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Diversification of Aquaculture Production in Relation to Global Change: The Case of the Domestication of Indigenous Euryhaline Catfish Species (Siluriformes) in the Mekong River Delta, Viet Nam

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ABSTRACT

The Mekong River Delta, the heart of Vietnam's aquaculture industry, is facing many challenges due to climate change, particularly salinity intrusion. In this context, this review aimed to assess the potential of indigenous euryhaline catfish species to diversify fish farming, strengthen food security, and build resilience in the region. Among the 1219 fish species recorded in the Lower Mekong Basin, 176 belong to the order siluriformes. Using a selection framework based on biological, ecological, market demand, and Aquaculture Readiness Levels criteria, 18 euryhaline catfish species were selected and analysed, with *Pangasius krempfi*, *Pangasius mekongensis*, *Mystus gulio*, and *Plotosus canius* emerging as the most promising candidates. These selected species are currently in the early phases of domestication and face key challenges. Of the four species, *P. krempfi* and *P. mekongensis* show high market value but are hindered by unreliable seed supply and significant knowledge gaps in breeding and other farming protocols. *M. gulio* appears as a promising candidate with already established reproduction techniques, though improvements in grow-out practices are required, while *P. canius* requires further research on artificial breeding and feeding optimization. For future developments, it is crucial to establish standardized hatchery protocols, broodstock management, improved farming practices, and species-specific formulated feeds. Additionally, as native species are locally consumed, implementing market-driven strategies is essential to increase profitability and ensure long-term sustainability.

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1 | Introduction

Aquaculture production is highly concentrated, with nearly 90% of global output derived from only 46 of the 730 species currently farmed [1, 2]. This trend is similarly reflected in the (Mekong River Delta) MRD, where aquaculture predominantly relies on a few species, including marine shrimp (*Penaeus monodon* and *Litopenaeus vannamei*) and striped catfish (*Pangasianodon hypophthalmus*), which together make up over 54% of the region's aquaculture production [3]. Such dependence on a limited number of species raises pressing concerns about biodiversity conservation and the long-term sustainability of aquaculture practices [4].

The Mekong River is one of the longest rivers in Asia, with a total length of about 4909 km, flowing from the Tibetan Plateau in China through Myanmar, China, Laos, Thailand, Cambodia, and Vietnam, where it forms a large delta [5]. The upper Mekong River Basin in China accounts for 24% of the total catchment area (795,000 km^2) and contributes about 15%–20% of the yearly water flow. On the other hand, the lower Mekong River Basin (LMB) encompasses 76% of the catchment and is primarily characterized as a broad, flat region [6, 7]. In the LMB, 1219 fish species have been documented [8–12]. The annual yield of capture fisheries in LMB was estimated at 2.3 million tonnes, worth approximately USD 11.15 billion in 2010 [13]. However, by 2020, this yield declined to 1.51–1.71 million tonnes annually, corresponding to USD 7.13–8.37 billion [14].

In the present study, we focused exclusively on the native siluriform group, not only due to their market acceptability, physiological adaptability, and favorable traits for aquaculture, but also to the existing foundation from the success of previously domesticated catfish species in the region (e.g., *P. hypophthalmus* and *Pangasius bocourti*). This provides valuable technical and practical insights for evaluating closely related species, thereby shortening the research and development timeline and enhancing the feasibility of establishing commercially viable aquaculture models.

Worldwide, approximately 3000 siluriform species are described, making it one of the largest teleost orders, accounting for up to 12% of all species [15]. Species in this order play important roles in commercial, subsistence, and recreational fisheries, as well as in aquaculture production systems [16]. Within the LMB, this order represents approximately 14% of the total number of recorded species, making it the second most abundant order with 176 species [8]. They exhibit traits that make them suitable as cultured species, including adaptability to intensive culture conditions, high fecundity, and resistance to a broad range of infectious diseases, and efficient feed conversion ratios [17–20]. Additionally, many siluriform species are devoid of intra-muscular bones, further increasing their desirability for aquaculture and consumer markets [17, 21, 22]. Some catfishes can tolerate low dissolved oxygen or even possess air-breathing organs (e.g., striped catfish *P. hypophthalmus*), which makes them particularly adapted for intensive aquaculture systems [23]. In 2022, catfish production ranked as the second highest-produced aquaculture fish group globally, with an estimated production volume of approximately 6.6 million tonnes [2].

Catfish farming, particularly of basa catfish (*Pangasius bocourti*) and striped/tra catfish (*P. hypophthalmus*), began in Vietnam in the 1940s. It was primarily focused in the MRD and initially relied on wild seed stock drifting downstream from the upper Mekong River regions in Laos and Cambodia. Originally practiced for household consumption and as a supplementary income source [24], the industry experienced significant growth following the development and dissemination of artificial propagation techniques [25, 26]. Over time, intensive catfish farming has become the leading practice, driven by the species' relatively fast growth rate, high flesh quality, appealing appearance, and consequently, its marketability [27]. Vietnamese striped catfish aquaculture production has increased remarkably since 2008 (Figure 1), reaching 1.71 million tonnes and generating an estimated value of approximately $1.8 billion in 2023 [28]. The MRD remained the dominant region, contributing nearly 100% of the country's striped catfish supply [28].

However, as a lowland area with a maximum elevation of 4 m above mean sea level, the MRD is highly vulnerable to climate change and has been identified as one of the three most severely impacted delta regions globally [30, 31]. In recent years, this region has experienced severe impacts from saltwater intrusion. During the 2015–2016 dry season, saline water deeply intruded, from 70 to 130 km from the river mouth, resulting in significant crop losses of 360 million USD in 9 of the 13 provinces of the MRD [32]. Similarly, during the dry seasons of 2016 and 2020, brackish water penetrated 110 km inland from the coast, directly affecting 8715.5 ha of aquaculture areas [33].

Although studies revealed that low salinity conditions from 2 to 10 parts per thousand (ppt) could provide favorable conditions for striped catfish, resulting in high survival rates and good growth performance [34–37], scenarios projecting sea level rises of 0.75 m for the MRD suggest that coastal areas in the region are likely to experience not only increased salinity intrusion but also prolonged periods of elevated salinity levels. Therefore, expanding striped catfish farming into these coastal provinces would be inadvisable unless a strain of catfish with salinity tolerance up to 17–20 ppt can be developed, as suggested by projections of salinity intrusion [38]. Recently, a 5-year selection programme was conducted to enhance the salinity tolerance of striped catfish. The selected fish demonstrated faster growth compared to the freshwater group, with optimal performance observed at

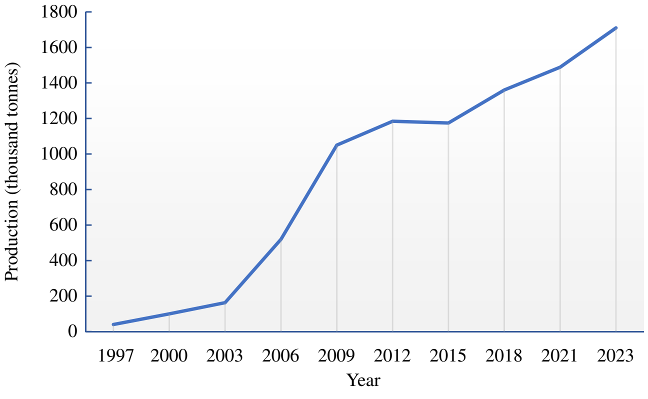

FIGURE 1 | Vietnamese production of farmed striped catfish, *Pangasianodon hypophthalmus*, 1997–2023 (data from [28, 29]).

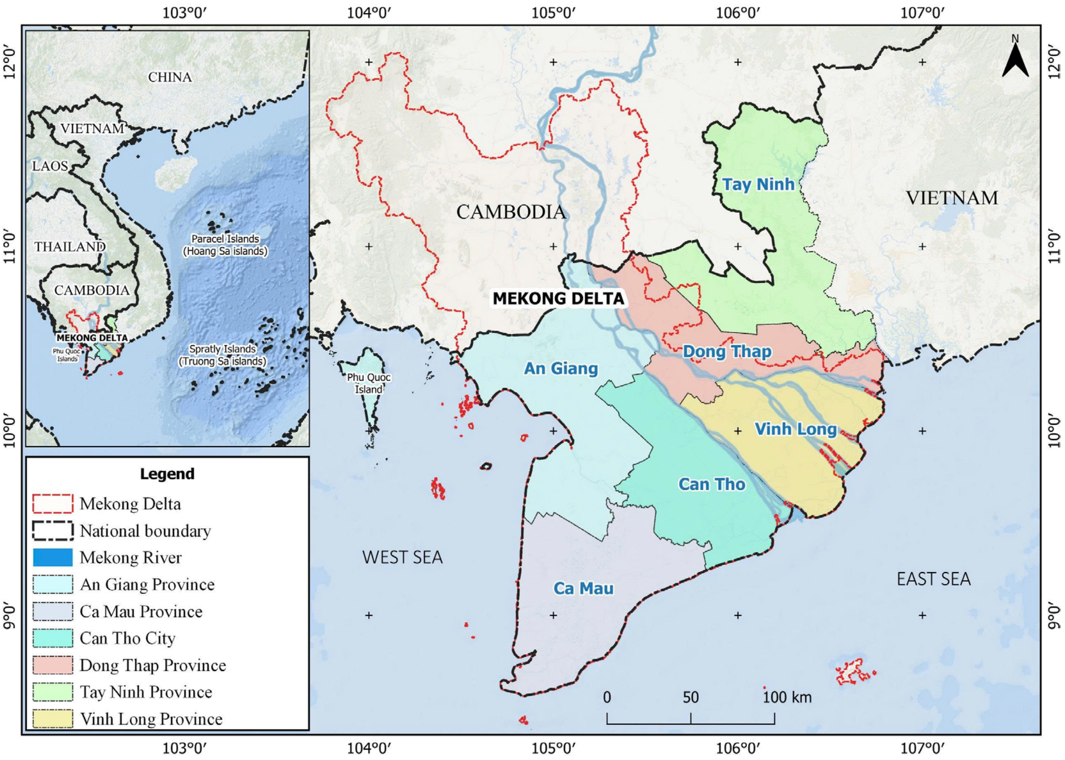

FIGURE 2 | Mekong River Delta.

salinities ranging from 0 to 10 ppt [39]. However, nearly all the larvae died at a salinity of 15 ppt, whereas at the later stages, from fry to fingerling, fish in both selected and non-selected groups showed similar survival rates from 0 to 15 ppt, with significant mortality observed at 20 ppt [39]. Hence, in the long run, another solution could be to identify alternative species better suited to the region's evolving environmental conditions to ensure sustainable aquaculture development.

It has been suggested that huge potential remains for domesticating new fish species, especially indigenous fish, to enhance the diversity of the aquaculture sector. This diversification could help the sector become more resilient to the challenges posed by environmental changes [40–42]. This approach could also help to mitigate the consequences associated with the introduction of alien species, which often range from ecological disruptions to unforeseen negative impacts [24, 43]. Given a biodiversity-rich system such as the LMB, the introduction of alien species is undesirable, particularly when there is significant potential for utilizing local species [4]. These findings highlight the necessity of a two-fold strategy to ensure the long-term sustainability of aquaculture in the MRD. First, genetically improving domesticated fish species, such as striped catfish, is essential to enhance their efficiency and adaptability in low-salinity-intruded areas. Second, diversifying aquaculture through the cultivation of new and native euryhaline species in salinity-affected inland and coastal regions can reduce reliance on a few dominant species. This dual approach is widely recognized as a sustainable path forward for aquaculture, enabling the industry to adapt to global changes while maintaining productivity and ecological balance [1, 26, 44]. The primary aim of this review was to evaluate the potential of indigenous euryhaline catfish species for aquaculture through a comprehensive literature review, applying a species selection framework. The focus was on identifying species that are both marketable and resilient to salinity changes driven by climate change, with the ultimate goal of improving the sustainability of aquaculture in the MRD. Additionally, this review provides an overview of the biological aspects of the selected species, including taxonomy, migration, reproduction, feeding behavior, and their fisheries and aquaculture status.

2 | Materials and Methods

2.1 | Study Area

The MRD (8°33′–10°55′ N; 104°30′–106°50′ E) is a low-lying region characterized by an average elevation of 1.0–1.5 m in its central areas and 0.3–0.7 m in its coastal regions (Figure 2). It is traversed by two major tributaries, the Tien River and the Hau River, which discharge into the East Sea of Vietnam through a network of eight estuaries [45]. Spanning an area of over 4 million km^2, this region plays a pivotal role in aquaculture, accounting for 70% of the aquaculture area and half of the food supplies of Vietnam [46, 47].

2.2 | Catfish Species Selection

Data on fish biology and distribution was sourced from FishBase [12] and studies on fish diversity in the LMB [8–10].

A species selection criteria framework, incorporating key traits considered essential for commercial inland aquaculture in the MRD under the climate change context, was developed with guidance from relevant literature [48–50]. Taking into account

TABLE 1 | Aquaculture readiness levels (ARL) [51].

Stage	ARL	Descriptions
Research	1	Observations from wild populations or fisheries provide basic biological information, but there are significant knowledge gaps and uncertainty regarding the species' potential for aquaculture.
	2	The species' basic biology is understood, and it is identified as having favorable characteristics for aquaculture and anticipated market demand
	3	The species' requirements for aquaculture are well understood, and experimental evidence confirms it can be successfully cultured.
Development	4	Testing is conducted on aquaculture technologies and husbandry practices to evaluate their suitability for the species.
	5	Trials are performed to evaluate the species' growth to harvest size and refine production technology and husbandry practices in the intended environment.
	6	Species can grow to harvest size in production technology in the intended location, in a cost-effective time frame. Standardization of production protocols.
Commercialization	7	The species is successfully farmed in prototype systems, production protocols are further refined, and initial product quality tests are conducted.
	8	The species is farmed at a commercially viable scale on a few farms, and production is being expanded to industrial levels.
	9	The species is produced at a large commercial scale, with products successfully delivered to the market, supported by established companies.
Adaptation	10	Production has reached a stable and advanced level, with sufficient resources and expertise to enable flexibility, resilience, and adaptation to environmental challenges, including climate change.

the increasing issue of climate change in the region, only euryhaline species capable of tolerating a wide range of salinity levels and inhabiting freshwater, brackish, and marine environments [51] have been considered. Some of these euryhaline species were excluded from further consideration for the following reasons:

Non-commercial species: Species that are inedible or primarily used as bait were excluded from the list.

Small size: Species with a maximum length of less than 25 cm were deemed unsuitable.

ARL: Aquaculture readiness levels (ARL) [52] is a framework adapted from technology readiness levels (TRLs) to assess the development stages of aquaculture species for commercial farming. It outlines the steps needed for the transition of a species from research to farming readiness status, addressing biological challenges (Table 1). The ARL score of each species was assigned based on the presence or absence of biological and technical information, including studies on biology, preproduction, and aquaculture trials (see Supporting Information). Domestication of new candidate species is undoubtedly a lengthy and challenging process, fraught with complexities and uncertainties [4]. Farming new species, particularly those at very low ARL, could be very difficult [52]. Therefore, species classified as ARL 1 were excluded from the final list. For example, *Arius maculatus*, a mouthbrooding species with very low fecundity (12–24 eggs per female) and limited biological research, would be classified at a low ARL (Level 1) (see Supporting Information). In contrast, *P. hypophthalmus*, with well-established hatchery protocols, large-scale grow-out systems, and strong global market integration [27, 28], represents a high ARL species (Level 9).

3 | Results

3.1 | Potential Euryhaline Catfish Species for Aquaculture in MRD

Of the 1219 fish species recorded in the LMB, 176 belong to siluriformes (see Supporting Information). Among these, 18 species were identified as euryhaline (Table 2).

Among the 18 euryhaline indigenous catfish species documented in the LMB (Table 1), four species (*P. krempfi*, *P. mekongensis*, *M. gulio*, and *P. canius*) were selected for inclusion in the final list (Figure 3). The striped catfish is included as a reference species (Table 3).

3.2 | Biological Characteristics of Selected Species

3.2.1 | Morphological Characteristics

Both *P. krempfi* (Figure 4A) (locally known as *ca bong lau* in Vietnamese) and *P. mekongensis* (Figure 4B) (locally known as *ca tra ban* in Vietnamese) are high-value market species in the Pangasiidae, which have gained significant attention from both scientists and aquaculturists. According to fishermen, *P.*

TABLE 2 | List of indigenous euryhaline catfish species in the Mekong River Delta (data from [28, 29]).

No.	Family	Scientific name	Max length (cm)	IUCN red list status
1	Ariidae	*Arius maculatus* (Thunberg, 1792)	80	NE
2	Ariidae	*Hemiarius stormii* (Bleeker, 1858)	50	NE
3	Ariidae	*Ketengus typus* (Bleeker, 1846)	24	NE
4	Ariidae	*Nemapteryx macronotacantha* (Bleeker, 1846)	30	NE
5	Ariidae	*Netuma bilineata* (Valenciennes, 1840)	90	NE
6	Ariidae	*Netuma thalassina* (Rüppell, 1837)	185	NE
7	Ariidae	*Osteogeneiosus militaris* (Linnaeus, 1758)	43	NE
8	Ariidae	*Plicofollis dussumieri* (Valenciennes, 1840)	85	LC
9	Ariidae	*Cryptarius truncatus* (Valenciennes, 1840)	42	NE
10	Pangasiidae	*Pangasius elongatus* (Pouyaud, Gustiano and Teugels, 2002)	28	DD
11	Pangasiidae	*Pangasius krempfi* (Fang and Chaux, 1949)	120	VU
12	Pangasiidae	*Pangasius mekongensis* (Gustiano, Teugels and Pouyaud, 2003)	100	LC
13	Plotosidae	*Euristhmus nudiceps* (Günther, 1880)	33	NE
14	Plotosidae	*Plotosus canius* (Hamilton, 1822)	111	NE
15	Bagridae	*Tachysurus sinensis* (Lacepède, 1803)	36	NE
16	Bagridae	*Mystus velifer* (Ng, 2012)	14	NE
17	Bagridae	*Mystus gulio* (Hamilton, 1822)	46	LC
18	Bagridae	*Hemibagrus planiceps* (Valenciennes, 1840)	33	V

Abbreviations: DD, data deficient; LC, least concern; NE, not evaluated; VU, vulnerable.

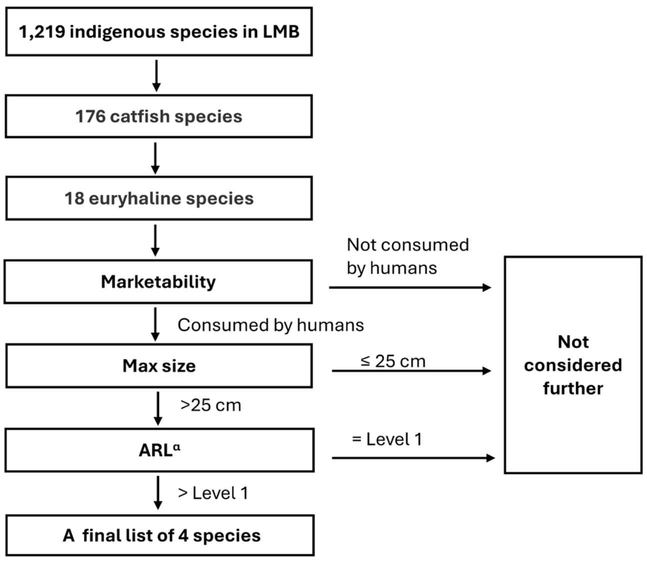

FIGURE 3 | Flowchart of the selection process. $^{\alpha}$For ARL information (see Supporting Information).

mekongensis is notably larger than *P. krempfi*. The maximum reported body weight for *P. mekongensis* is 40 kg, compared to 12 kg for *P. krempfi* [60]. Notably, wild-captured *P. krempfi* exhibit female-biased sexual size dimorphism, as females are significantly heavier and longer than males, with mean body weights of 5.1 kg ($n=18$) and 3.2 kg ($n=9$), and mean total lengths of 76 and 64 cm, respectively [60]. Moreover, the gas bladder of *P. krempfi* is notably well-developed and characterized by its thickness, solidity, and considerable volume. Extending to the caudal peduncle, it constitutes 50% of the total gross visceral mass. These features, resembling those of striped catfish, indicate the species' ability to use atmospheric air. This physiological adaptation is very interesting for intensive aquaculture [62]. However, these two species share similar physical traits, including a slender body shape, a short distance between the snout and dorsal fin, and a similarly shaped, sometimes yellow, low-cut caudal fin. As a result, they can be easily mistaken for one another.

Mystus gulio (Figure 4C) (locally known as *ca chot trang* in Vietnamese) [10] is highly valued for its delicate taste and nutritional content, which drive significant consumer preference and strong market demand in India, Bangladesh, and Vietnam [65, 74–76]. *M. gulio* has a compressed and elongated body. This species displays significant color variations, with individuals ranging from plain silvery to gold, as observed in LMB populations [9] or exhibiting a bluish-brown coloration on the head and dorsal regions, gradually fading to a dull white ventrally [77]. It has been reported that fish inhabiting salinity gradient environments exhibit variations in body shape, including differences in dorsal-ventral width, snout shape, tail morphology, head structure, and eye size [59]. Fish collected from three different estuaries in Cianjur District, West Java Province, Indonesia showed condition factor values ranging from 0.904 to

TABLE 3 | The final list of potential species for aquaculture in the Mekong River Delta (*P. hypophthalmus*) is included for comparison.

	P. hypophthalmus	***P. krempfi***	***P. mekongensis***	***M. gulio***	***P. canius***
Domestication level	5	2	2	3	2
ARL	9	5	3	5	3
Biological traits					
Maximum size (cm)	130	120	100	46	111
Fecundity (eggs/kg female)	11,589–15,802	61,122	n/a	661,132–792,481	2500–3043
Migratory strategies	Potamodromy	Anadromy	Anadromy	Anadromy	Amphidromy
Environmental condition tolerance	High	High	n/a	High	High
Trophic level position	Omnivore	Omnivore	Omnivore	Carnivore/Omnivore	Omnivore
Available aquaculture knowledge					
Artificial preproduction	Available	Some trials but further efforts required	Available	Available	n/a
Larval rearing	Available	n/a	n/a	Available	n/a
Grow-out husbandry	Available	Preliminary trials	n/a	Available	n/a
Processed feed acceptability	Accepted	Accepted	Accepted	Accepted	Accepted but not preferred
Nutritional requirements	Understood	n/a	n/a	Understood	n/a
Consumption					
Market scope	Regional and international	Regional	Regional	Regional	Regional
Market forms	Filet and round	Filet, round, and dried products	Filet and round	Whole body	Whole body
Annual production (Million tons)	1.71	n/a	n/a	n/a	n/a
Farm-gate price (USD kg^{-1})	1.00–1.15	n/a	n/a	n/a	n/a
Export value (Billion USD $year^{-1}$)	1.8	n/a	n/a	n/a	n/a
References	[12, 39, 53–55]	[12, 56–62]	[12, 56, 63, 64]	[12, 65–69]	[12, 70–73]

Note: Economic indicators are presented for *P. hypophthalmus* based on data from 2023 [4].
Abbreviation: n/a, not available.

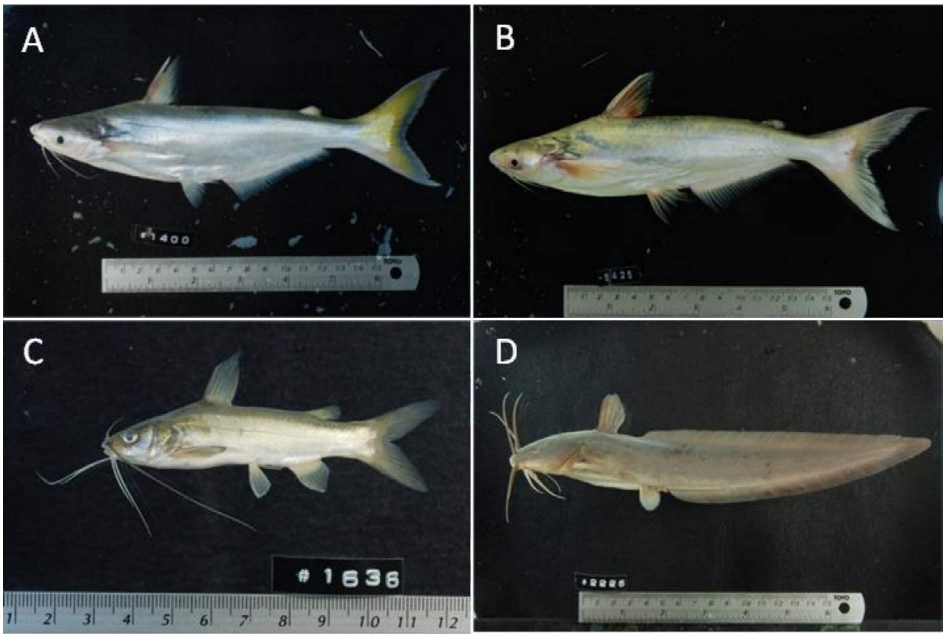

FIGURE 4 | (A) *Pangasius krempfi*, (B) *Pangasius mekongensis*, (C) *Mystus guilo*, (D) *Plotosus canius* (image source: Ffish.asia).

1.042, with the fish length values ranging from 5.7 to 18.6 cm for males and 5.2–26.5 cm for females [78]. On the other hand, specimens measuring 10.0–29.2 cm, collected from rivers, swamps, and shrimp farms in Khulna province, Bangladesh had a correlation coefficient (r) between length and weight from 0.8290 to 0.9662 [79]. The growth coefficients of *M. gulio* were 0.94 year^{-1} for males and 0.81 year^{-1} for females, whereas the growth performance index (Ø′) was 2.55 and 2.64 for males and females respectively [80].

Plotosus canius (Figure 4D) is characterized by a broad, slightly depressed head with a laterally flattened tail and a wide mouth. They possess two dorsal fins, the first with stiff spines, while the base of the second dorsal fin is fused with the caudal and anal fins. Individuals typically range from 50 to 80 cm in total length, with maximum sizes reported up to 150 cm [81]. However, available information on the growth and economic aspects of this species is very limited, with only a single report on growth, which estimated a growth coefficient of 0.28 year^{-1} [82].

In aquaculture, morphological traits play a fundamental role in growth dynamics, reproductive efficiency, and overall performance in cultured systems [83]. With their elongated body shape, these four species show high potential, particularly due to a high filet yield. Female-biased dimorphism indicates strong growth capacity and offers opportunities for selective breeding. Although *M. gulio* is smaller in size, it exhibits relatively rapid growth rates, making it favorable for aquaculture, particularly for short production cycles.

3.2.2 | Distribution and Migratory Behavior

Pangasius krempfi has been identified as ‘vulnerable’ in the IUCN Red List due to threats such as habitat degradation, overharvesting, or river infrastructure along their migration stretches [56, 84–87]. They are often caught in the Khone Falls area and sometimes recorded in catches in upper Laos, approximately 1500 km from the sea, and also in southern Laos when they migrate into freshwater for spawning [86, 88]. As a transboundary anadromous species, *P. krempfi* spends the majority of its life in brackish water, with adults undertaking extensive upstream migrations to spawning grounds along the Mekong River mainstream, ranging from Phnom Penh (Cambodia) to Nong Khai (Thailand) and possibly further. After hatching, larvae drift downstream, often rapidly, to the MRD, where they spend most of their life in brackish water [56, 58, 84]. They spend about 4 years of their early life feeding in these habitats before returning annually to the freshwater breeding grounds upstream of the Mekong River [89]. The migration in *P. krempfi* is believed to be triggered by a water level rise, which starts suddenly at the beginning of the wet season and lasts possibly 40–50 days [88].

Pangasius mekongensis has been found throughout the LMB, from Laos to Thailand, Cambodia, and Vietnam, but it is primarily distributed in the Mekong estuary and coastal areas. Fish in spawning condition, however, have only been reported in freshwater areas, from Nakhon Phanom (Thailand) to Kandal (Cambodia) [87]. Recent analyses using otolith microchemistry have, for the first time, confirmed that *P. mekongensis* is an anadromous species [56]. It is primarily distributed in the Mekong estuaries but undertakes long-distance upstream migrations along the Mekong River for spawning [56]. Unlike *P. krempfi*, which spends most of its life in brackish water before returning annually to freshwater spawning grounds at around 4 years of age, *P. mekongensis* displays diversity in migratory strategies. The majority of larvae and juveniles (72%) drift directly to the Mekong River estuary, which serves as their primary nursery habitat. A smaller group (17%) initially migrates to the estuary, briefly returns to freshwater, and then relocates back to the estuary. The remaining 11% stay in freshwater for about 6 months before eventually moving to the estuary. Additionally, it is suggested that individuals return to freshwater for spawning between the ages of 2 and 7 years, although the exact spawning areas remain unexplored [56].

Mystus gulio is primarily distributed along estuarine tidal shores and sometimes migrates into freshwater rivers and lakes [90] across Bangladesh, India, Sri Lanka, Indonesia, Vietnam, Pakistan, Thailand, Malaysia, Myanmar, and Nepal [9, 12, 65, 91]. In the Vietnamese MRD, this species is relatively common in mangrove canals and associated ponds [9].

Plotosus canius has been documented displaying migratory behavior between marine and freshwater habitats [92]. Otolith analysis of individuals along the Khone Falls to the MRD estuaries identified four distinct migration strategies: (I) freshwater residents that never migrate to brackish or marine waters; (II) marine residents with high Sr.:Ca ratios, occasionally traveling to brackish water but not freshwater; (III) amphidromous fish (34% of samples) spawning in marine environments, with juveniles transitioning to freshwater before returning to the sea; and (IV) estuarine–marine migrators (21%), whose larvae briefly drift to the sea, transition to brackish water, and later return to marine habitats [89].

Overall, the transboundary anadromous migrations of *P. krempfi* and *P. mekongensis* pose formidable challenges for captive reproduction, as they require precise simulation of complex environmental cues such as upstream flows, salinity fluctuations, and turbidity changes. In contrast, the ability of *M. gulio* and *P. canius* to complete their life cycles across diverse salinity gradients reduces their dependence on rigid environmental triggers, enhancing their adaptability to controlled culture systems.

3.2.3 | Reproductive Traits

The gonadosomatic index (GSI) was 3.3% in 5.1 kg wild females and 0.3% in 3.2 kg wild males. The fecundity of *P. krempfi* was estimated at 330,062 large oocytes for a female weighing 5.4 kg (about 60,000 eggs kg^{-1} bodyweight) [60]. However, insights gained from previous breeding projects suggest that the maturity of both male and female spawners caught varied greatly [61, 93]. This variability in maturity may be attributed to the possibility that the individuals originate from different spawning groups. This is supported by ISSR (inter-simple sequence repeat) analyses of *P. krempfi* collected from the Tien and Hau River estuaries, which suggest that these individuals may originate from distinct spawning populations [94]. Mitochondrial sequences of *Cytochrome b* and the control region further confirm the presence of multiple genetic lineages of *P. krempfi* in the MRD [95]. Moreover, Duong [96] reported the absence of individuals at stage III gonadal development among wild *P. krempfi*. However, there is no clear evidence that *P. krempfi* spawns only once during the breeding season; consequently, its annual fecundity remains undetermined, although females exhibit heterogeneous maturation stages, with oocyte diameters ranging from 0.9 to 1.3 mm [60].

In contrast, *P. mekongensis* exhibited advanced and homogeneous oocyte maturation, with mean oocyte diameters of 1.3 ± 0.1 mm and over 94% of oocytes measuring ≥ 1.1 mm. The GSI was 19.3% in an 11 kg wild female and 3.3% in an 11.2 kg wild male. In general, both *P. krempfi* and *P. mekongensis* exhibit high fecundity, making them favorable candidates for aquaculture development [60].

For *M. gulio*, first maturity in the wild occurs early, at the sizes of 8.3 and 8.5 cm for males and females, respectively [97]. Under captive culture conditions, *M. gulio* achieves sexual maturity at an average length of 6.5 cm [65]. The fecundity of *M. gulio* (total length: 12.30–24.50 cm) was reported to vary between 3891 and 168,358 eggs female^{-1}, with the highest fecundity recorded in July [60]. The spawning of *M. gulio* varies regionally but aligns closely with the monsoon season, which reduces both temperature and salinity triggers for final oocyte maturation and spawning [65]. Peak spawning occurs in July in the Hooghly estuary and Bangladesh [60], while in Tamil Nadu's Pulicat Lake, India, it peaks from August to October [98]. Given the early maturation in this species, if broodstock and spawning can be effectively managed under controlled conditions, this trait could enable continuous, year-round seed production and grow-out cycles. Furthermore, its early sexual maturation may reduce the time needed for reproductive studies and accelerate domestication efforts.

Regarding *P. canius*, it has been reported that their breeding season could extend from February to August (peak season falls between May and June for both sexes). The fish produces large eggs, with an average diameter of 5.34 mm [73]. Consequently, they have rather low fecundity, ranging from 643 to 2250 eggs female^{-1}, which positively correlates with body length [71–73]. However, this low fecundity may also be advantageous, as egg diameter is positively correlated with larval length and weight. More yolk allows delayed feeding and later starvation, and larger larvae have bigger mouths and better swimming ability to find food, all of which greatly enhance survival in both the wild and hatcheries [99]. The males attained sexual maturity earlier than females, with average sexual maturity sizes of males and females being 46 and 42 cm, respectively [73].

3.2.4 | Feeding Ecology

Among the four species reviewed, *P. krempfi, P. mekongensis, and P. canius* are omnivorous, while *M. gulio* is generally considered carnivorous but has also been classified as omnivorous.

Pangasius krempfi primarily feed on fruits, leaves, filamentous algae, and crustaceans [87]. However, it is believed that *P. krempfi*, during their upstream migration, consumes less food. For instance, observations of *P. krempfi* individuals ($n = 20$) collected between Kratie and the Khone waterfalls revealed empty stomachs [60]. Currently, *P. krempfi* farmers rely on commercial diets formulated for striped catfish or tilapia, which typically contain 26%–30% crude protein [57, 58]. However, the feed conversion ratio (FCR) in *P. krempfi* farming (2.0–2.7) is generally higher than that observed in striped catfish farming (1.62–1.65), likely due to the use of nutritionally inappropriate feed formulations [100]. This suggests that *P. krempfi* requires a relatively low dietary protein level, although possibly not as low as that of striped catfish.

Pangasius mekongensis primarily consumes insects, worms, submerged vegetation, and seeds. While *P. mekongensis* juveniles and sub-adults inhabit flooded areas, using them as nurseries and feeding grounds with a diet largely composed of plant material, adults are typically found in the main river channels, where they exhibit a more diverse diet [87].

Plotosus canius lacks a true sac-like stomach, having instead a slightly expanded portion of the intestine [72, 73]. Studies on feeding biology have indicated that feeding activity diminishes during the spawning period [73]. *P. canius* is a predatory omnivorous species with a diverse diet including crustaceans, fish, worms, mollusca, detritus, and other feeds [70]. In a Malaysian mangrove estuary and mudflat, 70% of the dietary composition of *P. canius* specimens primarily consisted of resident crustaceans, comprising brachyuran crabs and penaeid prawns, whereas individuals in mudflats feed mostly on bivalves such as the blood cockle, *Anadara granosa* (L.), *Xenostrobus* and *Placuna* sp., with a smaller amount of fish *Stolephorus* sp. and *Glossogobius sp* [101, 102]. This species possesses a relative length of gut (ratio of gut length to body length) range from 0.534 for fish weighing under 5 g to 1.129 for fish weighing over 15 g, and this variation is likely an adaptation to the different types and sizes of prey in its diet, allowing *P. canius* to efficiently digest and absorb nutrients from the various food sources it consumes [70].

Mystus gulio is primarily a carnivorous fish, feeding predominantly on crustaceans, zooplankton, zoobenthos, and small fish [65, 67]. However, they have also been classified as omnivorous, with a diet including various plankton types, invertebrates, and plant matter [103]. Additionally, when food is scarce, *M. gulio* demonstrates a non-selective feeding habit and consumes any available food resources [104].

On the whole, these species have great potential for aquaculture due to their omnivorous feeding habits, which are associated with lower protein requirements [105]. However, to optimize feed formulations, further studies on digestibility and nutritional requirements, including crude protein, lipid, and energy ratios, are necessary.

3.3 | Fishery

In the Khone waterfalls and the surrounding areas, *P. krempfi* is mostly caught by seine net and wing trap, while *P. mekongensis* is frequently captured by angling using a variety of fruit baits [60, 106]. These two species are abundant in these regions from May to July while the water level is rising. The fishing season varies between locations. In An Giang province, fishing activities commence in November and continue until May of the following year. In Can Tho City, the season begins in October and ends in April of the following year [107]. These findings align with previously reported migration strategies of *P. krempfi* [56, 84, 101]. The observed fishing grounds and seasons correspond well to the upstream migration pathways and strategies of *P. krempfi*. In the Tien River, fishing for *P. krempfi* and *P. mekongensis* occurs year-round across five estuaries, with peak catches from March–April and September–October [64]. *P. krempfi* and *P. mekongensis* fishing activities have been important for improving the livelihoods of local fishers in these coastal areas [64]. On the other hand, the season for collecting *P. krempfi* fingerlings was reported to fall in September to December in MRD estuaries with two common fishing tools (stow net and push net). Fingerling production using the stow net reached 461 fingerlings ship^{-1} day^{-1}, with an annual estimate of 29.2 thousand fingerlings ship^{-1}. In contrast, the push net yielded 421 fingerlings ship^{-1} day^{-1}, with an estimated annual production of 31.5 thousand fingerlings ship^{-1} [108]. In this survey, participants also noted a decline in the wild population of *P. krempfi*, and the reasons given were changes in climate as well as over-exploitation over the last decades. In response, certain fishing gear, including stow nets and push nets traditionally used to collect wild stocks, have been listed as prohibited methods in some coastal regions of the Mekong Delta under Circular No. 19/2018/TT-BNNPTNT, issued by the Vietnamese Ministry of Agriculture and Rural Development on November 15, 2018.

It is evident that while both species possess high market value, the fishing activities remain largely seasonal and dependent on natural migratory patterns, which may limit consistent supply. In addition, fingerling collection is restricted to specific months, which constrains stocking to only a few months. These factors highlight the potential role of aquaculture in ensuring year-round market availability. Developing reliable hatchery protocols would reduce dependence on wild seed and support year-round stocking.

To our knowledge, there are no published data on the fisheries of *M. gulio* and *P. caniu*.

3.4 | Domestication Status

3.4.1 | *Pangasius krempfi*

Early domestication efforts for *P. krempfi* began in 2003, led by pioneering scientists from the Research Institute for Aquaculture No. 2 (RIA 2, Vietnam). Adult fish were captured in Tan Chau district (An Giang province) and Tran De district (Soc Trang province) and maintained in captivity under cage and pond conditions. Over a three-year period, it was concluded that cage culture provided a suitable environment for normal grow-out and sexual maturation (90%), whereas all fish stocked in ponds died. This outcome was attributed to the inability of adult *P. krempfi* to adapt to static water conditions and non-natural diets. Additionally, *P. krempfi* were found to be highly sensitive to handling and sampling, leading to cessation or drastic reduction in feeding, which ultimately caused 100% mortality shortly after stocking [109].

In 2004, the artificial reproduction of *P. krempfi* near the Khone waterfalls in Cambodia was attempted from June 14 to July 27 [60]. Unfortunately, all the hormone treatments failed to induce ovulation. A significant challenge during this trial was ensuring the survival of wild-captured breeders, as they often died immediately after capture or within a few hours, with only a few individuals surviving up to 3 days. The underlying cause of this high mortality remains unclear, but it is suspected to be related to exhaustion from extensive migratory journeys, sensitivity to handling, or injuries sustained during trapping [60].

In June to July 2006, another trial was conducted, during which spawners exhibited wide variability in maturity, with no females being 'ready-to-lay' [61]. This heterogeneity presented significant challenges for synchronized artificial reproduction. Slow-releasing implants containing luteinizing hormone-releasing hormone analog (LHRHa) were used as the priming treatment, followed by resolving injections of Suprefact (a GnRH analog) combined with Domperidone, with or without human chorionic gonadotropin (hCG). At the time, most of the tested treatments were largely ineffective, with only one female achieving ovulation. Males also exhibited reproductive issues, with some showing poorly developed or non-functional testes, potentially due to stress, transport, or environmental factors (e.g., temperature fluctuations). Although fertilization and incubation succeeded, larval survival was poor, likely due to unsuitable feeding (e.g., food size, palatability, nutrient deficiencies) and environmental stress. Larvae appeared thin and gracile, indicating ineffective feeding or metabolic inefficiencies exacerbated by suboptimal rearing conditions [61]. In 2007, 87 individuals were captured, but acclimatization challenges resulted in 55% mortality. New trials were conducted using various hormonal strategies; however, most failed to induce ovulation. Successful ovulation was observed in only a 3 kg female, which responded to a two-step hormonal protocol consisting of six priming injections of hCG, followed by two ovulatory injections (the first containing hCG alone, and the second comprising a combination of LHRHa, Domperidone and additional hCG). Male *P. krempfi* also suffered from stress-induced sperm loss post-capture and hormonal treatments yielded inconsistent results. Larvae failed to consume the provided *Moina* and died within 6 days post-hatching. This outcome was attributed to a combination of factors, including gamete quality, maternal stress, and inappropriate early feeding strategies. Despite these challenges, artificial fertilization was successfully achieved, demonstrating potential for breeding this species in captivity [62].

It was not until 2012 that better results were achieved using a six-dose hormonal induction protocol [110]. Unlike previous studies, this trial used fresh carp pituitary gland extract in the first four priming injections, followed by two ovulation-inducing injections using hCG. *P. krempfi* aged 3–4 years were sufficiently mature for ovulation induction [110]. Males were treated with a single injection of hCG at the same time as the females' ovulation dose. This protocol resulted in an ovulation rate of 71.2%, fertilization rates ranging from 0% to 96.4% (average 54.1%), and hatching rates from 0% to 93.0% (average 51.9%). While the study reported some success in breeding this species, significant variations in ovulation, fertilization, and hatching rates remained, and the efforts were limited to experimental trials with no reports of commercial production. To date, despite anecdotal claims of successful artificial propagation of *P. krempfi*, no seed production farms have been reported and farmers continue to rely heavily on wild seed to maintain *P. krempfi* production. More recently, artificial hybridization in both directions between *P. krempfi* and *P. mekongensis*, with farmed offspring individuals being confirmed as hybrids through genetic analysis of mitochondrial *Cytochrome C oxidase subunit I* (COI) and the nuclear *Rhodopsin* (Rho) genes [111].

Pioneer provinces for farming *P. krempfi* in Vietnam, such as Can Gio District (Ho Chi Minh City), Tra Vinh, Bac Lieu, and Soc Trang, have initiated a shift in farming activities from shrimp to these euryhaline species [57, 58]. Farmers in these regions have repurposed uncultivated shrimp ponds for the culture of this species, providing an alternative source of income. Trial culture models were in two districts of Soc Trang Province, Ke Sach District (freshwater region) and Cu Lao Dung District (brackish water region), to compare the growth performance of *P. krempfi* under freshwater and brackish water conditions [57]. Fingerlings with an average length of 9.68 ± 0.26 cm were stocked at a density of 2 individuals m^{-2} in earthen ponds. After 11 months of culture, fish raised in brackish water in Cu Lao Dung exhibited superior growth, reaching 1.09–1.20 kg $fish^{-1}$, with a survival rate of 79.3%. In contrast, fish from freshwater ponds showed significantly lower growth (0.31–0.35 kg $fish^{-1}$) and a much lower survival rate of 22.3%. The productivity of *P. krempfi* cultured in brackish water ponds was 14.9 tons ha^{-1}, generating a profit of 16,500 USD ha^{-1} for farmers. In Can Gio District (Ho Chi Minh City), *P. krempfi* farming emerged in 2015 with just 2 households using wild-caught fingerlings. During the period from 2015 to 2020, *P. krempfi* farming in Can Gio experienced remarkable development, with the number of farms expanding 12-fold and the cultivated area expanding 29-fold in comparison to the figures recorded in 2015 [58]. Compared to striped catfish seeds, the prices of *P. krempfi* juveniles were much higher, ranging from 0.6–0.8 USD $juvenile^{-1}$ (values in 2021). Fish with an initial size of 8.33 ± 0.48 cm were stocked at densities ranging from 1 to 2 individuals m^{-2} in earthen ponds. The cultivation period required for these fish to reach a commercial size of 1.15 ± 0.03 kg was approximately 12–14 months. Notably, the survival rate of the fish shows a wide variation, ranging from 18.5% to 87.5%, with FCR between 2.00 and 2.70. Farmers sold the fish to traders at prices ranging from 3.8 to 5 USD kg^{-1}), generating an income of approximately 16,000 USD ha^{-1} [58]. Recently, a study was carried out to investigate the optimal stocking density for wild-sourced *P. krempfi* fingerlings (46.0 ± 7.0 mm, 1.4 ± 0.6 g) in hapas at densities of 20, 30, and 40 individuals m^{-2} [59]. The juveniles were initially fed with pellet feed (55% protein) to satiation. After 1 week, they transitioned to a 44% protein diet fed at 2%–5% of body weight day^{-1}. After 35 days, growth rates did not differ significantly among treatments, but survival was highest at 20 individuals m^{-2} (91.0%) compared to 30 individuals m^{-2} (55.1%) and 40 individuals m^{-2} (39.6%) ($p < 0.05$).

3.4.2 | *Pangasius mekongensis*

Information on the artificial reproduction of *P. mekongensis* has remained scarce. To date, only one effort has been reported [63], in which an ovulation method using hCG was developed with wild breeders. This method involved the administration of a total dose of 5000 IU hCG kg^{-1} for females, divided into two priming doses and two ovulation doses, along with a single dose of 1000 IU hCG kg^{-1} for males administered simultaneously with the ovulation injection for the females. This approach resulted in the ovulation, fertilization, and hatching rates of 100%, 77.8%, and 75.2%, respectively, with a survival rate of approximately 35.1% for 5 cm fingerlings [63]. However, the seed supply remains inconsistent and uncoordinated, and to date, there are no documented reports of farming *P. mekongensis*.

3.4.3 | *Mystus gulio*

Observations indicate that *M. gulio* can achieve maturity in farming ponds; however, there are no recorded cases of natural spawning in captivity. This has been attributed to the failure to achieve final oocyte maturation and ovulation [65].

The first reported case of artificial breeding induction for captive reproduction was conducted in India in 2002, using wild-caught broodstock [91]. The breeding operation was carried out in a 20 ppt water condition using synthetic gonadotropin-releasing hormone analogue (SGnRH), administered at a single dose for males and double doses for females. This protocol resulted in an impressive hatching success rate of 80%. Subsequent studies also utilized SGnRH for spawning induction, achieving promising fertilization and hatching rates [112, 113]. A comparative study on the effectiveness of luteinizing hormone-releasing hormone analog (LHRHa) + domperidone and hCG in induced spawning of *M. gulio* revealed that the highest spawning rate (83.3%) was achieved with LHRHa + domperidone. In contrast, the highest fertilization rate (81.1%) and hatching rate (82.2%) were observed with hCG at 1500 IU kg^{-1} for females [114]. In 2018, *M. gulio* were successfully induced to spawn in a recirculating aquaculture system (RAS) at a salinity of 18 ppt using hCG. The results demonstrated that hCG is an effective hormone for the induced spawning of *M. gulio* [115]. More recently, a hatching rate of 96.0% was reported using a single injection of LHRHa [116].

Eggs of *M. gulio* successfully survive up to hatching across all salinity levels ranging from 0 to 20 ppt, with the highest hatching rate (72.0%) observed at a salinity of 10 ppt and an incubating density of 100 eggs L^{-1} [114]. Larvae stocked at a density of 25 individuals L^{-1} in 50 L tanks and fed freshly hatched *Artemia* spp. (3000 nauplii L^{-1}) achieved significantly higher growth and survival rates than those in low feed densities (500, 1000, and 2000 nauplii L^{-1}) [115]. In addition, larvae reared at densities of 25 individuals L^{-1} and fed four times a day showed better growth (525% ± 1.5%) and survival rates (48.0%–52.0%) than those reared at 50 individuals L^{-1} under both two- and four-times daily feeding schemes [115]. In earthen ponds treated with organic fertilizer (cattle dung), 4-day-old post-hatching larvae were stocked at a density of 250 individuals m^{-2} and reared for 4 weeks on a finely powdered diet comprising mustard oil cake, rice bran, and fish meal in a 2:3:5 ratio, with a protein content of 30%. This rearing practice achieved a survival rate of 69.4% [117]. Similarly, in another study conducted under earthen pond conditions, 5-day-old fry stocked at densities of 250 and 300 individuals m^{-2} were fed the same feed mixture (mustard oil cake, rice bran, and fish meal) but in a 2:1:1 ratio. After 42 days of rearing, the survival rates were reported as 89.3% and 88.7%, respectively [118]. Grow-out farming of *M. gulio* comprises monoculture, polyculture, and fish-rice integrated cultures [65].

In a monoculture model, *M. gulio* (11.8–12.4 g) was stocked in 500 m^2 ponds at the densities of 8, 12, and 16 individuals m^{-2} and fed a commercial pellet feed (30% crude protein). After 5 months of culture, there were no significant differences in growth performance among the different stocking densities. However, the highest stocking density (16 individuals m^{-2}) achieved the maximum production yield, reaching 950 kg ha^{-1} [69]. Traditionally, *M. gulio* are cultured in polyculture systems in India alongside wild seed of species such as *Liza parsia*, *Lates calcarifer*, *Penaeus monodon*, *Acanthopagrus* spp., and *Oreochromis niloticus*, with prolonged culture durations [65]. In a study comparing monoculture and polyculture systems for *M. gulio*, fish growth was higher in monoculture; this system showed lower survival rates, lower nutrient utilization efficiency, and decreased net profitability compared to polyculture systems involving *Heteropneustes fossilis* and *Anabas testudineus* [119].

In coastal West Bengal, India, rice-fish farming incorporates short-duration brackish water aquaculture during summer fallow periods, with no adverse effect on monsoon-season rice cultivation in the same plots [120]. Additionally, in a 120-day field experiment to evaluate cage culture of *M. gulio*, fish (1.10 ± 0.6 g) were stocked in 1.115 m^2 cages at densities of 90, 135, and 180 fish m^{-2}. The results showed that while the density of 90 fish m^{-2} showed the best growth and feed utilization, 135 fish m^{-2} was the most profitable considering survival, production, and cost–benefit analysis [68].

3.4.4 | *Plotosus canius*

In 2011, a study was conducted to identify suitable diets for *P. canius* fingerlings, testing four types of feed: *Artemia*, *Moina*, tubificid worms, and artificial feed. After 30 days of rearing, treatments using trash fish resulted in the best growth and survival rates, followed by treatments with tubificid worms. In contrast, treatments using artificial feed yielded the poorest outcomes [121]. To date, no reports on the breeding or grow-out farming practices for this species have been documented.

4 | Discussion and Future Directions

Domestication has been defined as the process of completing the entire life cycle of a species under captivity, with successive generations bred [122]. Behavior is the first trait to change during domestication, with domesticated fish becoming less reactive to external stimuli, including human presence and handling [123, 124]. Furthermore, domesticated individuals often become reproductively active irrespective of environmental cues, allowing them to spawn out of season and more frequently throughout the year [124]. Domesticated species are also better adapted to artificial environments, including high stocking densities, formulated feeds, and controlled temperature or salinity regimes. These traits allow for stable performance across life stages and support large-scale production, contributing to aquaculture resilience in the face of environmental challenges such as water scarcity and sea-level rise [122]. Additionally, domestication plays a vital role as a foundation for applying selective breeding to improve other important traits such as disease resistance [125, 126], feed efficiency [127, 128] and flesh quality over successive generations [129]. It has been reported that successfully completing the life cycle in captivity seems closely tied to high production, with the top 15 most-produced species in 2009 all reaching domestication levels 4 or 5 [130].

Based on the criteria defined by Teletchea [4], domestication levels range from 0 (initial capture and acclimation of wild individuals) to 5 (completion of the full life cycle in captivity with selective breeding; see Supporting Information). On this scale, higher levels indicate more advanced domestication progress. According to this framework, the four species selected in this study are in the early domestication phase with three (*P. krempfi*, *P. mekongensis*, and *P. canius*) at domestication level 2, while one species (*M. gulio*) has reached level 3 (Table 3). This implies that significant gaps remain in several farming practices such as artificial reproduction or defining nutritional requirements, which are critical factors contributing to the failure of domestication efforts for many new species after a few years [130]. It was reported that 70% of the 250 fish species recorded in aquaculture globally in 2009, as recorded in FAO aquaculture datasets, fell within the first three domestication levels. Additionally, the cultivation of 67 species was terminated after only a few years of farming [1].

Among the selected species, *P. krempfi* and *P. mekongensis* appear to be viable candidates for aquaculture in the coastal regions of the MRD. Their suitability is supported by several factors, including sufficient biological knowledge, large body, high fecundity, high filet yield, low bone content, and good flesh quality [87, 96, 101]. The wild populations of *P. krempfi* and *P. mekongensis* have decreased, and harvest yields have significantly diminished compared to 5–10 years ago. This decline is primarily attributed to overfishing and the use of harmful fishing practices [64]. Additionally, the discovery of hybrids between these two species raises concerns about potential impacts on species diversity [111]. Although the cause of hybridization between *P. krempfi* and *P. mekongensis* is currently unknown, it has been hypothesized that males and females of *P. krempfi* reach sexual maturity at different times, resulting in asynchronous spawning and potential hybridization [93, 111], particularly since the two species share the same spawning season during the early rainy months (May–August) [60, 106].

In recent years, capture-based aquaculture for *P. krempfi* has been established, largely dependent on wild fingerlings. However, production levels remain inconsistent and low due to the limited availability of wild seed, which in turn drives up costs and necessitates substantial financial investments from farmers, with seedstock alone accounting for approximately 23.30% of the total production cost [58], compared to approximately 7.10% in the case of fully domesticated striped catfish [132]. Although capture-based aquaculture has been described as a transitional form of fish production, viable only while wild resources remain available for collection [133, 134], it is essential to proceed with domestication by completing their life cycle in captivity. This will enable consistent production independent of wild stocks and facilitate the improvement of desirable traits through selective breeding [135–137].

Despite some remaining technical challenges, *P. krempfi* has been reported to spawn under captive conditions, indicating its potential for hatchery development. In addition, *P. krempfi* exhibits relatively high fecundity, which is a significant advantage for ensuring a stable seed supply for commercial aquaculture. Under captive conditions, the species has shown the ability to accept pellet feed, although no commercial diets have been specifically formulated for *P. krempfi* to date. The rather high survival rate (90%) of juveniles reared at a density of 20 individuals m^{-3} under earthen pond conditions further demonstrates its potential for intensive culture farming. Further efforts should prioritize the development of artificial reproduction techniques for *P. krempfi*, including identifying the specific environmental triggers for their spawning, given their transboundary migratory behavior, followed by improvements in juvenile growth performance, survival rate, and FCR. Refining species-specific feed formulations based on nutritional requirements is also essential to enhance growth and filet yield. It is necessary to generate practical protocols through well-designed trials under controlled conditions and implemented collaboratively by research institutions, hatcheries, and local authorities. However, this process is resource-intensive and time-consuming. Effective stakeholder participation is essential to identify and overcome bottlenecks, avoid redundant efforts, and optimize the allocation of limited resources [122]. These advancements are essential for ensuring a reliable seed supply for aquaculture, mitigating ecological risks associated with hybridization, and supporting conservation efforts while boosting the marketability of these species.

Findings from previous domestication efforts for *P. krempfi* suggest that controlled maturation in tank or pond conditions, utilizing wild-captured fingerlings, could provide a viable approach to managing and enhancing the spontaneous maturation process in this species. During the maturation process, environmental factors such as temperature, salinity, water levels, and flow rate can be manipulated to regulate the timing of fish spawning, facilitating the production of viable gametes year-round [138, 147]. In addition, a significant challenge in ovulation induction for this species is its high sensitivity to handling, which often leads to substantial mortality. Minimizing handling during this stage is therefore critical. An injection of vitamin C immediately after capture has been shown to effectively reduce stress [60]. In addition, the use of salt ($4\,g\,L^{-1}$) in holding tanks has shown potential in reducing stress in this euryhaline species [61]. The hormonal treatment protocol established by Huynh et al. [110] remains the most effective method published to date; however, further research is necessary to optimize hormone dosages and injection timing to enhance its efficacy. Variability in fish maturity is another phenomenon that requires attention. This has been observed in species such as brown trout (*Salmo trutta*) and Atlantic salmon (*Salmo salar*). In these species, individuals attain maturity over a range of age groups, with this variability being particularly pronounced when access to diverse feeding habitats is available [131]. Additionally, larval rearing practices for *P. krempfi* remain largely underexplored and require further development.

Although *P. mekongensis* shares similar characteristics with *P. krempfi* and has been recognized as a potential candidate for aquaculture, there are currently no reports on its rearing in captivity. This is primarily due to the limited availability of stocks in both upstream and estuarine regions [60, 64]. Furthermore, compared to *P. krempfi*, *P. mekongensis* has a lower market value, with the price of wild-caught *P. mekongensis* being approximately half that of *P. krempfi* [64]. To address these challenges, research on *P. mekongensis* should prioritize the development of broodstock management and breeding protocols to ensure consistent seed availability. As *P. mekongensis* and *P. krempfi* share similar biological characteristics, distributions, and nutrition requirements, future directions for *P. mekongensis* are likely to align closely with those for *P. krempfi*. Additionally, efforts to improve its market appeal such as promoting its nutritional benefits and flesh quality are essential for enhancing its competitiveness within the aquaculture industry.

With well-established breeding and larval rearing protocols under captive conditions, along with initial trials of grow-out farming, *M. gulio* is poised for commercialization, provided that production protocols are standardized. Unlike *P. krempfi* and *P. mekongensis*, which require freshwater conditions for breeding, *M. gulio* exhibits notable reproductive plasticity across a broad salinity range, suggesting its suitability for hatchery operations in both inland and brackish water areas. In addition, *M. gulio* also demonstrates adaptability to various culture systems, including monoculture, polyculture, and integrated rice-fish farming. The species also exhibits relatively rapid growth rates, making it favorable for aquaculture, particularly for short production cycles [65, 68, 69, 80, 119]. However, all breeding programmes reviewed in this study still rely on wild broodstock, resulting in an incomplete, non-closed life cycle [79, 91, 112, 114]. Besides, gaps remain, including maturation culture, nutrition during the grow-out phase, and the economic viability of rearing *M. gulio* to marketable plate size. Additionally, the early sexual maturity of *M. gulio* can negatively impact productivity by leading to stunted growth and reduced overall yield [97]. This early maturation, observed in many species, diverts energy for somatic growth to reproduction, often resulting in smaller adult sizes and reduced market value [139–141]. Future research should prioritize strategies to mitigate the effects of early maturation, such as selective breeding for delayed reproduction or optimized rearing conditions that promote somatic growth. Reducing dependence on wild broodstock and the development of cost-effective grow-out phase nutrition will be critical in establishing economically viable and sustainable production systems.

Similarly, while extensive studies on *P. canius* have documented its morphology, feeding habits, and reproductive biology, critical knowledge gaps persist. This includes the lack of well-defined artificial breeding protocols, early life-stage rearing techniques, and effective broodstock management under controlled conditions. In addition, poor performance with artificial feeds highlights the need for advanced feed formulations and cost-effective rearing protocols to support commercial aquaculture. However, it is possible that *P. canius* may adapt to captive conditions over generations, improving feed acceptance, as shown by research on rapid adaptive changes in fish in captive environments [142]. For instance, after three generations of domestication, Asian redtail catfish (*Hemibagrus nemurus*) exhibited a significant reduction in FCR and an improvement in feed efficiency, resulting in enhanced growth rates. Eurasian perch (*Perca fluviatilis*) larvae from first-generation domesticated broodstock exhibit better growth performance compared to those from wild spawners. This improvement is primarily attributed to the enhanced ability of domesticated larvae to digest compound feed, which presents a specific challenge during early development [143]. Despite its potential to reach a large body size, the lower growth rate indicates a longer grow-out period. Future research should focus on breeding protocols and broodstock management; additionally, improving juvenile nutrition through appropriate feeding strategies and diet formulation will be a critical next step to enhancing growth and feed efficiency.

The case of striped catfish highlights the critical role of artificial breeding in advancing aquaculture. Within a few years, the establishment of hundreds of hatcheries in the MRD has ensured a reliable seed stock supply for farms [53]. By achieving control over its reproductive cycle in captivity, striped catfish aquaculture has shifted from a resource-intensive practice that relied heavily on wild stocks to a sustainable model that significantly alleviates pressure on natural populations [144].

Additionally, as indigenous species are primarily consumed locally, marketing is a key consideration for promoting these selected fish and enhancing their potential for export to international markets. Although domestic markets are readily available and offer high prices for these species, the relatively small market size could pose a limitation to their broader economic impact. Also, it is critical to assess the competitiveness of these new species in existing markets, particularly against established species such as striped catfish. Furthermore, it has been reported in other fish that many producers are capable of raising potential organisms to a marketable size, but they often fail to address the key factors of supply and demand, which are crucial for determining their profitability [145]. This is exemplified by the case of the Vietnamese striped snakehead (*Channa striata*). Fluctuations in market demand and oversupply have caused sharp price declines during peak harvest periods [146].

5 | Conclusions

Domestication of new aquaculture species is necessary to diversify aquaculture practices, particularly in areas such as the MRD, which face serious challenges from salinity intrusion and climate variability. This review identifies four indigenous euryhaline catfish species including *P. krempfi*, *P. mekongensis*, *M. gulio*, and *P. canius* as promising candidates for aquaculture, especially in coastal regions. Generally, all four species remain in the early stages of domestication and commercial development. Among them, *P. krempfi* and *P. mekongensis*, characterized by large body size, high fecundity, consumer preference, and some reported success in artificial reproduction, show strong potential to supplement or replace traditional species such as striped catfish. *M. gulio* also demonstrates considerable aquaculture potential due to its established breeding and larval rearing techniques under captive conditions, as well as its adaptability to diverse culture systems. *P. canius* is the least studied among the selected species, with existing information primarily limited to its biological characteristics and basic nutritional requirements. There is currently little to no data available on reproduction, hatchery techniques, or farming practices.

To advance the cultivation of these species, the development of standardized hatchery protocols including broodstock management, artificial breeding, larval rearing, and species-specific formulated feeds is essential to ensure a reliable seed supply and reduce reliance on wild-caught stocks. Additionally, market-driven strategies, such as branding that highlights their tolerance of environmental impacts, can be employed to promote them as sustainable and traceable alternatives to wild-caught fish, thereby reducing harvest pressure on wild populations. Adding value through product diversification (e.g., filets and dried products) may help increase profitability and market competitiveness, especially since wild-caught fish are currently traded primarily as whole fish. Given the complexity and long-term nature of this process, active stakeholder involvement is required including representatives from capture and culture fisheries, scientific research, resource management, producers, consumers, relevant societal sectors, and public authorities.

Author Contributions

Nguyen Tinh Em: conceptualization, methodology, writing – review and editing, writing – original draft. **Nguyen Thanh Phuong:** conceptualization, supervision, writing – review and editing, funding acquisition, methodology. **Bui Thi Bich Hang:** writing – review and editing. **Duong Thuy Yen:** writing – review and editing, methodology. **Le Quoc Viet:** writing – review and editing. **Do Thi Thanh Huong:** writing – review and editing. **Vo Nam Son:** writing – review and editing. **Huynh Viet Khai:** writing – review and editing. **Nguyen Hong Quyet Thang:** writing – review and editing. **Nguyen Tan Tai:** writing – review and editing. **Fabrice Teletchea:** methodology, writing – review and editing. **Frédéric Clota:** writing – review and editing. **Frédéric Farnir:** writing – review and editing. **Philippe Lebailly:** writing – review and editing. **Patrick Kestemont:** conceptualization, supervision, writing – review and editing, funding acquisition, methodology.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

All the data used in this review paper is available in already published papers.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Data S1:** (A) List of catfish species distributed in the Mekong River Delta. (B) Aquaculture readiness level (ARL) scoring of candidate species, based on biological and technical information (biology, reproduction, aquaculture trials). (C) Domestication level criteria defined by Teletchea.

Biographies

Nguyen Tinh Em I am a PhD student registered at the University of Namur, Belgium. My PhD research is conducted in close collaboration with Can Tho University, Vietnam. My research focuses on fish physiology, reproduction biology, immunology and aquaculture, with a particular emphasis on indigenous aquatic species. My approach integrates technological advancement and climate resilience to boost fish and shrimp farming productivity.

Nguyen Thanh Phuong He is a distinguished aquaculture scientist in Vietnam with studies focusing on fish physiology, aquaculture production systems, fish reproduction, fish nutrition. He has published extensively on topics such as climate change adaptation in aquaculture, immune response, plant extracts in aquafeeds and the effects of environmental factors on fish physiology and growth.

Bui Thi Bich Hang She specializes in fish immunology, environmental toxicology. Her works focus on the understanding of immune responses, disease resistance and the effects of environmental stressors on aquaculture species, particularly striped catfish and marine shrimp.

Duong Thuy Yen She works deeply genetics, reproductive biology, and aquaculture of indigenous fish in Mekong River. She employs a range of molecular techniques to study genetic diversity, broodstock management and phylogenetics, with a view to contributing to sustainable aquaculture and conservation.

Le Quoc Viet He specializes in indigenous fish domestication and aquaculture. His words focus on farming husbandries and the research for environmental factors on cultured species for productivity improvement and sustainability.

Do Thi Thanh Huong She is a distinguished researcher in the fields of aquatic animal physiology, aquaculture and environmental adaptation. Specially, she has many years in the study of the effects of climate change on fish species including temperature, salinity, carbon dioxide (CO_2) or water acidification.

Vo Nam Son He is a leading researcher in aquaculture, fisheries management and aquaculture economics. His research intensively focuses on improving aquaculture productivity, sustainability and economic efficiency. He also specializes in data analysis of technical and economic efficiency of aquaculture systems.

Huynh Viet Khai He is an economist and researcher specializing in agricultural economics and policy and resource management in Mekong Delta, Vietnam. He works extensively on economic valuation, environmental sustainability and the economic impact of climate change on agriculture, aquaculture and rural livelihoods.

Nguyen Hong Quyet Thang He has several years of experience in reproduction, larval development, and aquaculture system optimization of indigenous species. He particularly focuses on improving the efficiency of hormone injection protocols in artificial breeding and increasing hatchery success rates.

Nguyen Tan Tai Dr. Tai is specializing in accounting, microfinance and transfer pricing. His research focus on economic issues including microfinance accessibility for farmers, agricultural policy efficiency, financial literacy and the role of trade policies in economic growth.

Fabrice Teletchea He is specializing in fish domestication, reproductive strategies, and aquaculture development. Dr. Teletchea developed STOREFISH, a comparative database of reproductive strategies for European freshwater fish species. This framework has significantly advanced the understanding of early life-stage trade-offs in fish and has contributed to optimizing domestication and breeding programs in aquaculture.

Frédéric Clota He specializes in fish biology, reproduction biology, ecology applied to aquaculture. Specially, he works deeply in fish domestications. He has led two domestication missions of indigenous fish in the Mekong River in 2006 and 2007. Additionally, His research explores sex determination, thermal effects, growth performance, and genomic selection for feed efficiency.

Frédéric Farnir He is a researcher specializing in animal genetics and veterinary sciences. He has extensive expertise in quantitative genetics, genomic selection and genetic diversity analysis for the development of breeding programs for livestock and aquaculture species.

Philippe Lebailly He specialized in rural economics with extensive experience in economic assessments, risk management and cooperative systems. He has collaborated on several international projects in Vietnam. His works focuses on agricultural development, rural sustainability and aquaculture economics.

Patrick Kestemont He is a distinguished researcher, specializing in aquaculture, fish physiology, environmental toxicology and fish immunology. Over the past decade, he has collaborated with national and international institutions to improve fish farming sustainability, particularly in freshwater species like trout, catfish, tilapia or carp, supporting aquaculture sustainability conservation and climate change adaptation. He is author, co-author or last author of about 326 peer-reviewed papers (according to Scopus), most of them dealing with aquaculture and ecotoxicology, with a H-index of 56 and more than 11,000 citations.