REVIEW

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

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ABSTRACT. The global expansion of aquaculture has driven significant technological advancements, including raceways, Integrated Multitrophic Aquaculture (IMTA) and marine offshore cages. However, unregulated aquaculture escapees pose a severe threat to aquatic biodiversity, acting as a potential time bomb for the entire ecosystem. Addressing this issue requires a comprehensive understanding of the impact of unintentional escapees on aquatic ecosystems, particularly in India and riparian East African countries (Kenya, Uganda, and Tanzania). Using an exploratory research design drawing from various peer-reviewed sources, this study outlines the dynamic growth of aquaculture in these countries, identifies high-impact escape incidents, and correlates risks and remedies with global cases, especially in regions such as Norway, Scotland, Ireland, Colombia, and the United States, where serious incidents of aquaculture escapees have been reported. The research categorizes aquaculture development trends, discusses mechanisms of escapee impact, proposes remedies, assesses methods and inferential strength, and highlights gaps in the existing literature. The study revealed complex ecological shifts caused by aquaculture escapees from invasive non-native fish species, affecting predation, competition, and genetic diversity. Escaped fish from aquaculture facilities pose a significant threat to aquatic biodiversity, especially in the study regions. The escalating risk of unintentional escapes was highlighted in India and three East African countries. To mitigate this, the study proposes integrating escapee management into national fisheries systems, amending fisheries laws, holding fish farmers accountable for aquaculture system failure, and developing comprehensive regulations for non-native species in aquaculture within the study regions. It is recommended to standardize the planning for aquaculture facilities and implement emergency plans, training, local mobilization and further research on the impact thresholds of aquaculture escapees in the study regions. Ecological education in aquaculture communities and the recognition of the role of translational scientists are crucial for the dissemination of knowledge. Urgent government action is needed to address unreported aquaculture escapes, preventing further ecosystem degradation and ensuring global aquaculture sustainability.

Key words: Aquaculture escapes, invasive species, fisheries policy, biodiversity, aquatic ecosystem, sustainable aquaculture.

Consecuencias ecológicas de los escapes accidentales de la acuicultura: una visión general de los riesgos, las estrategias de remediación y las lagunas de conocimiento en el sector de la acuicultura de la India y los países ribereños de África Oriental

RESUMEN. La expansión global de la acuicultura ha impulsado importantes avances tecnológicos, incluidos los *raceways*, Sistemas Integrados Multitróficos en Acuicultura (IMTA) y jaulas marinas en alta mar. Sin embargo, los escapes de la acuicultura clandestina representan una grave amenaza para la biodiversidad acuática, actuando como una potencial bomba de tiempo para todo el ecosistema. Abordar esta cuestión requiere una comprensión integral del impacto de las fugas involuntarias en los ecosistemas acuáticos, particularmente en la India y los países ribereños de África Oriental (Kenia, Uganda y Tanzania). Utilizando un diseño de investigación exploratoria basado en varias fuentes evaluadas por pares, este estudio describe el crecimiento dinámico de la acuicultura en estos países, identifica incidentes de escape de alto impacto y correlaciona riesgos y soluciones con casos globales, especialmente en regiones como Noruega, Escocia, Irlanda, Colombia y Estados Unidos, en donde se han reportado incidentes graves de escapes de la acuicultura. La investigación categoriza las tendencias de desarrollo de la acuicultura, analiza los mecanismos del impacto de los escapes, propone soluciones, evalúa métodos y la fuerza inferencial, y destaca las lagunas existentes en la literatura. El estudio reveló complejos cambios ecológicos causados por la fuga de especies de peces invasoras no nativas provenientes de la acuicultura, que afectan la predación, la competencia y la diversidad genética. Los peces que se escapan de las instalaciones acuícolas representan una amenaza significativa para la biodiversidad acuática, especialmente en las regiones de estudio. El creciente riesgo de fugas involuntarias se puso de relieve en la India y en tres países de África Oriental. Para mitigar este hecho, el estudio propone integrar la gestión de los escapes en los sistemas pesqueros nacionales, modificar las leyes pesqueras, responsabilizar a los piscicultores por las fallas del sistema de cultivo y desarrollar regulaciones integrales para las especies exóticas en la acuicultura en las regiones de estudio. Se recomienda estandarizar la planificación de las instalaciones de acuicultura e implementar planes de emergencia, capacitación, movilización local y más investigaciones sobre los umbrales de impacto de los escapes de especies cultivadas. La educación ecológica en las comunidades acuícolas y el reconocimiento del papel de los científicos transnacionales son cruciales para la difusión del conocimiento. Se necesita una acción gubernamental urgente para abordar los escapes no reportados de la acuicultura, evitando una mayor degradación de los ecosistemas y garantizando la sostenibilidad de la acuicultura global.

Palabras clave: Escapes de la acuicultura, especies invasoras, política pesquera, biodiversidad, ecosistema acuático, acuicultura sostenible.

INTRODUCTION

Aquaculture, commonly referred to as aquafarming, involves the controlled cultivation and husbandry of aquatic species such as finfish, crustaceans, and aquatic plants such as seaweeds within enclosed or managed water environments (Tisdell 2003; Bartley and Halwart 2007; Kumaran et al. 2020). It stands out as the fastest growing sector globally. According to the Food and Agriculture Organization, the aquaculture industry has experienced rapid expansion in recent years, with particular emphasis on Asian countries, mainly India and China, which currently contribute more than half of the global aquaculture production (FAO 2022a). This notable growth can be mainly attributed to the introduction of exotic fish species for aquaculture or the farming of native fish species beyond their natural habitat ranges. These non-native aquaculture species collectively have experienced significant expansion (Gozlan et al. 2010a; Jeschke et al. 2014), and the latest FAO fishstat database reports approximately 5,857 non-native aquatic species globally (FAO 2022a). The farming of non-native fish species through aquaculture has been identified as a significant contributor, accounting for around 22% of global aquaculture production, with Asian countries at the forefront (Pauly and Zeller 2019; FAO 2022a).

In China, non-native exotic aquaculture fish species, such as Nile tilapia (*Oreochromis niloticus*), have significantly formed self-sustaining populations in the wild aquatic ecosystem as a result of repeated releases or accidental escapes from aquaculture (Ju et al. 2020; Yongo et al. 2023). Out of these instances, the majority of non-native fish species that escaped from aquaculture systems were reported to pose potential dangers to indigenous aquatic ecosystems (Bbole et al. 2023; Yongo et al. 2023). Beyond affecting national biodiversity and ecosystem processes, non-native fish species that escape from aquaculture facilities can jeopardize the biosecurity of adjacent countries that share water resources.

Nobile et al. (2018) reported that many developing countries, such as India, Brazil, Vietnam, Thailand, Cuba, and the Philippines, heavily rely on the farming of exotic fish species such as Nile tilapia, trout and catfish for freshwater aquaculture. Due to failures in the culture system, these species have eventually infiltrated natural ecosystems, posing a long-term threat to the biodiversity of both marine and freshwater ecosystems. The adoption of these non-native species has not only profoundly impacted the global environment but has also influenced economies and socio-cultural arrangements (Pimentel et al. 2005). Nevertheless, the incorporation of the North African catfish (*Clarias gariepinus*), a non-native species, into aquaculture has been linked to the decrease in indigenous fish species in natural ecosystems in India. This is attributed to its invasive characteristics, posing potential threats to indigenous fish species (Nobinraja et al. 2023).

The escalating growth of aquaculture has raised concerns about increased cases of escapees into natural ecosystems. According to Arechavala-Lopez et al. (2012), the release of seabream, a non-native fish species from aquaculture facilities (escapees), has become a significant concern for aquatic ecosystems, impacting both marine and freshwater biodiversity. Dempster et al. (2018) also noticed the great challenge of recapturing escapees from an aquaculture system as an alternative to reduce the number of escapees in wild marine ecosystems. Despite the difficulty in accurately estimating the magnitude and threshold impact of aquaculture escapees on aquatic ecosystems due to limited data, the trend is alarming, with documented escapes occurring in various parts of the world, particularly in developing countries. For instance, in Norway, letting fish escape from fish farms or fish-holding facilities such as cages is against the law, and fish farming companies could potentially be subject to legal action after a considerable number of fish escape from their fish farm. These occurrences can pose the most critical risks to the aquaculture business and industry, adversely affecting their reputation (Fredheim et al. 2010). In addition to causing economic losses, escapees of non-native species from aquaculture can result in multiple ecological impacts and contribute to the loss of aquatic biodiversity, as reported in Atlantic salmon farms in Norway (Glover et al. 2012). In Scotland, escapees from Atlantic salmon farms were reported, and they were subsequently found in the wild ecosystem after an arbitrary one-year period post-escape (Stevens et al. 2018). Hence, as aquaculture activities expand offshore for mariculture, the incidence of escapees affecting marine ecosystems has been increasing.

Aquaculture escapees, like other invasive fish species, have caused significant marine and freshwater bioinvasions, resulting in a decline in aquatic biodiversity and affecting the ecological health of aquatic ecosystems. The International Union for Conservation of Nature (IUCN) recognizes the substantial and often irreversible impact of invasive fish species on aquatic ecosystems (Thorvaldsen et al. 2015; Kang et al. 2023). The new framework of the Blue Growth Initiative (FAO 2022a) emphasizes escape incidents and invasions from alien aquatic fish species as major challenges in the global aquaculture industry.

In Africa, there is limited literature on the impacts of aquaculture escapees on natural ecosystems and biodiversity. However, this scarcity does not imply the absence of cases, with studies by Njiru et al. (2019) and Syanya et al. (2023) indicating potential threats posed by cage fish farming systems in Lake Victoria. These systems lack proper reinforcement, making them susceptible to breakdowns that could lead to the release of cultured fish into the lake, adversely impacting biodiversity. Banadda et al. (2009) also highlight the environmental impact of land-based culture systems contributing to aquatic pollution in Uganda. To enhance aquaculture sustainability, Odende et al. (2022) proposed transforming smallholder aquaculture into cohesive hybrid aquaparks, reducing the likelihood of aquaculture escapees.

In Tanzania, the intentional relocation of three mouth-brooding tilapias beyond their native range has been noted, impacting freshwater eco-regions (Chuhila et al. 2024). In India, the introduction of invasive fish species such as *O. niloticus* and the common carp (*Cyprinus carpio*) has displaced local carp from major rivers, causing a loss of biodiversity (Singh et al. 2013). Similarly, the introduction of *Penaeus vannamei* has affected the production of *Macrobrachium rosenbergii* and *Penaeus monodon* (Nguyen 2016). Kerala state, India, known for its rich fish diversity, faces threats from floods and escapees of exotic species such as arapaima (*Arapaima gigas*) and alligator gar (*Atractosteus spatula*) from aquaculture (Kumar et al. 2019). The illegal introduction of these species poses risks to native fish populations in aquatic ecosystems. Consequently, to protect Kerala's biodiversity, a total ban on dangerous species, such as alligator gar and arapaima, is recommended (Sandilyan 2023). The lack of proper infrastructure in aquaculture farms has contributed to escape incidents, urging the need for stringent regulations. A pre-flood assessment revealed the negative impact of introducing common carp on endemic species in Kerala (Krishnakumar et al. 2011).

Our research explores the dangers posed by aquaculture escapees globally, with a focus on India and the three riparian East African countries (Kenya, Uganda and Tanzania), which collectively share fisheries activities in Lake Victoria. We propose policy guidelines for governing aquaculture escapee cases in developing nations to decrease instances of escapees and mitigate their impact on biodiversity and ecosystems. While most accidental escapees from aquaculture, both native and exotic species, are considered invasive, in development countries such as China, Norway, Scotland, the USA and Canada they have been the subject of extensive review, the impact of which on aquatic biodiversity in developing countries remains less explored. Our study aims to fill this gap, providing clear and coherent policy directions for managing unintentional aquaculture escapees into natural aquatic ecosystems. The study addresses potential risks associated with aquaculture escapees and examines global and regional scenarios. As local-level cases in India are not well-documented, the study specifically identifies areas of concern related to aquaculture escapees and their impact on indigenous fish species and the entire aquatic ecosystem. Acknowledging the global variations in reported experiences, the proposed solutions and recommendations aim to benefit other developing countries experiencing rapid expansion in aquaculture activities as well.

MATERIALS AND METHODS

An exploratory research design was employed in this study. An initial literature search was conducted using the Google Scholar search engine, Web of Science, Science Direct, and Wiley Article Finders. This search encompassed peer-reviewed articles on non-native farmed fish, alien fish species, and aquaculture escapes worldwide, as well as technical reports from the FAO, policy directions and briefs, and other related sources such as organizational websites and periodic reports. A total of 163 literature pieces, reports, policy documents, and conference proceedings available from the period 1965 to 2024 were included in this study. To identify closely related literature, eligibility criteria included any document containing keywords such as 'Aquaculture escapees', 'invasive fish species', 'Non-native', 'Alien and impact', or 'non-native farmed fish or native escapees'. The search yielded over 400 papers. The process of selecting appropriate papers concerning aquaculture escapees and their impact on aquatic ecosystems for inclusion in the review began with a basic screening using keywords, and non-English papers were excluded. These papers provided insights into the state, nature, and impact of both native and non-native aquaculture escapees on a global scale, as well as from India and the three East African countries (Kenya, Uganda and Tanzania). Similarly, papers related to aquaculture escapees concerning other fish species cases from different parts of the world were included. The impact associated with aquaculture escapees on the inversion of marine and freshwater ecosystems and biodiversity loss was also considered. Both negative and positive impacts were documented, as indicated in the following section of this study.

RESULTS AND DISCUSSION

Aquaculture production in India and cases of unintentional escapees

Aquaculture has witnessed significant global growth from 2019 to 2021, according to FAO (2022a). This growth trend is mirrored in the Indian aquaculture sector, often referred to as the 'sunrise Sector', which not only ensures nutrition and food security but also provides significant employment opportunities. India ranks second globally in aquaculture production (Chaudhari et al. 2023) and is home to over 10% of the world fish biodiversity (Jana and Jana 2003).

Brackish water aquaculture in India has shown a remarkable and steady rise, particularly in whiteleg shrimp production (FAO 2023). The production of whiteleg shrimp (*P. vannamei*) has increased from under 5,000 t in 2009 to surpass 800,000 t in 2021 (Figure 1). Freshwater aquaculture production plays a crucial role, particularly in the cultivation of Indian major carp and different shrimp species (Gopakumar 2003; Munilkumar and Nandeesha 2007; Mahadevan 2011; Singh et al. 2013; Roshni et al. 2022; Zhang et al. 2023). The production of Indian major carp, such as *Catla catla* and *Roho labeo*, has consistently increased, with catla's total production exceeding 30 million metric tons over the last decade (FAO 2022a). Other freshwater fish species, including striped catfish (*Plotosus lineatus*), grass carp (*Ctenopharyngodon idella*), and orangefin labeo (*Labeo calbasu*), have also contributed significantly (Research and Markets 2023) (Figure 2).

Mariculture in India presents opportunities with commercially important species of marine fishes, Indian backwater oysters (*Magallana bilineata*), red seaweeds, and green mussels (Figure 3). While green mussel production has declined and the In-

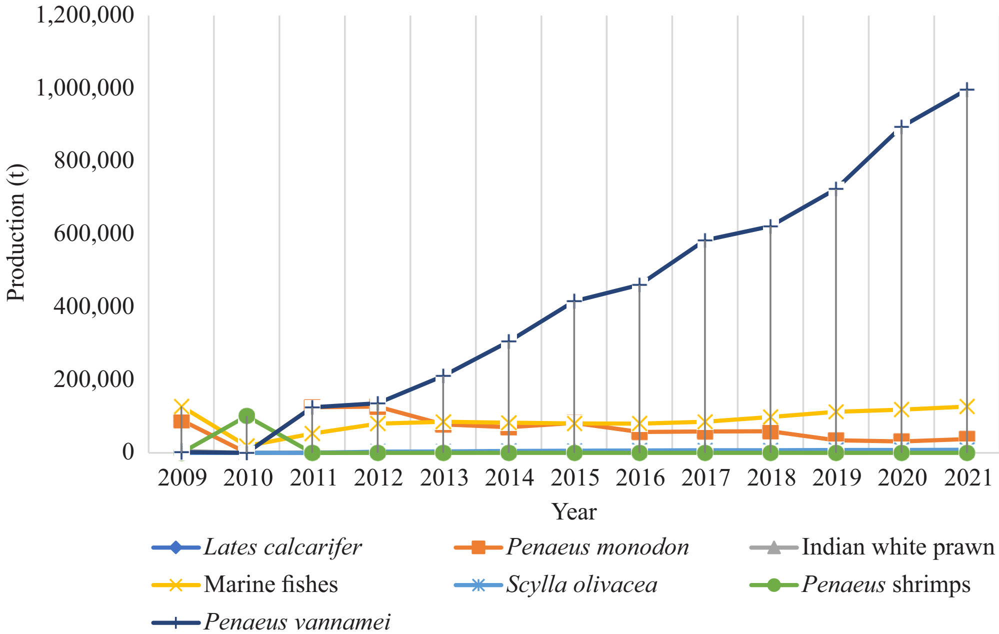

Figure 1. Trend in Indian brackish water aquaculture production from 2009 to 2021 (FishStatJ database –FAO 2023).

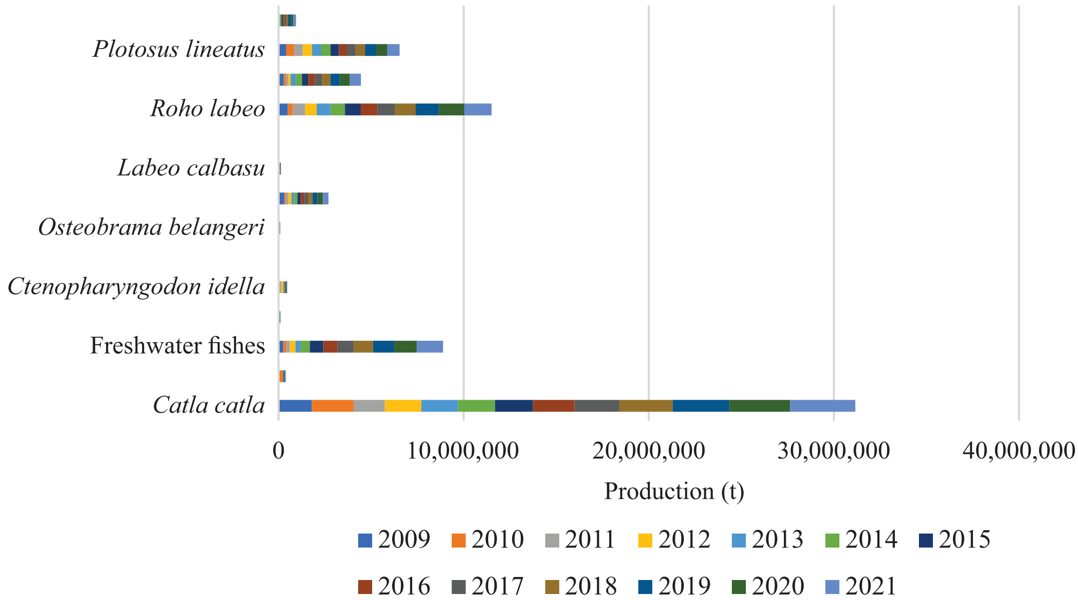

Figure 2. Trend in Indian freshwater aquaculture production from 2009 to 2021 (FishStatJ database –FAO 2023).

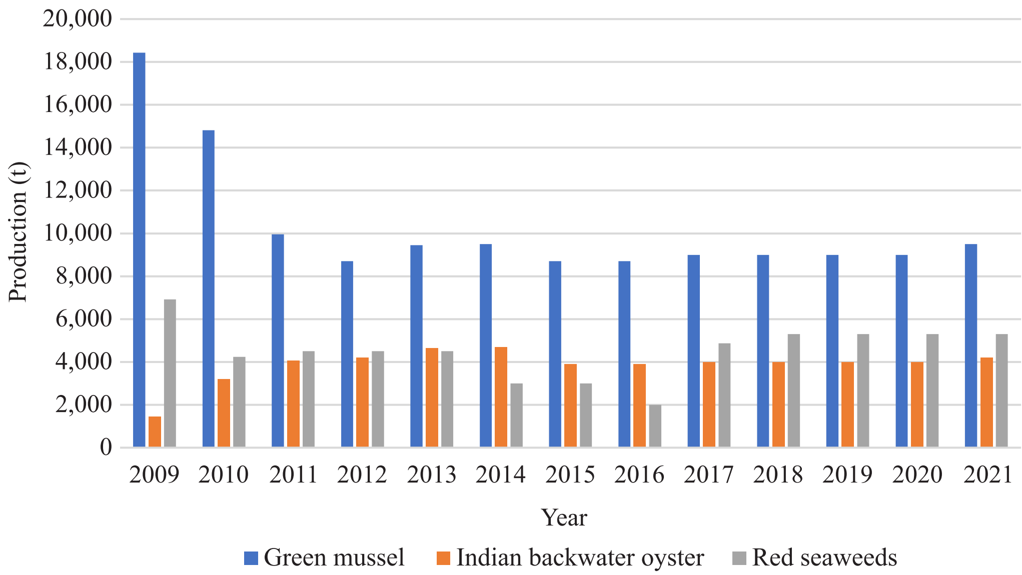

Figure 3. Trend in Indian marine water aquaculture production from 2009 to 2021 (FishStatJ database –FAO 2023).

dian backwater oyster production has remained constant, the production of red seaweeds has significantly increased from 2016 to 2021 (FAO 2023) (Figure 3). However, unintended consequences of aquaculture, such as the escape of farmed fish species into marine aquatic ecosystems, pose a serious threat to the balance and health of marine and freshwater aquatic ecosystems in India. Despite the absence of clear policies to regulate and prevent aquaculture escapees, numerous instances have been reported, attributed to climate change such as sea upwelling, flooding and culture system failures. This highlights the need for effective measures to mitigate the impacts of aquaculture escapees on aquatic ecosystems in India (FAO 2023; Sandilyan 2023).

In the aftermath of the 2015 flood in Tamil Nadu, *P. vannamei* shrimp escaped from ponds in Marakkanam, Viluppuram district, entering the East Coast region which was associated with shrimp pond system failures due to prolonged flooding (Sandilyan 2023). Shrimp and freshwater prawn farming is lucrative in India, particularly in Andhra Pradesh, Kerala, and Tamil Nadu (Mahadevan 2011; Bijoy et al. 2018; Jayanthi et al. 2019). Escapes occur due to facility breaches, natural disasters, or improper containment, leading to the transfer of diseases and parasites to the wild aquatic ecosystem (Gusmawati et al. 2018). Escapees can outcompete native species, disrupting the aquatic ecosystem balance. Escaped shrimp populations have proliferated in the Indian Ocean, altering prey-predator dynamics and impacting biodiversity, as observed in Bangladesh shrimp farms (Jamal et al. 2023). This has cascading effects on marine life and the entire food web.

Similarly, tilapia escapes have been reported in various Indian states, including Tamil Nadu, Kerala, Gujarat, West Bengal, and Andhra Pradesh (Arumugam et al. 2023). Tilapia, a non-native farmed fish from Africa, is hardy and adaptable, thriving in both brackish and freshwater ecosystems (Menaga et al. 2017). Once released into natural waters, tilapia can outcompete native fish, leading to a decline in indigenous species (Gozlan et al. 2010; Chifamba and Videler 2014). In Kerala state, India, the tilapia competes with the pearl spot (*Etroplus suratansis*) for a similar ecological niche and is considered invasive (Krishnakumar et al. 2011). Invasive species like *C. gariepinus* in Kerala pose threats to native cichlids, especially in the backwaters and its farming has since been banned by both the state and central governments (Krishnakumar et al. 2011; Raj et al. 2019).

Nile tilapia and common carp, recognized as invasive fish species and escapees, displaced Indian major carp from the Ganga and Yamuna rivers (Singh et al. 2013). The Ganga River anticipates a sustained rise in tilapia and common carp productivity due to increasing escape cases from aquaculture units (Singh 2021). China and Thailand also face emerging risks of non-native fish escapees impacting aquatic ecosystems (Lebel et al. 2013; Ju et al. 2020). The prolific reproductive behaviour of Nile tilapia in the wild results in spatial overlap, hindering local species to thrive and causing a loss of biodiversity in Indian aquatic ecosystems.

Aquaculture escapees in India pose a significant threat to aquatic ecosystems. *Macrobrachium rosenbergii* and *P. monodon*, crucial species in Indian aquaculture, have been reported to escape into natural water bodies due to climate-induced pond flooding (Nguyen 2016; Jayanthi et al. 2019). The introduction of *P. vannamei* has further endangered *P. monodon*, causing a decline in its production due to a shift in farmer interest toward *P. vannamei*, resistant to viral diseases.

The North African catfish (*C. gariepinus*) introduction in northern India had adverse effects on native fish species, leading to bans on its breeding and distribution (Singh 2014; Khan et al. 2021). In Kerala state, India, 'fugitive fish', including harmful alien species such as arapaima and alligator gar, escaped during the 2018 floods, posing a threat to native species (Kumar et al. 2019). Ornamental aquaculture systems lack proper control, contributing to the escape of exotic fishes into natural ecosystems (Raghavan et al. 2008; Singh 2014).

Escape cases involving carp species in river systems result in genetic introgression, weakening the resilience of native populations (Bentsen and Olesen 2002). In the Ganges River basin, escaped carp interbreeding with native mahseer species (*Tor* spp.) jeopardizes genetic purity and ecological balance (Sarkar et al. 2012). Despite the limited development of offshore sea cage fish farming in India, inland aquaculture systems contribute significantly, with minimal reports of the presence of escapees in the wild ecosystem (Basavaraja, 2015;

Jayasankar 2018; Jayanthi et al. 2019). The scarcity of invasive non-native fish species and minimal biodiversity impact suggests a limited occurrence of aquaculture escapees in marine ecosystem of India (Karthik et al. 2005).

According to the literature, climate events and system failures have caused aquaculture escapees in India to the introduce non-native species, disrupting native ecosystems. Despite efforts of banning and regulations to mitigate these threats, challenges persist. The impact on biodiversity and ecosystem health necessitates comprehensive monitoring and stricter preventive measures in Indian aquaculture practices (Raghavan et al. 2008; Singh 2014; Kumar et al. 2019).

Aquaculture production in Kenya and cases of unintentional escapees

Aquaculture development in Kenya witnessed a period of stagnation until 2009 when the Kenyan government launched the Fish Farming Enterprise Productivity Program (FFEPP) (Munguti et al. 2014; Nguka et al. 2017; Kaminski et al. 2024). This initiative resulted in a significant production increase until 2016. However, there was a notable decline in both Nile tilapia and catfish production from 12,000 t to about 10,000 t for Nile tilapia and less than 2,000 t for North African catfish in 2016 (Figure 4). This decline is attributed to inadequate funding mechanisms for aquaculture activities, which became solely the responsibility of county governments following the promulgation of the new constitution in 2010 and the subsequent formation of county governments. This resulted in the transfer of major fisheries and aquaculture services to the county governments. According to Amankwah et al. (2018), the inadequacy of quality fish seeds and feeds, coupled with outdated technology, has been detrimental to sustainable aquaculture development in Kenya, leading to a production decline below the projected levels and Kenyan Vision 2030. Therefore, the provision of government subsidies for fish feeds to fish farmers in the country is highly recommended. This has rendered Kenya less competitive than India in the

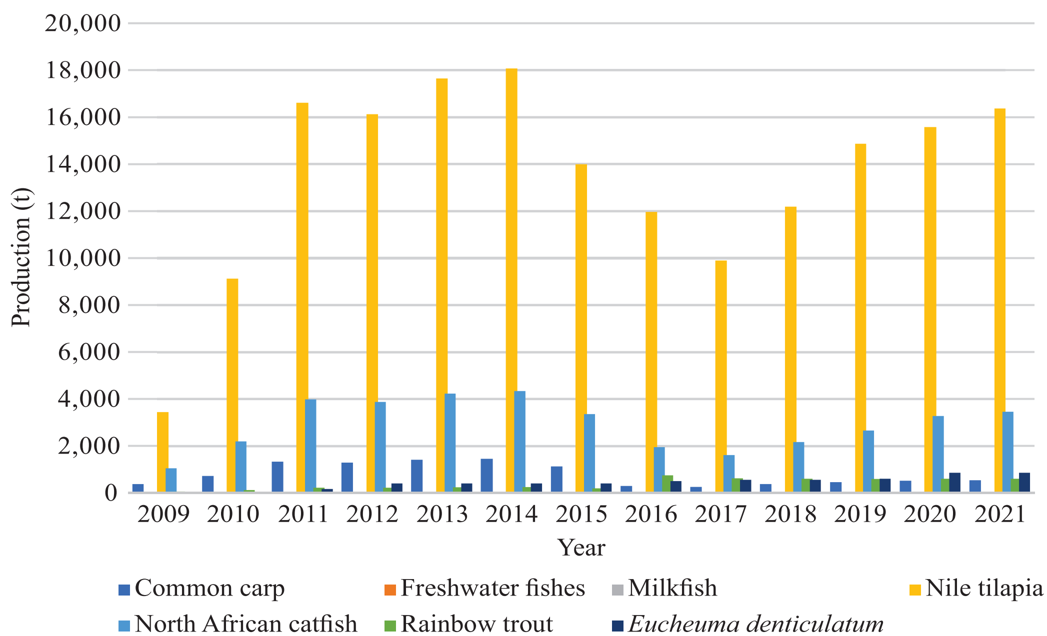

Figure 4. Trend of aquaculture production in Kenya in terms of species in the last decade (FishStatJ database –FAO 2023).

aquaculture sector, where technology is prevalent, and most fish farmers have embraced technological advancements in fish seed and feed production (Jayasankar 2018).

The primary objective of the FFEPP program was to stimulate the national economy, alleviate poverty, and promote regional development (Munguti et al. 2014). Before the introduction of the program, aquaculture in the country was at an extensive level where very few fish ponds could be traced across the country. However, the implementation of the FFEPP program led to substantial growth in aquaculture, with production increasing from 1,012 t in 2003 to 22,487 t in 2014 (Figure 4) (Munguti et al. 2014, 2022; Abwao et al. 2023). The awareness generated during the implementation of the program resulted in a shift in aquaculture production systems from extensive to semi-intensive methods. Different hatcheries have been established and approved by the government through Kenya Fisheries Services (Abwao et al. 2023; Syanya and Mathia 2023). According to Syanya et al. (2024), this has facilitated the transportation of live fish in the form of fingerlings and broodstock to regions where aquaculture is densely practised, such as Central Nyanza and Western regions. Similarly, Nguka et al. (2017) noted that this transition led to heightened fish farming activities and increased utilization of commercial fish feeds and pond fertilization practices to augment fish production. Furthermore, some farmers have adopted intensive systems for fingerling production, utilizing tanks and recirculation aquaculture systems (RAS) cages especially in Lake Victoria for increased Nile tilapia production and reduce pressure on capture fisheries of the lake (Syanya et al. 2023b; Kaminski et al. 2024).

In coastal regions, fish farming has been significantly reported, along with engagement in mariculture activities such as the farming of milkfish (*Chanos chanos*) in ponds and cages, Zanzibar tilapia (*Oreochromis hornurum urolepis*), shrimp collecting and farming, and crab fattening (Mirera et al. 2014, 2023; Holeh et al. 2020). These activities aimed to enhance the livelihoods of the coastal community in Kenya and boost nutritional demand associated with fish protein (Golden et al. 2017; Syanya et al. 2023a). Another milestone in the aquaculture sector in Kenya was reported in response to the escalating demand for fish in local markets. Intensive cage fish farming was introduced in Lake Victoria, Kenya, in 2013, and the number of cages in the lake has been progressively increasing each year (Njiru et al. 2019; Syanya et al. 2023b). The Kenyan side of Lake Victoria alone is reported to have over 6,000 cages dedicated to intensive Nile tilapia production (Aura et al. 2020). These cages have recorded enormous unprecedented cases of escapees of farmed fishes within the lakes. Owners of fish cages have reported cage breakage and the fish escapees into the lake (Njiru et al. 2019).

Despite the increase in fish production through cages and land-based pond systems, which is currently being heavily promoted by the Aquaculture Business Development Program (ABDP), a program under collaborative funding from the International Fund for Agricultural Development (IFAD) and Kenya Fisheries Service, the aquaculture sector still faces various challenges. These challenges include impacts of climate change, which have led to the breakdown of pond culture systems and cages in open waters of Lake Victoria. This not only caused significant financial losses for fish farmers in the country but globally, as reported by Jensen et al. (2010a) in Norway, but also led to an increase in the number of escaped Norwegian salmon species into natural aquatic ecosystems such as rivers, lakes, reservoirs, and dams. However, the specific impact of aquaculture escapes on aquatic biodiversity in Kenya remains scantily reported and documented. Similarly, based on different species of tilapia, which are the dominant fish species in Kenyan aquaculture, farmed Nile tilapia (*O. niloticus*) and North African catfish (*C. gariepinus*) (Opiyo et al. 2018; Munguti et al. 2022) have been widely reported in open natural waters following the heavy rainy season, indicating that flooded ponds were associated with escaped cultured fish.

Unintentional fish escapes from ponds to the ocean along the coastal region have been reported. Fujita et al. (2023) suggested that offshore farm site infrastructure vulnerability to weather events and vessel collisions may contribute to escape incidents. The robust design of structures like cages and pens aims to prevent unintentional escapes, emphasizing their capability to withstand powerful waves and tides.

North African catfish, known for its hardiness and market demand, faces challenges in pond culture due to burrowing behaviours causing escapes into natural aquatic ecosystems (Aura et al. 2020). Fishermen along rivers and Lake Victoria wetlands report cases of catfish disrupting local ecosystems by preying on native fish species. The invasive nature of North African catfish globally, including its ban in Indian water systems (Singh and Lakra 2011; Khan et al. 2021; Chakma et al. 2024), highlights its detrimental impact on indigenous aquatic fauna.

Ornamental fish farming in Kenya, particularly of non-indigenous species, is a rapidly growing industry contributing to the economy. However, the lack of policy enforcement leads to the unregulated disposal of ornamental fishes into aquatic ecosystems, posing ecological risks. Implementing clear policies for quarantine and disposal, as suggested by Opiyo (2016) and Sandilyan 2023, is essential to ensure the sustainable development of ornamental aquaculture and hence reduce the cases of release of ornamental fishes in the wild.

Tilapia production witnessed a substantial increase in 2014, reaching 18,000 t, while common carp farming trended upward (Figure 4). Escapes of common carp into natural ecosystems in central Kenya were observed, impacting local ecosystems. Hyder (1970) observed an increased population of common carp within Lake Naivasha, despite them being non-native to the lake.

The invasive Nile tilapia poses a threat to native tilapia fish species in Lake Victoria through interbreeding, leading to changes in genetic integrity. The unregulated increase in fish cages in Lake Victoria is deemed a significant threat to aquatic biodiversity (Njiru et al. 2019). The accumulation of biofouling from waste in fish cages has detrimental impacts on zooplankton and phytoplankton within lake ecosystems. This affects breeding sites of various fish species, as cages are designed along sheltered shorelines of lakes (Aura et al. 2018; Opiyo et al. 2018).

Rainbow trout (*Oncorhynchus mykiss*), commonly cultured in central Kenya (Munguti et al. 2014; Syanya et al. 2024; Weyl et al. 2017), faces unintentional escapes during flooding events from upstream trout farms. Escaped rainbow trout may disrupt local ecosystems, emphasizing the importance of understanding their thermal requirements to predict potential spread in diverse environments (Jensen et al. 2010a; Peeler et al. 2011; Benjamin et al. 2013). Therefore, mariculture and aquaculture practices in Kenya and Tanzania bring economic benefits but pose environmental challenges such as unintentional fish escapes and invasive species. Effective policy implementation is crucial to mitigate these challenges and ensure sustainable development in the aquatic farming industry.

Aquaculture production in Tanzania and incidents of unintentional escapees

Tanzania exhibits significant potential for advancing aquaculture, driven by favourable climate and land conditions conducive to fish farming. The increasing demand for fish, attributed to population growth and rising incomes, further enhances the promising prospects of the aquaculture sector. Mzula et al. (2021) note a decline in wild fish catches in Tanzania, particularly from Lake Victoria and Tanganyika, owing to climate shifts, environmental degradation, and instances of overfishing. Consequently, households are increasingly turning to aquaculture to supplement diminishing capture fisheries production.

While aquaculture has become imperative for the country's fisheries, associated side effects have not received sufficient attention from stakeholders. Salin and Arome Ataguba (2018) reported environmental concerns related to aquaculture, including the use of chemicals and biodiversity alteration in natural aquatic ecosystems due to unintentional escapees, which are inconsistently reported globally. The history of aquaculture in Tanzania traces back to 1927 with the introduction of rainbow trout from Scotland into streams around Mount Kilimanjaro and the Mbeya region for sport fishing purposes (Mmanda et al. 2020). Subsequent efforts involved experimental tilapia farming in the Tanga and Mwanza regions. Post-independence in 1961, there was a surge of interest in aquaculture among rural communities, supported by government and non-governmental organizations providing communities with fingerlings and technical and financial aid (Charisiadou et al. 2022). Inland aquaculture, particularly of Nile tilapia and North African catfish, has experienced significant growth, with over 21,000 freshwater ponds estimated across mainland Tanzania (Charisiadou et al. 2022). Nile tilapia dominates fish production, reaching about 25,000 t in 2021, with a steady increasing trend over the last decade (Figure 5) (Research and Markets 2023). The production of spiny (*Eucheuma denticulatum*) has been declining from 2017 to 2021, while there was an impressive improvement in the production of North African catfish in 2018 (Figure 5). This data reveals the dynamic nature of Tanzania's aquaculture sector and its contributions to the country's fisheries.

Milkfish (*C. chanos*) stands out as the most commonly farmed finfish for mariculture activities among coastal communities in Tanzania. According to Shalli et al. (2024), the adoption of milkfish farming traces back to the late 1990s in Zanzibar, where initial trials were conducted in Makoba ponds. Milkfish has become a favoured mariculture species along the coastal regions of Tanzania and Kenya due to its herbivorous dietary preferences and robust tolerance to salinity and temperature fluctuations (Charisiadou et al. 2022). Consequently, it is integrated into various mariculture systems, including cages, pens, raceways, and earthen ponds (Mosha and Daudi, 2020; Shalli et al. 2024), and is currently being explored in the Integrated Multitrophic Aquaculture (IMTA) approach. This approach is being implemented by WorldFish under the Asia-Africa BlueTech Superhighway project, supported by the UK's Climate and Ocean Adapta-

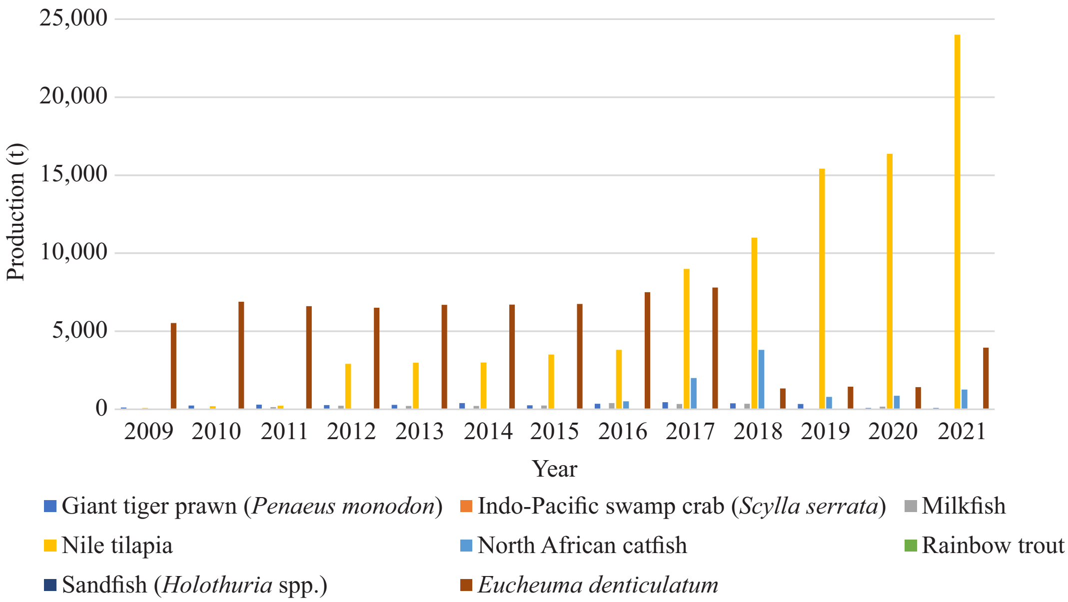

Figure 5. Trend of aquaculture production in Tanzania in terms of species in the last decade (FishStatJ database –FAO 2023).

tion and Sustainable Transition (COAST) program, part of the Blue Planet Fund. This initiative is set to be implemented in Kenya, Tanzania, Mozambique, Nigeria, and Bangladesh (WorldFish 2023). The success of this project is anticipated to pave the way for the sustainable development of mariculture in Kenya and Tanzania through the adoption of environmentally sound IMTA technologies along the coastal regions.

Currently, milkfish aquaculture primarily occurs in coastal earthen ponds located behind mangrove formations (Shalli et al. 2024), leveraging the nutrient-enriched environment provided by mangroves, as highlighted by Proisy et al. (2018) and Sreelekshmi et al. (2022). This approach was observed in India when shrimp ponds were abandoned. However, the current milkfish production in Tanzania falls short of meeting the escalating coastal population needs due to various challenges. These challenges include reliance on wild fingerlings, insufficient technical and financial support, gaps in market information, escapee cases due to pond flooding during high tides, and issues related to feeds and predation (Shalli et al. 2024). Nonetheless, the effectiveness of government and stakeholder interventions in addressing these challenges and enhancing milkfish production remains uncertain.

Fish farming in Tanzania is predominantly concentrated in the Ruvuma, Iringa, and Mbeya regions in the southern highlands, as well as the Kilimanjaro region in the north (Mmanda et al. 2020; Mzula et al. 2021; Chuhila et al. 2024). These regions are susceptible to aquaculture escape incidents, mainly associated with the collapse of pond systems during heavy rainfall and subsequent flooding events. Notably, Nile tilapia is the predominant farmed fish species, accounting for over 90% of total aquaculture production in the country. There have been sporadic reports of Nile tilapia in rivers following heavy rains or flooding incidents (Mulokozi et al. 2020a; Mramba and Kahindi 2023). In 2021, the total production of Nile tilapia exceeded 25,000 t (FAO 2023) (Figure 5).

Unlike Uganda and Kenya, where fish farming has reached advanced stages, Tanzanian aquaculture sector remains predominantly small-scale, with farmers typically owning modest-sized fish farms featuring one or a few small ponds ranging from 150 to 300 m^2 in size (Akoll and Mwanja 2012; Mosha and Daudi 2020; Mramba and Kahindi 2023). Consequently, the contribution of aquaculture to total fish production in Tanzania stands at a modest 4%, a figure significantly lower than the global average 46% (Mulokozi et al. 2020b). This limited production of farmed fish from aquaculture has mitigated the risks associated with unintentional aquaculture escapees in both freshwater and marine aquatic ecosystems. However, there are still numerous unreported cases of aquaculture escapees in the Tanzanian aquaculture sector believed to be detrimental to the biodiversity of aquatic ecosystems, especially due to failures in the culture system.

Despite the relatively limited scale of aquaculture activities, the occurrence of high tides along the coastal regions of Tanzania has also led to the breach of milkfish ponds, resulting in an increase in instances of farmed fish escaping into the natural aquatic marine ecosystems. Additionally, there have been reports of North African catfish being observed in the natural aquatic ecosystems along with socio-economic impacts associated with aquaculture on the local communities in the country (Slater et al. 2013).

Over the past decade, the aquaculture sector in Tanzania has experienced significant growth, attributed to the establishment and restructuring of the Aquaculture Development Division (DOA) in 2009, tasked with overseeing all aquaculture activities under the Ministry of Livestock and Fisheries Development (Mosha and Daudi 2020). Notably, the period between 2017 and 2021 witnessed a substantial increase in fish production, increasing from 11,800 t in 2017 to over 26,000 t (Figure 5). This upward trend is an indicator of the positive impact of institutional initiatives in the aquaculture sector. However, the same impact should be reflected in the control measures to curb the impacts associated with unintentional aquaculture escapees that are occasionally reported. Heightened demand for specific fish species, such as the North African catfish, has also been reported among the local fishermen along Lake Victoria for use as baits (Berg et al. 2021; Peter and van Zwieten 2022). Consequently, there has been an increase in the farming of North African catfish along the shores of Lake Victoria. However, its common use as bait has raised concerns, as this species has been reported to infiltrate natural aquatic ecosystems from fish farms and cages, notably within Lake Victoria, leading to its invasive presence. Furthermore, there have been reports of advancements in certain areas surrounding Lake Victoria, characterized by the establishment of larger vertically integrated production units that incorporate cage farming (Syanya et al. 2023b). This suggests a diversification and scaling-up of aquaculture practices in response to the growing demand and evolving dynamics of the sector.

Aquaculture production in Uganda and scenario cases of unintentional escapees

Uganda ranks as the third-largest contributor to aquaculture production in Africa, following Egypt and Nigeria. The nation plays a pivotal role in supplying aquaculture-related products, including fingerlings, fish feeds, and various inputs, to neighbouring countries such as Kenya, Tanzania, DRC, and Rwanda (Adeleke et al. 2021). Within Sub-Saharan Africa, Uganda secures the second position in aquaculture production, witnessing substantial growth from 800 t in 2006 to an impressive 138,558 t in 2021 (FAO 2022b) (Figure 6). Over 24,000 Ugandans are directly or indirectly engaged in the aquaculture sector. The fish industry is considered a valuable commodity, contributing 3.7% to Ugandan national GDP (Pearson et al. 2013; Research and Markets 2023).

The initiation of serious aquaculture in Ugan-

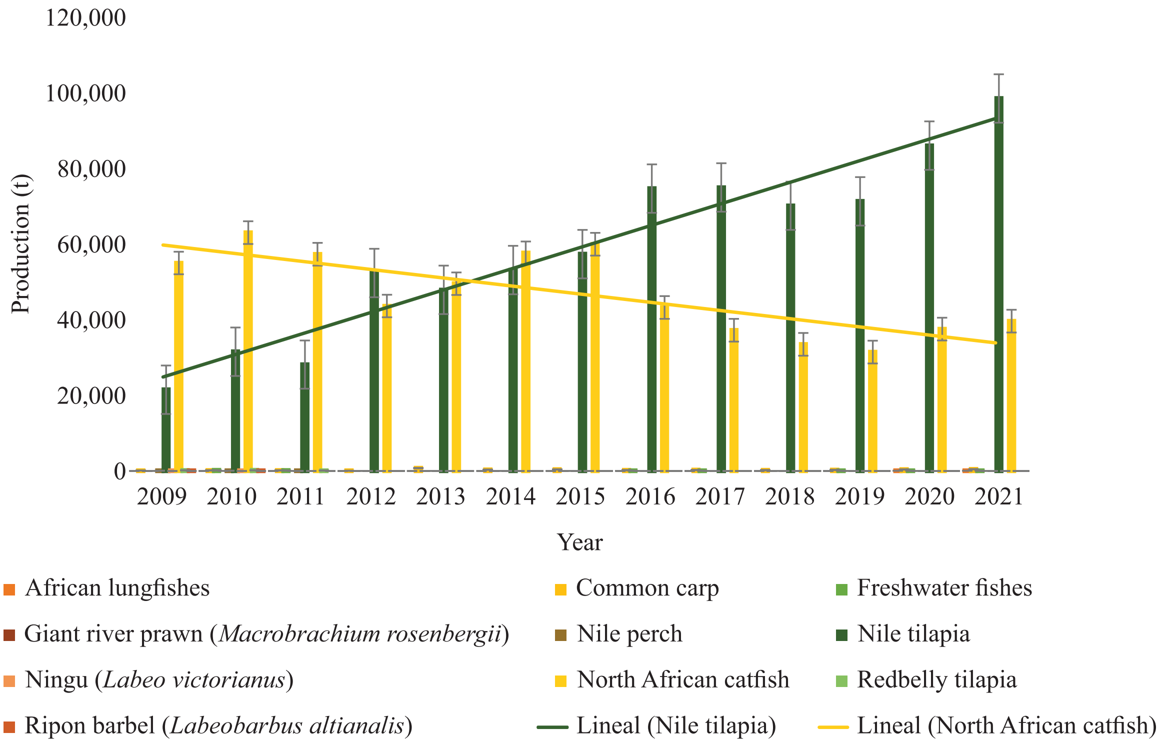

Figure 6. Trend of aquaculture production in Uganda in terms of species in the last decade (FishStatJ database –FAO 2023).

da dates back to 1953 with the establishment of the Kajjansi Experimental Fish Hatchery Station. According to Bolman et al. (2018), Adeleke et al. (2021), and Tumwesigye et al. (2022), the primary objective of introducing aquaculture in Uganda was to enhance the nutritional well-being of local communities in the rural setting of Kajansi. The goal was to provide an affordable source of animal protein with the ultimate aim of alleviating malnutrition among impoverished rural populations. However, aquaculture in Uganda can be traced back to 1941 with the importation of carp into the country and the subsequent establishment of the Kajjansi Fish Experimental Station in 1947 by the colonialists (Robledo et al. 2024).

The introduction of carp stirred controversies, as disagreements emerged among leading scientists regarding the potential adverse impact of common carp on the indigenous aquatic environment if they escaped from fishpond. Carps were initially considered invasive and capable of causing harm to indigenous fish species in local water ecosystems, such as streams and rivers. The conclusive decision favoured prioritising tilapia over carp as the primary fish species for introduction into Ugandan water bodies (Dadzie 1992; Tumwesigye et al. 2022). Consequently, the government implemented an intensive fish farming extension program with major pond construction in the southwestern part of the country and in the central region of Buganda, where Kabaka exercised control (Kigezi) (Dadzie 1992; Akena and Mwesigwa 2021). The potential risk of aquaculture escapees from these ponds entering the natural aquatic ecosystem was not considered by fisheries experts at that time. Decades after the inception of aquaculture activities in Uganda, serious cases of pond breakdown due to flooding have been reported across the country (Mugisha et al. 2007). However, the actual impact threshold of escapes from fish ponds to the natural aquatic ecosystem in Uganda remains poorly documented.

The aquaculture sector in Uganda is divided into three main farming practices: subsistence fish farms, semi-commercial fish farms, and commercial fish farms (Adeleke et al. 2021). Small-scale fish producers typically focus on local markets, while semi- and fully-commercial fish farms aim at regional markets, expanding to neighbouring countries like Burundi, Congo, and Kenya. Recent analyses of the fish market in Uganda indicate that commercial viability holds significant potential for expanding aquaculture production in the country (Jagger and Pender 2001; Kigongo Sserwambala et al. 2017). According to data from the FishStatJ (FAO 2023), *O. niloticus* has emerged as the predominant species for aquaculture in Uganda, with production of over 80,000 t in 2021 (Figure 6). This increase can be attributed to the implementation of advanced cage culture programs in the country, with *O. niloticus* being the main species employed in such systems (Mbowa et al. 2017; Mutyaba et al. 2024). The incidence of aquaculture escapes into natural water bodies resulting from the proliferation of fish cages in the country is not well-understood. With the continually changing climate in Lake Victoria, which has witnessed a rise in the number of fish cages (Kashindye et al. 2015; Opiyo et al. 2018; Njiru et al. 2019), particularly stocked with *O. niloticus*, the potential for cage system failure is elevated. Currently, there are no measures to control unintentional fish escapes from these cages into the natural aquatic bodies of Uganda's major lakes, including Lake Victoria, Kyoga, and Lake Albert. Indeed, instances of unintentional aquaculture escapes exist in Uganda but are not adequately documented or reported. Furthermore, the relative simplicity of fish seed production for *O. niloticus* compared to other species contributes to its widespread popularity. The cultivation of *C. carpio* has gradually diminished to nearly negligible levels (Figure 6) (FAO 2023). Similarly, *Coptodon zillii* has been disregarded by farmers due to its sluggish growth rate, with preference given to Nile tilapia within the pond culture system. Several minor fish species introduced in the country for aquaculture purposes.

Addressing risks and knowledge gaps in unintentional aquaculture escapees' impact on ecosystems

Recent reports highlight concerns about the escape of fish bred through aquaculture, posing a global threat to biodiversity and aquatic ecosystems. Quiñones et al. (2019) noted that escapees from aquaculture could pose two distinct risks to aquatic organisms and the overall ecosystem: genetic impacts and ecological modifications. The primary worry surrounding fish escaping from aquaculture facilities in various countries lies in their potential to negatively affect wild stocks and the entire aquatic ecosystem. Ecological consequences of aquaculture escapees are worrying, but not enough attention is paid to assessing their impact on aquatic ecosystems. This can manifest itself through competition for resources or habitat, transmission of diseases, or interbreeding.

Fish escapes may happen during severe weather events such as storms, flooding damaged nets, or during harvesting period where the harvested fish escapes from fishing net or holding tanking into the natural water bodies especially for cages (Hindar et al. 2006; Thorvaldsen et al. 2015; Siddique et al. 2022). Aquaculture has been linked to the introduction of invasive alien fish species, where most of these species are believed to be associated with aquaculture activities (Arechavala-Lopez et al. 2012). However, it is crucial to understand that aquaculture should not bear sole responsibility for the majority of invasive fish species in various aquatic ecosystems globally. Accidental introductions of unrelated invasive fish species through unintentional aquaculture activities remain unidentified (Casal 2006). Consequently, the only pathway for such introductions appears to be solely through unintentional aquaculture activities.

In aquaculture, the primary objective is generally to culture fish within a controlled system and subsequently harvest them for the market (Munguti et al. 2022; Nair et al. 2023; Syanya et al. 2023a). Less attention is given to the potential adverse effects associated with the escape of aquaculture-bred fish to the ecosystem during the farming process. Despite the fact that Gozlan (2008) and Singh (2014) both eluded that aquaculture is directly linked to instances of alien escapees in various aquatic ecosystems, contributing to the distribution of approximately 17.6% of non-native fish species globally, there has been insufficient policy action to regulate the potential impacts of aquaculture on wild fish species.

Furthermore, Arechavala-Lopez et al. (2013) found that nearly about 19% of the global finfish under capture production is derived from non-native species that were previously under aquaculture, potentially escaping from aquaculture holding units to natural waters. Notably, popular aquaculture species such as Nile tilapia (Johnson et al. 2022) and North African catfish (Vitule et al. 2006) commonly cultured in Asian countries such as India, Thailand, Bangladesh, and Vietnam as non-native fish species, have been reported in the wild aquatic ecosystems, leading to cases of invasiveness among indigenous fish species following their colonization of natural environments like rivers and lakes. These farmed fishes, particularly Nile tilapia, have demonstrated faster growth than indigenous species in these countries, becoming the preferred cultured tilapia fish species, particularly in China and India (Wang and Lu 2016; Yuan et al. 2017; Arumugam et al. 2023).

A similar scenario was documented in Chile, where the introduction of salmonids facilitated the rapid growth of the aquaculture industry. According to Sepúlveda et al. (2013) the country is reported to contribute nearly 21% of the global farmed salmon and directly employs over 32,000 people. However, escapees from salmon cages in Chile have been identified in natural ecosystems, leading to their colonization and significant impacts on indigenous fish species, affecting biodiversity and genetic modification through interbreeding.

Escapes, whether intentional or unintentional, from aquaculture have been reported to have detrimental effects on the introduced aquatic ecosystems. The practice of introducing fish intentionally and unintentionally has historical roots dating back to the first century in Rome, where common carp were transported from rivers to reservoirs for artificial maintenance and feeding (Bianco and Ketmaier 2015). Later on, the Fish Commission in Rome, Italy, initiated the importation of different alien carp species from Germany with the aim of enhancing the national food supply and nutritional value (Castaldelli et al. 2013). These imported carp species were subsequently found to infiltrate natural wild ecosystems by competitively outcompeting indigenous wild fish species in terms of food availability and causing ecological modifications.

A comparable situation was documented by Chick et al. (2003) in the USA, Canada, Mexico, and Ecuador, where around 2.6 million carp seeds were introduced as an alien species. Currently, introduced carps, particularly the black carp (*Mylopharyngodon piceus*), are reported as the most abundant yet underrated freshwater fish in North America (Li 1999; Kroboth et al. 2019). Incidences of carp escaping from aquaculture units into the natural environment have been extensively reported in the USA, Canada, and Mexico, leading to ecological impacts on aquatic ecosystems. As most carp species are herbivorous and inherently competitive for resources, they pose a challenge to indigenous fish species. A comparable situation has also been documented in India, where grass carp and common carp have penetrated the natural aquatic ecosystem from aquaculture facilities such as earthen ponds and Rice paddy especially in states like Gujarat (Munilkumar Nandeesha 2007; Chaudhari et al. 2023). These carp species have been subsequently identified as invasive to the aquatic environment, posing a threat to biodiversity.

Similarly, cases of Atlantic salmon escaping from cages into natural water ecosystems have been reported in regions like British Columbia, Canada, the USA, and Chile, where Pacific salmon is also farmed (Sepúlveda et al. 2013; Soto et al. 2023). This not only resulted in significant losses for the aquaculture industry but also raises ecological concerns for the aquatic biodiversity and ecosystems where these escaped fish end up. One of the most severe cases of escape from aquaculture involved approximately 2000 Atlantic salmon (Salmo salar) and was reported in British Columbia (Skilbrei and Jørgensen 2010; Li et al. 2015). Initially thought to be escapees from salmon farms, these fish were later caught a year later. Searching for aquaculture escapees in the natural aquatic ecosystems in these countries is regarded as a conservation measure to mitigate the impact of escapees on the aquatic flora and fauna.

In Northern Ireland and Norway, the annual average percentage of farmed salmon escaping from cages and subsequently caught in the wild has been reported to range from 0.26 to 5.4 (Hansen 2006; Fredheim et al. 2010; Hansen and Youngson 2010; Jensen et al. 2010a). Similarly, a significant proportion of farmed Atlantic salmon in Scotland, has been known to escape due to factors such as storms and equipment failure, subsequently being recovered in marine capture fisheries (Stevens et al. 2018). The implementation of recovery measures represents one of the regulatory and control approaches in Europe aimed at reducing the impact of aquaculture escapees on natural aquatic biodiversity.

Additionally, the escape of the giant Malaysian prawn (*M. rosenbergii*), originally introduced from Southeast Asia, has been documented in the USA. Woodley et al. (2002) recorded multiple instances of these crustaceans and their eggs escaping from culture units into the wild, although the full extent of their invasiveness in the aquatic ecosystem was not thoroughly documented. While intentional introductions of fish for food and sport are comprehensible, the distribution of small non-indigenous fish species with no apparent value lacks clear explanation in the literature.

The environmental consequences of escaped fish species from aquaculture system are manifold, as documented in the United States of America (Pimentel et al. 2005). These repercussions entail various aspects, including predation (De Silva et al. 2009), competition, alterations of aquatic habitats

(Bueno et al. 2021), and changes in the genetic makeup of native conspecifics (Katsanevakis et al. 2014; Abd Hamid et al. 2023a). Nonetheless, responses of natural communities to invasive species are intricate, and the outcomes can be positive, negative, or negligible, depending on factors such as species involved, location, age, or type of habitat (van der Veer and Nentwig 2015). Therefore, not all escapes from aquaculture inherently pose invasiveness to the aquatic ecosystem. The invasiveness depends on the ecology of the species.

The escape of farmed fish from sea cages can have adverse effects on wild populations, both genetically and ecologically; due to competition with wild fish stock for limited resources. The current prevalence of escapees is viewed as a significant concern for the long-term sustainability of sea cage aquaculture in Norway, as emphasized by (Glover et al. 2012). Similarly, Fredheim et al. (2010) and Jensen et al. (2010b) reported that over 325 million Atlantic salmon in Norway were typically held in sea cages, the magnitude of escapees surpasses the annual return of approximately 500,000 to 1 million salmon from the ocean to Norwegian rivers for spawning, as reported by the Norwegian Directorate of Fisheries in 2009 and the Scientific Advisory Committee in the same year.

While effects of environmental impacts of escaped alien fish species on wild populations have been extensively studied in the context of Atlantic salmon, with considerable research on these interactions, there is comparatively limited information available regarding the impact of other fish species in developing countries such as Kenya, Tanzania and Uganda. Depending on whether escapees and introduced alien fish species for aquaculture purposes contribute to a decrease or increase in habitat complexity, invasive escapes can either enhance or deplete species diversity (Ricciardi and Kipp 2008; Taylor and Dunn 2017). While the effects on non-indigenous fish species are varied, this study focuses specifically on the consequences of introduction of fish species into foreign regions for aquaculture purposes (alien non-indigenous aquaculture species) which were subsequently reported to have escaped from a culture system into the wild.

Among the five major regions identified as global hotspots for marine biodiversity, Indonesia and the Philippines are significant aquaculture producers (Raghavan et al. 2008; Krishnakumar et al. 2011). In 2010, 66% of Chilean aquaculture production, one of the top 25 hotspots, consisted of introduced non-native alien species associated to aquaculture escapees (Sepúlveda et al. 2013). One notable impact of non-native aquaculture escapees fish species is the competition with native fish species for available food and resources. For instance, brown trout (*Salmo trutta*) (Lobón-Cerviá and Sanz 2017) and rainbow trout (Stanković et al. 2015; Taranger et al. 2015) are large, generalist predators consuming numerous native fish species, leading to declines in wild aquatic indigenous fish species and loss of biodiversity. These fish species engage in competition and interbreeding with native counterparts, facilitating the transmission of exotic diseases. Their primary influence is documented as predatory behaviour, as they consume small native fish species and displace indigenous species from their aquatic habitats to evade predation. Brown trout have also been observed to compete with native fish species for food in its juvenile stage, transforming into predator as they mature. This impact is particularly pronounced in Australia and New Zealand, where freshwater fish have thrived in the absence of larger fish species (Crowl et al. 1992).

The introduction of grass carp (*C. idella*) and bighead carp (*Aristichthys nobilis*) from the Yangtze River to the southern Chinese provinces of Guangdong, Guangxi, and Yunnan, for aquaculture purposes, has had a severe impact, leading to the extinction of local fish species due to cases of escapees into the wild (Wang et al. 2015; Zhao et al. 2015). This explains the profound influence that an intentional non-native escapees fish species can exert on the biodiversity of aquatic organisms.

The unintentional introduction of the Mediterranean mussel (*Mytilus galloprovincialis*) in South

Africa, has resulted in its prolific presence along the South African coast after having escaped from holding units (Branch and Nina Steffani 2004). This has led to a decline in native aquatic organisms and consequential changes in marine biodiversity.

Another consequence associated with unintentional escapes of non-native invasive fish species from aquaculture is the genetic impact in aquatic ecosystems. Inbreeding practices in aquaculture have contributed to the development of genetic complexity in marine biodiversity of fish populations (Canonico et al. 2005; Castaldelli et al. 2013; Nobinraja et al. 2023). Non-native and aquaculture escapees can serve as disease vectors to wild fishes, even if they are not invasive. According to Peeler et al. (2011), diseases can be transmitted in Europe with the movement of cultured fish into the wild. Woodley et al. (2002) also expressed concern that *M. rosenbergii*, introduced by aquaculture along the Mississippi River could act as a disease vector detrimental to other marine aquatic organisms.

The introduction of non-native fish species can significantly impact new ecosystems. Many biological invasions have resulted in a net gain at local and regional levels, causing an overall increase in diversity in the ecosystem. For instance, as indicated by Xiong et al. (2023) and Yongo et al. (2023), tilapias contributed to the suppression of benthic algal growth by inducing sediment resuspension, degrading water quality, and intensifying eutrophication in Chinese freshwater systems. Additionally, these fish species lead to a reduction in the biomass of native fish species through competitive interactions, posing a potential threat to fish biodiversity. Therefore, the direct removal of tilapias can serve as an effective strategy for their control and prevent the invasion and proliferation of tilapias. Countries with high tilapia production such as Kenya, Tanzania and Uganda may be experiencing a similar situation. However, less study has been done on how tilapia escapees from aquaculture culture farms affect aquatic ecosystem in these countries.

Additionally, alterations in an ecosystem by the aquaculture escapes have the potential to diminish biodiversity. One example is the significant impact that tilapia can have on the ecosystems it invades, though predicting the extent of this impact is often challenging, as seen in China (Yongo et al. 2023). The redbelly tilapia (*C. zillii*), inadvertently introduced into the riverine and Shadegan wetlands of Iran, has diminished all aquatic macrophytes through grazing, coinciding with the decline in native fishes. According to Tabasian et al. (2021), the herbivorous nature of the redbelly tilapia raises concerns about potential ecosystem changes that could negatively impact native species, particularly those commercially valued. The reluctance of fishermen to catch this species presents challenges both in physically removing it and managing its population growth, a similar situation found in riverine systems of North Carolina, USA (Cassemiro et al. 2017).

Common carps can also attain high densities, leading to elevated water turbidity preventing photosynthetic activities in culture units such as ponds and subsequently reducing the abundance of aquatic plants. According to Weber and Brown (2009), the influence of common carp on ecological processes extends to bottom-up effects, altering nutrient and turbidity levels, as well as the abundance and diversity of phytoplankton, primarily through benthic foraging. Concurrently, Yaqoob (2021) reported top-down effects observed on zooplankton and benthic invertebrates due to predation and decreased foraging efficiency as an impact of the common carp in India. Additionally, the reduction of aquatic macrophytes by this species contributes to the potential shift of lakes from clear to turbid water equilibrium. Although important fish species are cultivated in Uganda and Kenya, there has been limited consideration for the potential repercussions of *C. carpio* on natural aquatic ecosystems. This lack of attention is attributed to the absence of documented incidents involving *C. carpio* escapees into the wild in these countries. This creates a research gap because adverse weather conditions can cause system failures, but occurrences of aquaculture escapees remain poorly documented.

Pinto et al. (2005) reported that an 8-year program aimed at removing non-native common carps and goldfish (*Carassius auratus*) from the Botany wetlands of Australia resulted in a significant reduction of cyanobacterial counts and 25% increase in transparency of the Secchi disc. This was expected to enhance biodiversity in the aquatic ecosystem. Similarly, Japanese brown seaweeds (*Colpomenia* spp.) have become problematic in European oyster farms due to their gas-inflated bodies, attaching to oysters and carrying them away, earning it the common name 'oyster thief' for this species (Fletcher and Farrell 1998).

However, on a better side of the coin, some fish species escape aquaculture facilities and create new habitats. These species can introduce habitat complexity, which may, in the long run, enhance species biodiversity. For instance, areas with soft sediments hosting invasive gastropods and mat-forming mussels were reported to exhibit higher species diversity and abundance compared to non-invaded areas (Crooks 2002).

Similarly, concerning the economic consequences for fish farmers, it is evident that escapees from aquaculture significantly impact the production and income of fish farmers. However, there is limited information available on the direct costs of escapes from aquaculture in any specific cultured unit. Currently, the European Union's Research Framework project, Prevent Escape, is evaluating the cost of escapes to the fish farming industry across Europe (Ju et al. 2020). The true cost of escapes remains unknown as some incidents go unreported.

Reported escapes of salmon result in average losses of negligible value, accounting for less than 0.15% of the fish cultured under cages in Norwegian waters (Madhun et al. 2023). The relative cost of escape cases is lower than the actual expenses incurred for repairing the cage facility and recapturing escaped fish. European regulations demand that escapees from aquaculture should be recaptured from the natural ecosystem at the expense of the individual farmer (Hansen 2006; Skilbrei and Jørgensen 2010). This makes handling escapee cases in aquaculture more economically challenging. However, in developed countries, insurance claims are likely to offset these costs.

The most significant cost of escapes to the industry is indirect, as it damages the industry's reputation. In Europe, escape events are often widely reported in the popular press, casting a negative light on the industry and tarnishing its reputation (Ju et al. 2020). In India and East African countries, escapees from aquaculture are not recaptured, causing them considered lost stock. This has been identified as one of the losses in aquaculture. Although the Indian aquaculture system has developed to the point of having insurance policies (De and Pandey 2014; Xiong et al. 2017; Nair et al. 2023), these policies do not cover unintentional escape cases and related economic impacts. Nevertheless, aquaculture systems in Kenya, Uganda, and Tanzania lack well-elaborated control policies to monitor and report cases associated with aquaculture escapees into the wild. There is no policy on mandatory insurance and recapture of escaped fish from the aquatic ecosystem back to holding units. This lack of regulation has rendered the aquaculture sector detrimental and perceived as lethal to the aquatic ecosystem.

Aquaculture escapees proposed control measures at different spatial levels

Proposed aquaculture escapees control measures and methodologies aim to mitigate further impacts in India, Kenya, Tanzania, and Uganda through a combination of regulatory frameworks, community engagement, and technological innovations. In India, strict enforcement of aquaculture escape-proof cage designs and regular inspections in aquaculture facilities are crucial. Additionally, the adoption of underwater cameras and remote monitoring systems enhanced early detection and response capabilities since India has well advanced technology adoption in the aquaculture sector.

In Kenya, community-based initiatives play a pivotal role in aquaculture escape related case prevention. Training local fishers in cage maintenance at Lake Victoria regions and escape prevention techniques empowers communities to actively participate in safeguarding aquaculture operations. Collaborative efforts between government agencies and NGOs further strengthen aquaculture escape control strategies, fostering knowledge exchange and awareness raising among aquaculture fisheries and biodiversity conservationist stakeholders.

Habitat restoration projects are proposed in Tanzania to mitigate aquaculture escape related impacts in Tanzania. By rehabilitating natural habitats in affected areas, these projects aim to restore ecological balance and reduce the proliferation of escaped fish species into the aquatic ecosystem. In addition, targeted efforts to remove aquaculture escapes from natural aquatic ecosystems are essential for managing invasive fish populations and preventing their future spread.

Similarly, regulatory enforcement combined with community participation is emphasized in Uganda. Strict adherence to aquaculture licensing requirements ensures compliance with escape prevention protocols, while community-led monitoring programs enable swift detection and reporting of escape incidents, facilitating prompt response and containment efforts. The Kajjansi Hatchery and Research Centre, plays a crucial role in raising awareness among local fish farmers about the risks associated with escaped farmed fish species entering natural ecosystems. Supported by institutional backing from the Lake Victoria Fisheries Organization (LVFO) in Jinja, Uganda, and the Fisheries Training Institute located in Entebbe, it has been entrusted with the responsibility of leading training initiatives focused on aquaculture sustainability. These efforts also aim to promote the conservation of aquatic ecosystems by addressing the potential invasiveness of fish species escaping from aquaculture activities. These proposed control measures and methodologies give emphasis on the importance of a comprehensive approach involving regulation policy formulation, community engagement, and technological innovation to effectively curb the impacts of aquaculture escapees in these regions.

Policy implications, recommendations for enhanced escapees management and areas for further research

Policy implications for enhanced management of aquaculture escapees in other developed countries such as Norway, Scotland, Canada, USA and Ireland include but not limited to stricter enforcement of existing regulations, development of comprehensive escape prevention measures, and establishment of monitoring protocols (Hansen 2006; Hansen and Youngson 2010; Skilbrei and Jørgensen 2010; Li et al. 2015). Recommendations include implementing escape-proof infrastructure, enhancing fish health monitoring, and promoting responsible aquaculture practices. However, considering the ongoing trends in the expansion of aquaculture in India and the three riparian East African countries (Kenya, Uganda, and Tanzania), we anticipate a rise in unintentional escapes from fish culture units, including cages and ponds in the near future. Moreover, we predict that global aquatic biosecurity and the sustainability of aquaculture will face significant challenges unless a clear policy on controlling, managing, and reporting escapees related to aquaculture activities is established.

However, inefficiencies in policy regulations persist in many countries, including European nations such as Norway, Scotland, and Ireland, which have witnessed a surge in salmon escape cases from cages (FAO 2022a). India is not exempted from such concerns, as irresponsible farming of non-native fish species, such as tilapia, for short-term profits has been documented. Similarly, Kenya, Uganda, and Tanzania exhibit comparable issues, particularly with the intensive farming of African catfish, which is considered more invasive. Other developing countries heavily reliant on aquaculture, such as China, Indonesia, Bangladesh, and Taiwan, have reported cases of aquaculture escapees impacting natural wildlife (Abd Hamid et al. 2023b).

In light of these challenges, more effective management measures are imperative, especially in India where cage fish farming is transitioning to an intensive level, as well as in other developing countries such as Kenya, Uganda, and Tanzania. In this context, we propose four strategies to enhance aquaculture management and reduce instances of unintentional aquaculture escapes, thereby mitigating their invasion risks to the aquatic ecosystem.

Initially, the management of unintentional aquaculture escapees must be seamlessly integrated into the national, state, or county fisheries management systems. This integration is crucial for preventing and controlling the occurrence of aquaculture escapees, which could potentially be deemed invasive in the natural aquatic ecosystem. Countries like India and numerous developing nations signatories of the Convention on Biological Diversity should undertake comprehensive measures to address the introduction, control, and eradication of non-native fish species in their waters. Such species should be designated exclusively for aquaculture purposes, ensuring they never enter the marine ecosystem.

In the three riparian countries moving in this direction, amendments to fisheries laws may be necessary. For example, the Kenya Fisheries Development Act of 2016 could be amended to incorporate control measures and punitive actions against fish farmers whose fish escape into the wild. Similar to the practices in Scotland and Norway, fish farmers should bear full responsibility for recapturing escaped farmed fish from holding units, as well as maintaining a clear insurance policy covering escape incidents resulting from failures in aquaculture system. While this scenario may seem complex for developing countries such as Kenya, Uganda, and Tanzania, it is crucial to establish effective laws to regulate unprecedented cases of aquaculture escapees. Unfortunately, despite having robust fisheries laws in India, cases related to aquaculture escapees are inadequately addressed, despite being the world's second largest aquaculture producer. Galappaththi and Nayak (2017) and Katiha et al. (2005) highlighted several laws and regulations in India governing the management of non-native species related to aquaculture, primarily focusing on terrestrial species.

Therefore, we strongly recommend the introduction of a comprehensive law in India and the three riparian East African countries that encompasses all non-native species under intensive aquaculture, considering the potential for them to be classified as escapees. These fisheries laws should address prevention and early warning, risk assessment, detection and monitoring, as well as control and emergency response to cases of aquaculture escapees in these countries.

Secondly, there is a pressing need to establish an effective agency dedicated to monitoring the impacts of aquaculture on ecological biodiversity for the governance of unintentional aquaculture escapees in each of the three riparian countries and India. Currently, the responsibility for aquaculture management in these countries is fragmented among national, county, or state governments. For example, considering the existing administrative system in Kenya involving county and national governments, it is essential to have an interdepartmental agency under Ministry of Mining, Blue Economy, and Maritime Affairs to regulate the impacts associated with aquaculture escapees to the ecosystem. This agency would coordinate the management of aquaculture activities as a unified entity across the 47 county governments, a sector currently dispersed across various directorates and departments in different counties. This dispersion complicates the monitoring of the impact of aquaculture on the ecosystem. The proposed agency would be tasked with unintentional aquaculture escapees risk assessment, monitoring and control, adhering to sound management practices outlined in the FAO Code of Conduct for Responsible Fisheries and the Code of Practice on the Introductions and Transfers of Marine Organisms (Sanda et al. 2024) in India and other developing countries such as Kenya, Uganda, and Tanzania.

Thirdly, national planning standards need to be developed for the construction and operation of aquaculture facilities, particularly cages, which are currently the fastest-growing fish culture systems in Lake Victoria among the three riparian countries. This is also relevant for marine cage development in India due to the increasing number of IMTA systems in the Indian marine ecosystem. However, in India, Kenya, Uganda, and Tanzania, a significant portion of aquaculture is currently dominated by small- and medium-scale farmers whose facilities may not withstand large floods or severe storms exacerbated by climate change. This vulnerability makes them susceptible to aquaculture escape incidents, increasing the risk of non-native aquaculture species.

To mitigate unintentional aquaculture escapes, the establishment of national standards and planning should prioritize aquaculture zoning to reduce risks, especially for new aquaculture projects. This involves considering relocation to less exposed areas for existing farms. Additionally, measures should be taken to decrease shallow-pond aquaculture and prevent illegal aquaculture, particularly in flood-prone regions. Strengthening fish farming systems is crucial, incorporating improved holding structures for cage construction, such as sturdier and depth-adjustable cages, as well as deeper ponds.

To counteract the adverse effects of aquaculture escapes from facilities, fishery agencies in these countries must develop emergency plans and provide training to fish farmers on the proper disposal of escapees. Mobilizing local fish farmers to promptly recapture and eliminate escapees can be an effective strategy. Encouraging the farming of local or regional species, considered less invasive, is another crucial step in these countries. The emphasis should be on avoiding reliance on non-native or native invasive fish species for increased aquaculture production. While intensive aquaculture, whether with local/regional or non-native species, may pose environmental challenges, proper management can address these issues.

Regarding India, which boasts over 2,546 fish species of high economic value, it is vital to note that only about 28 species are commonly used for aquaculture (Nobinraja et al. 2023; Pragathi et al. 2023). The Indian government should, therefore, formulate policies to promote the use of local/regional species for aquaculture, mirroring the successful initiative undertaken by the state government of Kerala in promoting Karimeen. Karimeen (*Etroplus suratensis*) is a year-round delicacy in Kerala and is the preferred farmed fish species in the backwaters of the region (Aswathy and Imelda 2019).

Finally, there is a pressing need for comprehensive research and education focused on preventing and controlling unintentional aquaculture escapees. Despite global aquaculture studies predominantly concentrating on technology and disease control, the potential ecological impacts of many farmed fish species remain unknown (Naylor et al. 2021). Therefore, further research is crucial to gain a clear and coherent understanding of the socioeconomic and ecological risks linked to aquaculture escapees within aquatic ecosystems, adjacent areas such as river, lakes and sea in the distant regions, and the overall aquatic biodiversity since a clear empirical data is lacking on the threshold of effects associated with aquaculture escapees to nearby rivers and lakes within India and even worse in the three riparian countries of East Africa.

Equally vital is the mandatory inclusion of ecological education within the aqua cultural community, ensuring the rapid transfer of knowledge from research to aquaculture managers and the public. 'Translational scientists', often undervalued in developing countries, play a crucial role in enhancing the understanding of non-specialists regarding invasive non-native aquaculture escapees and conservation issues. Increased public understanding is paramount, as an informed public can exert pressure on authorities to formulate appropriate policies.

In conclusion, unreported cases of aquaculture escapes have already caused adverse ecological effects in India and the three riparian developing countries to the extent that is yet to be documented. The risk of aquaculture escapes is not adequately recognized by current conservation policies, and unless prompt action is taken, these escapes will continue to degrade aquatic ecosystems not only in the case study countries but globally. To preserve biodiversity and support sustainable aquaculture, the governments and citizens of both India and the three riparian countries must acknowledge and address the problems arising from aquaculture escape cases. Besides enacting legislation, each country should establish an agency to handle risk assessment, prevention, monitoring, and control of incidents of aquaculture escapes. Furthermore, integrated research and knowledge transfer should be strengthened, especially in the case of India. As the second-largest producer of aquaculture globally, India's efforts to control the impacts and cases of aquaculture escapees can serve as a model for other developing countries, including but not limited to Kenya, Uganda, and Tanzania, significantly contributing to the biosecurity and sustainability of global aquaculture.

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Conflict of interest statement

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Author contributions

Mahadevan Harikrishnan: conducted proofreading and editing, ensuring the clarity and coherence of the content. Fredrick Juma Syanya: conceived the manuscript and played a leading role in the writing process. A. R. Nikhila Khanna: conceived the manuscript and played a leading role in the writing process. Paul Mumina: contributed significantly to data analysis and presentation, drawing insights from the FishStat J FAO 2023 portal. Wilson M. Mathia: contributed significantly to data analysis and presentation, drawing insights from the FishStat J FAO 2023 portal. All authors actively participated in drafting the manuscript and provided their approval for publication.

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