viral disease cases across different hatcheries indicates effective preventive measures or underreporting, emphasizing the importance of robust surveillance. The predominance of sanitizing the environment and using well-formulated feeds across all disease types underscores their role in disease prevention, aligning with best practices recommended for maintaining a healthy aquaculture environment.

On various aspects of hatchery operations and their interrelationships, the moderate reliance on disease case reporting for fish disease cases, indicated by a mean of 1.96 ± 1.007, suggests a consistent reporting pattern among fish hatchery owners, with significant variation observed in the types of fish diseases encountered. Similarly, the moderate diversity in encountered fish diseases (2.45 ± 1.267) highlights the complexity of disease management strategies required in hatcheries, with significant differences noted in reporting practices. The higher engagement of respondents in treatment and management practices (2.72 ± 0.958) compared to disease reporting reveals the importance placed on disease control measures. The fact was also reported by Mugimba et al. (2018) and Jansen et al. (2019), especially concerning tilapia lake virus disease at the global aquaculture level.

However, varied practices were observed in broodstock sources, biosecurity measures, and establishment periods, emphasising the need for tailored approaches to disease prevention and management in hatcheries.

Based on biosecurity challenges, results reveal critical challenges faced by hatchery managers. The foremost issue is financial support, affecting infrastructure and input procurement. Secondly, an inexperienced workforce indicates a need for skill enhancement in hatchery management. Similar challenges were reported among fish farmers and hatchery managers (Syanya et al. 2024b) especially while transporting live fish to the farms and markets in Kenya. Additionally, a notable percentage reported insufficient knowledge of fish disease management, underscoring the necessity for training programs. High mortalities during production suggest potential issues with disease outbreaks or poor husbandry practices, emphasizing the need for improved biosecurity measures. Addressing these challenges is crucial for sustainable hatchery operations and ensuring the health and productivity of fish stocks.

CONCLUSIONS

The study provides crucial information on hatchery operations and biosecurity challenges. Firstly, it underscores the importance of robust hatchery management practices, particularly in broodstock management, to ensure successful fingerling production. Disease surveillance and management are vital, with bacterial diseases posing significant threats to hatchery operations. The predominant use of multipurpose antibiotics and chemical interventions reflects standard treatment protocols for bacterial infections. The findings also highlight the reliance on local administrative bodies and national authorities for disease reporting, indicating the need for improved reporting mechanisms to address potential underreporting. Additionally, the study reveals challenges such as financial constraints, an inexperienced workforce, and inadequate knowledge of disease management among hatchery managers. Addressing these challenges requires investments in training programs, improved biosecurity measures, and tailored approaches to disease prevention and management. Further research is warranted to explore the effectiveness of different treatment methods, the impact of biosecurity measures on disease prevention, and the long-term sustainability of hatchery operations in mitigating disease risks.

Policymakers in the aquaculture sector should consider, establishing financial support mechanisms tailored to hatcheries, ensuring adequate funding for infrastructure, technology upgrades, and input acquisition. Both county and national governments should implement comprehensive training programs to address the skills gap among hatchery workers in fish disease identification and treatment. Research collaborations should be promoted with institutions like the Kenya Marine Fisheries Research Institute to strengthen disease surveillance and management strategies in the country. Lastly, incentivising biosecurity measures adoption at hatcheries through regulatory frameworks and capacity-building initiatives to mitigate disease risks and enhance overall production efficiency should be adopted by the Kenya fisheries services and fisheries directorates of the respective county governments in Kenya.

ACKNOWLEDGEMENTS

I extend my sincere appreciation to the following individuals for their invaluable contributions to this research: Mr Paul Mumina from the Kenya Fisheries Service in Nairobi for initiating the process of authenticating and registering fish hatcheries in the country. Mr Sifuna Imbofu, Fisheries Officer in Kakamega County; Mr Joel Anyula, Fisheries Officer in Vihiga County; Mr Samuel

Njoroge, Fisheries Officer in Kiambu County; Mr Moses Wambua Mwangangi, Fisheries Officer in Machakos County; Mr Zackary Winamu, Officer in Homa Bay County; Mr Wambua, Fisheries Officer in Embu County; Mr Geoffrey Thuranira in Meru County; Ms Ann Kibera in Nyeri County; and Mr George Akunga and Ms Elizabeth Abanji, Fisheries Officers in Kisii County and Busia County, respectively. Their support, expertise, and dedication greatly contributed to the successful completion of this research.

Author contributions

Fredrick Juma Syanya: conceptualization; data collection; writing-original draft (equal). Harikrishnan Mahadevan: data analysis; review and editing. A. R. Nikhila Khanna: conceptualization; data collection; writing-original draft (equal). Wilson Munala Mathia: formal analysis; review, editing, and proofreading. Paul Mumina: formal analysis, review, editing, and proofreading. Joel Anyula Litabas: conceptualization; data collection; writing-original draft (equal). Caleb Sifuna: conceptualization; data collection; writing-original draft (equal).

Competing interests

The author declares that there is no competing interests in this work.

Funding

The author received no financial support during the data collection process, authorship, and/or publication of this article.

Ethical statement

The respondents provided informed consent during the data collection process, and all research procedures received approval from the relevant institutions. A research permit was also obtained from NACOSTI. Efforts were made to minimize potential risks to participants, and due respect was given to their rights and privacy.

REFERENCES

Abwao J, Jung'a J, Barasa JE, Kyule D, Opiyo M, Awuor JF, Ogello E, Munguti JM, Keya GA. 2023. Selective breeding of Nile tilapia, *Oreochromis niloticus*: a strategy for increased genetic diversity and sustainable development of aquaculture in Kenya. J Appl Aquacult. 35 (2): 237-256. DOI: https://doi.org/10.1080/10454438.2021.1958728

Ahmed N, Thompson S, Glaser M. 2019. Global aquaculture productivity, environmental sustainability, and climate change adaptability. Environ Manage. 63 (2): 159-172. DOI: https://doi.org/10.1007/S00267-018-1117-3

Akoll P, Mwanja WW. 2012. Fish health status, research and management in East Africa: past and present. Afr J Aquat Sci. 37 (2): 117-129. DOI: https://doi.org/10.2989/16085914.2012.694628

Arumugam M, Jayaraman S, Sridhar A, Venkatasamy V, Brown PB, Abdul Kari Z, Tellez-Isaias G, Ramasamy T. 2023. Recent advances in tilapia production for sustainable developments in Indian aquaculture and its economic benefits. Fishes. 8 (4): 176. DOI: https://doi.org/10.3390/fishes8040176

Assefa A, Abunna F. 2018. Maintenance of fish health in aquaculture: review of epidemiological approaches for prevention and control of infectious disease of fish. Vet Med Int. 2018: 5432487. DOI: https://doi.org/10.1155/2018/5432497

Aswathy N, Imelda J. 2018. Economic viability of cage farming of Asian seabass in the coastal waters of Kerala. [accessed Mar 2024]. https://eprints.cmfri.org.in/13247/.

BHATNAGAR A, BUDHALIA K. 2023. Fish epidermal mucus analytes with reference to physiological threats: non- intrusive approach to evaluate health status of carp fishes. Int Aquat Res. 15 (3): 205-218. DOI: https://doi.org/10.22034/iar.2023.1983914.1426

BRUMMETT RE, WILLIAMS MJ. 2000. The evolution of aquaculture in African rural and economic development. Ecol Econ. 33 (2): 193-203. DOI: https://doi.org/10.1016/S0921-8009(99)00142-1

CHAUDHARI AK, KUMAR AIL SS, MISRA CK, DE HK, RATHOD R, BHATT JH, SWAIN SK, VIGYAN KENDRA K. 2023. Status of freshwater aquaculture in Gujarat: a trend analysis and potential. Int J Bio-Resource Stress Manage. 14: 59-67. DOI: https://doi.org/10.23910/1.2023.3284a

CHAUDHARY P, KUMAR YADAV P, KUMAR JHA D. 2021. Status of fish hatchery and nursery management in Dhanusha, Nepal. Mal Anim Husbandry J. 1 (1): 14-25. DOI: https://doi.org/10.26480/mahj.01.2021.14.25

DADAR M, DHAMA K, VAKHARIA VN, HOSEINIFAR SH, KARTHIK K, TIWARI R, KHANDIA R, MUNJAL A, SALGADO-MIRANDA C, JOSHI SK. 2017. Advances in aquaculture vaccines against fish pathogens: global status and current trends. Rev Fish Sci Aquacult. 25 (3): 184-217. DOI: https://doi.org/10.1080/23308249.2016.1261277

DEWANGGANI AP, SARI LA, SARI PDW, NINDARWI DD, ARSAD S. 2021. The effect of feed management technology (life and pellet feed) on the maintenance of mutiara catfish (*Clarias* sp.) in freshwater cultivation. IOP Conf Ser Earth Environ Sci. 718: 012017. DOI: https://doi.org/10.1088/1755-1315/718/1/012017

GENSCHICK S, MEKKAWY W, ROSSIGNOLI C, BENZIE JAH. 2021. Growth performance of three strains of Nile tilapia (*Oreochromis niloticus*) on four different feeds in Western and Central Kenya. Aquacult Reports. 20: 100701. DOI: https://doi.org/10.1016/j.aqrep.2021.100701

HARIKRISHNAN M, SYANYA FJ, KHANNA ARN, MUMINA P, MATHIA WM. 2024. Ecological implications of unintentional aquaculture escapees: an overview of risks, remediation strategies and knowledge gaps in the aquaculture sector of India and riparian East African countries. Mar Fish Sci. 37 (4). DOI: https://doi.org/10.47193/mafis.3742024010709

HENRIKSSON PJG, RICO A, TROELL M, KLINGER DH, BUSCHMANN AH, SAKSIDA S, CHADAG MV, ZHANG W. 2018. Unpacking factors influencing antimicrobial use in global aquaculture and their implication for management: a review from a systems perspective. Sustainability Sci. 13 (4): 1105-1120. DOI: https://doi.org/10.1007/S11625-017-0511-8

HOSSAIN S, SHEFAT T, KARIM MA. 2018. Nutritional diseases of fish in aquaculture and their management: a review. Acta Sci Pharm Sci. 2: 2581-5423.

JANSEN MD, DONG HT, MOHAN CV. 2019. Tilapia lake virus: a threat to the global tilapia industry? Rev Aquacult. 11 (3): 725-739. DOI: https://doi.org/10.1111/raq.12254

JAYASANKAR P. 2018. Present status of freshwater aquaculture in India-a review. Indian J Fish. 65 (4): 157-165. DOI: https://doi.org/10.21077/ijf.2018.65.4.81300-20

JIA B, ST-HILAIRE S, SINGH K, GARDNER IA. 2017. Biosecurity knowledge, attitudes and practices of farmers culturing yellow catfish (*Pelteobagrus fulvidraco*) in Guangdong and Zhejiang provinces, China. Aquaculture. 471: 146-156. DOI: https://doi.org/10.1016/j.aquaculture.2017.01.016

JIANG Q, HUANG S, DU Y, XIAO J, WANG M, WANG X, SHI W, ZHAO Y. 2023. Quality improvement of tilapia fillets by light salting during repeated freezing-thawing: contribution of structural rearrangement and molecular interactions. Food Chem. 406: 135097. DOI: https://doi.org/10.1016/j.foodchem.2022.135097

KALIBA AR, NGUGI CC, MACKAMBO J, QUAGRAINIE KK. 2007. Economic profitability of Nile tilapia (*Oreochromis niloticus* L.) production in Kenya. Aquacult Res. 38 (11): 1129-1136. DOI: https://doi.org/10.1111/j.1365-2109.2007.01772.x

Kaminski AM, Pounds AM, McAdam B, Bostock J, Opiyo MA, Little DC. 2024. Growing smaller fish for inclusive markets? Increasing stocking density and shortening the production cycle of Nile tilapia in cages on Lake Victoria. Aquaculture. 581: 740319. DOI: https://doi.org/10.1016/j.aquaculture.2023.740319

Kumar R, Gokulakrishnan M, Debbarma J, Damle DK. 2022. Advances in captive breeding and seed rearing of striped murrel Channa striata, a high value food fish of Asia. Anim Reprod Sci. 238: 106957. DOI: https://doi.org/10.1016/j.anireprosci.2022.106957

Li N, Wang R, Zhang J, Fu Z, Zhang XS. 2009. Developing a knowledge-based early warning system for fish disease/health via water quality management. Expert Syst Appl. 36 (3): 6500-6511. DOI: https://doi.org/10.1016/j.eswa.2008.07.065

Liti D, Cherop L, Munguti J, Chhorn L. 2005. Growth and economic performance of Nile tilapia (*Oreochromis niloticus* L.) fed on two formulated diets and two locally available feeds in fertilized ponds. Aquacult Res. 36 (8): 746-752. DOI: https://doi.org/10.1111/j.1365-2109.2005.01265.x

Mehrim AI, Refaey MM. 2023. An overview of the implication of climate change on fish farming in Egypt. Sustainability. 15 (2), 1679. DOI: https://doi.org/10.3390/su15021679

Miller JW, Atanda T. 2011. The rise of peri-urban aquaculture in Nigeria. Int J Agricult Sustainability. 9 (1): 274-281. DOI: https://doi.org/10.3763/ijas.2010.0569

Mohanty B, Vivekanandan E, Mohanty S, Mahanty A, Trivedi R, Tripathy M, Sahu J. 2017. The impact of climate change on marine and inland fisheries and aquaculture in India. In: Pillips BF, Pérez-Ramírez M, editors. Climate change impacts on fisheries and aquaculture. Wiley Online Library. p. 569-601. DOI: https://doi.org/10.1002/9781119154051.ch17

Mugimba KK, Chengula AA, Wamala S, Mwega ED, Kasanga CJ, Byarugaba DK, Mdegela RH, Tal S, Bornstein B, Dishon A, et al. 2018. Detection of tilapia lake virus (TiLV) infection by PCR in farmed and wild Nile tilapia (*Oreochromis niloticus*) from Lake Victoria. J Fish Dis. 41 (8): 1181-1189. DOI: https://doi.org/10.1111/jfd.12790

Munguti JM, Kim JD, Ogello EO. 2014. An overview of Kenyan aquaculture: Current status, challenges, and opportunities for future development. Fish Aquat Sci. 17 (1): 1-11. DOI: https://doi.org/10.5657/fas.2014.0001

Munguti JM, Mboya JB, Iteba JO, Kirimi JG, Obiero KO, Kyule DN, Opiyo MA, Njonge FK, Jimmy Mboya CB, Marine K. 2024. Status and prospects of the ornamental fish industry in Kenya. Aquacult Fish Fish. 4 (3): e172. DOI: https://doi.org/10.1002/aff2.172

Mutyaba JL, Ngigi MW, Ayuya OI, Livingstone Mutyaba J, Ingasia Ayuya O. 2024. Determinants of knowledge, attitude and perception towards cage fish farming technologies among smallholder farmers in Uganda. Cogent Food Agric. 10 (1): 2313252. DOI: https://doi.org/10.1080/23311932.2024.2313252

Njiru JM, Aura CM, Okechi JK. 2019. Cage fish culture in Lake Victoria: a boon or a disaster in waiting? Fish Manage Ecol. 26 (5): 426-434. DOI: https://doi.org/10.1111/fme.12283

Novoslavskij A, Terentjeva M, Eizenberga I, Valciņa O, Bartkevičs V, Bērziņš A. 2016. Major foodborne pathogens in fish and fish products: a review. An Microbiol. 66 (1): 1-15. DOI: https://doi.org/10.1007/S13213-015-1102-5

Opiyo MA, Marijani E, Muendo P, Odede R, Leschen W, Charo-Karisa H. 2018. A review of aquaculture production and health management practices of farmed fish in Kenya. Int J Vet Sci Med. 6 (2): 141-148. DOI: https://doi.org/10.1016/j.ijvsm.2018.07.001

Opiyo MA, Obiero KO, Abwao J, Awuor FJ, Kyule D, Munguti J. 2021. Comparative growth performance of genetically male, sex-reversed, and mixed-sex nile tilapia (*Oreochro-*

mis niloticus) reared in earthen ponds in sagana, Kenya. Aquacult Stud. 21 (1): 23-30. DOI: https://doi.org/10.4194/2618-6381-V21_1_03

OTIENO NE. 2019. Economic impact of predatory piscivorous birds on small-scale aquaculture farms in Kenya. Aquacult Rep. 15: 100220. DOI: https://doi.org/10.1016/j.aqrep.2019.100220

OTIENO NE, WASONGA DV, IMBOKO D. 2021. Pond-adjacent grass height and pond proximity to water influence predation risk of pond fish by amphibians in small fish ponds of Kakamega County, western Kenya. Hydrobiologia. 848 (8): 1795-1809. DOI: https://doi.org/10.1007/S10750-021-04551-8

OTOH AJ, EKANEM IE, OKOKO AC, ASANGUSUNG PS, GEORGE UU. 2024. Comparative study of inducing broodstock with natural and artificial hormones on reproductive performances of *Clarias gariepinus*. Asian J Fish Aquat Res. 26 (3): 31-38. DOI: https://doi.org/10.9734/ ajfar/2024/v26ı3744

PATHAK SC, GHOSH SK, PALANISAMY K. 2000. The use of chemicals in aquaculture in India. In: ARTHUR JR, LAVILLA-PITOGO CR, SUBASINGHE RP, editors. Use of Chemicals in Aquaculture in Asia. Tigbauan: Southeast Asian Fisheries Development Center, Aquaculture Department. p. 87-112. http://hdl.handle.net/10862/604.

PRIETO-CAROLINO A, PILAPIL-ANASCO C, MEDIODIA HJP, GELVEZON RPL, GABUNADA FM. 2018. Prospects of community-based co-management of Philippine abalone fishery. Ocean Coast Manage. 163: 185-191. DOI: https://doi.org/10.1016/j.ocecoaman.2018.06.006

QUEVEDO CASCANTE M, ACOSTA GARCÍA N, FOLD N. 2022. The role of external forces in the adoption of aquaculture innovations: an ex-ante case study of fish farming in Colombia's southern Amazonian region. Technol Forecasting Social Change. 174: 121185. DOI: https://doi.org/10.1016/j.techfore.2021.121185

RAHMAN ML, SHAHJAHAN M, AHMED N. 2021. Tilapia farming in Bangladesh: adaptation to climate change. Sustainability. 13 (14): 7657. DOI: https://doi.org/10.3390/su13147657

RESEARCH AND MARKETS. 2023. Aquaculture global market report 2023. Research and Markets. https://www.researchandmarkets.com/reports/5766638/aquaculture-global-market-report.

ROBLEDO D, OGWANG J, BYAKORA E, SCHULZE JN, BENDA KK, FRASLIN C, SALISBURY S, SOLIMO M, MAYEGA JF, PETER B, ET AL. 2024. Genetic diversity and population structure of farmed and wild Nile tilapia (*Oreochromis niloticus*) in Uganda: the potential for aquaculture selection and breeding programs. Genomics. 116 (1): 110781. DOI: https://doi.org/10.1016/j.ygeno.2024.110781

ROH HJ, PARK J, KIM A, KIM N, LEE Y, KIM BS, VIJAYAN J, LEE MK, PARK CIL, KIM DH. 2020. Overfeeding-induced obesity could cause potential immuno-physiological disorders in rainbow trout (*Oncorhynchus mykiss*). Animals. 10 (9): 1-15. DOI: https://doi.org/10.3390/ani10091499

SANTIAGO CB, LARON MA. 2002. Growth and fry production of Nile tilapia, *Oreochromis niloticus* (L.), on different feeding schedules. Aquacult Res. 33 (2): 129-136. DOI: https://doi.org/10.1046/J.1365-2109.2002.00664.x

SINGH AK. 2021. State of aquatic invasive species in tropical India: an overview. Aquat Ecosyst Health Manage. 24 (2): 13-23. DOI: https://doi.org/10.14321/aehm.024.02.05

SYANYA FJ, HARIKRISHNAN M, SIMIYU NN, KHANNA ARN, LITABAS JA, MATHIA WM. 2024a. Aquaculture: a hidden goldmine for the rural poor -a cost-benefit analysis of fish farming for sustainable development and food security in Vihiga County, Kenya. Bus Strategy Dev. 7 (2): e348. DOI: https://doi.org/10.1002/bsd2.348

SYANYA FJ, LITABAS JA, MATHIA WM, NTAKIRUTIMANA R. 2023a. Nutritional fish diseases in aquaculture: a human health hazard or mythical theory: an overview. Eur J Nutr Food Saf. 15 (8): 41-58. DOI: https://doi.org/10.9734/ejnfs/2023/v15i81326

SYANYA FJ, MATHIA WM. 2023. Status of fish health and biosecurity management systems in

Kenya's aquaculture production units. A case of government authenticated fish hatcheries. Research Square. DOI: https://doi.org/10.21203/rs.3.rs-2430657/v1

Syanya FJ, Mathia WM, Harikrishnan M. 2023b. Quality and safety concerns of farmed tilapia fish during freezing and frozen storage: review. Asian Food Sci J. 22 (6): 40-58. DOI: https://doi.org/10.9734/afsj/2023/v22i6641

Syanya FJ, Mathia WM, Mumina P, Litabas JA, Sifuna C. 2024b. Aqua perspectives: stakeholder attitudes and perceptions in live fish transportation practices within the Kenyan fisheries sector. Mar Fish Sci. 37 (2): 317-335. DOI: https://doi.org/10.47193/mafis.3722024010507

Syanya FJ, Winam ZO, Mathia WM. 2023c. Vanishing splendor: a comprehensive review of the decline in the original fish fauna of Lake Victoria. Mar Fish Sci. 37 (1): 209-231. DOI: https://doi.org/10.47193/mafis.3712024010107

Uppanunchai A, Apirumanekul C, Lebel L. 2015. Planning for production of freshwater fish fry in a variable climate in northern Thailand. Environ Manage. 56 (4): 859-873. DOI: https://doi.org/10.1007/S00267-015-0547-4

Watanabe WO, Losordo TM, Fitzsimmons K, Hanley F. 2002. Tilapia production systems in the Americas: technological advances, trends, and challenges. Rev Fish Sci. 10 (3-4): 465-498. DOI: https://doi.org/10.1080/20026491051758

WorldFish 2024. WorldFish 2023 Annual Report. Penang: WorldFish. https://digitalarchive.worldfishcenter.org/handle/20.500.12348/5974.

Yongo E, Zhang P, Mutethya E, Zhao T, Guo Z. 2023. The invasion of tilapia in South China freshwater systems: a review. Lakes Reserv Res Manage. 28 (1): e12429. DOI: https://doi.org/10.1111/lre.12429

Yuan Y, Yuan Y, Dai Y, Gong Y. 2017. Economic profitability of tilapia farming in China. Aquacult Int. 25 (3): 1253-1264. DOI: https://doi.org/10.1007/S10499-017-0111-8

Zongli Z, Yanan Z, Feifan L, Hui Y, Yongming Y, Xinhua Y. 2017. Economic efficiency of small-scale tilapia farms in Guangxi, China. Aquacult Econ Manage. 21 (2): 283-294. DOI: https://doi.org/10.1080/13657305.2016.1180644