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Invasive Amazon sailfin catfish (*Pterygoplichthys pardalis*) impacts the survivability and growth of native food fishes in India

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Abstract – The prevalence of sailfin catfishes (*Pterygoplichthys* spp.) in inland waters, including vast aquaculture systems of India is rising. This might be a serious threat to the country's native freshwater biological resources and aquaculture production. Therefore, studies were carried out to evaluate the impact of Amazon sailfin catfish *Pterygoplichthys pardalis* on different life-stages of native fishes. First, we analyzed the impact of three different size classes (small: 9.95 ± 0.70 cm, medium: 21.74 ± 0.87 cm and large: 30.81 ± 1.59 cm total length) of Amazon sailfin catfish on the survival of early life-stages (eggs, hatchlings, first-feeding fry, and 10-day-old fry) of two native fishes; native carp *Labeo rohita* (rohu) and native catfish *Ompok bimaculatus* (butter catfish). All size classes of Amazon sailfin catfish showed preference towards fish eggs over aquatic macro-invertebrates (*Tubifex* worms) and ingested over 90% of the eggs of both the native species. However, their effects on native species' mobile life stages (hatchlings forth) were found to be insignificant in terms of mortality. We then assessed the competition between advanced stages (fingerlings, advanced fingerlings, and sub-adult) of the Amazon sailfin catfish and the native fishes by evaluating growth and survival in three different experimental setups (indoor tanks with artificial feeds; outdoor tanks with natural food and artificial feed; and earthen pond with natural food) and in different combinations for a period of three to six months. In indoor experiment, no discernible impact of Amazon sailfin catfish on the growth of fingerlings of native species was found. But, in the outdoor experiment, growth of advanced fingerlings of rohu and butter catfish was decreased by 18.8–23.4% and 28.9–36.7%, respectively, in low- and high-biomass Amazon sailfin catfish treatments. The growth of rohu and butter catfish sub-adult was also reduced in the pond experiment, by 29.7% and 32.2%, respectively. However, impact of Amazon sailfin catfish on survival of native fish species at advanced stages was found minimal. Overall findings of this study indicate that sailfin catfish may have an adverse effect on the survival and growth of native fishes by either directly consuming or destroying native fish eggs or by competing with them for food and space.

Keywords: Biological invasion / invasive species / Loricariidae / *Labeo rohita* / *Ompok bimaculatus*

1 Introduction

Human dominance over the planet's ecosystems and global trade have accelerated the introduction of non-native species, leading to the disappearance or extinction of many native and endemic species worldwide (Vitousek et al., 1997; Rahel, 2002; Clavero and Garcia-Berthou, 2005, 2006). In fact, one out of every ten species listed on the IUCN Red List of Threatened Species version 2022-2, are threatened by invading non-native species (https://www.iucn.org/our-work/biodiversity). Furthermore, biological invasion by non-natives are often appraised as a key threat to the ecosystems and the services provided the ecosystems, including livelihoods, culture, human health and other aspects of human well-being (Simberloff et al., 2013; Pysek et al., 2020). Once non-native species integrate successfully into an ecosystem, it can cause significant changes in the composition of the ecosystem, which can make native fauna to compete with the non-natives for food and space (Gozlan and Newton, 2009; Blackburn et al., 2019). On the far side, non-native species are likely to cause socio-economic harm, for as by lowering crop or fishery output (Pysek et al., 2020). However, these effects of non-native invasions are frequently regarded as silent or invisible threats

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(i.e. Vitule et al., 2009), because they are rarely noticed right away and are often difficult to identify, for example, native species loss may reduce the ecological resilience of local assemblages, causing disturbance or disruption that may will be noted only in the future (Doria et al., 2021). Hence, many argued that, when invasive species establish themselves in new habitats, they have a more long-lasting detrimental effect on native biota by altering the disturbance regime and delaying ecosystem succession (Simberloff et al., 2012; Paolucci et al., 2013).

Freshwater ecosystems are more vulnerable to this phenomenon than their terrestrial counterparts worldwide, as they experience proportionately more invasions (Clavero and Garcia-Berthou, 2006; Gozlan et al., 2010). Over the half of the world's river basins were reported to be contaminated with at least one of the 600 globally introduced non-native freshwater fish species (Leprieur et al., 2008; Gozlan et al., 2010). In fact, freshwater fish species are among the most often introduced animal groups in the world (Gozlan et al., 2010) and also have higher rates of establishment compared to many other taxa (Jeschke and Strayer, 2006). Contrariwise, risks of extinction are also greatest for the freshwater fish, with a third of species facing the threat of extinction (https://www.iucnffsg.org), as they are adapted to live in a highly differentiated, fragmented and isolated habitat with rare opportunities for natural range expansion (Moyle and Marchetti, 2006; Arthington et al., 2016). Of the 15,351 evaluated fishes, the IUCN Red List version 2022-2 puts the number of known threatened fish species at 3,551 (IUCN, 2023), majority of which are freshwater fishes (WWF, 2020). According to Arthington et al. (2016), the main causes of this threat are overexploitation, pollution, climate change, habitat loss and degradation, and invasive non-native species.

Even though many nations have laws in place to regulate non-natives and their introduction, non-native fish are still regularly released locally to support fisheries and aquaculture practices, such as food aquaculture, sport fishing, and decorative fish. This practice is becoming more and more common as a way to bolster fisheries in developing countries (Copp et al., 2005). India, a subtropical country in South Asia, has imported more than 450 non-native aquatic species, mainly fish (>291 finfish species), that are made available for aquaculture and aquarium trade, despite having a rich biodiversity of native fish and other aquatic species including 877 freshwater finfish, 504 freshwater crustaceans, and 1,700 freshwater mollusk species (Jena and Gopalakrishnan, 2012; Sundaray et al., 2022).

Pterygoplichthys spp. (Siluriformes: Loricariidae), commonly known as sailfin catfishes, are among the most popular and frequently traded aquarium fish throughout the world and are slowly becoming a global invasive species (Orfinger and Goodding, 2018). Native of inland natural water bodies of South America, these fishes are a group of medium to relatively large-sized catfish, usually with a length of 30 to 55 cm, but can occasionally reach 100 cm (Nico et al., 2009a). The large dorsal fin with nine to fourteen rays sets them apart from the majority of other Loricariids (suckermouth armored catfishes), which generally have eight or fewer rays (Armbruster, 2004). There are currently 16 recognized species in the genus *Pterygoplichthys* (Fricke et al., 2024) (Tab. S1). However, species-level identification is tenuous and misidentification is common since many species in the genus share close morphological and genetic characteristics (Armbruster, 2004; Hossain et al., 2018). For instance, the main characteristic that sets apart species like Amazon sailfin catfish *Pterygoplichthys pardalis* (Castelnau 1855), vermiculated sailfin catfish *Pterygoplichthys disjunctivus* (Weber 1991), southern sailfin catfish *Pterygoplichthys ambrosettii* (Holmberg 1893) and Orinoco sailfin catfish *Pterygoplichthys multiradiatus* (Hancock 1828) is their abdominal spots and patterns (Armbruster and Page, 2006; Page and Robins, 2006). Of these four species, majority of the invaded nations have reported the presence of *P. pardalis* and/or *P. disjunctivus*, which may be due to their popularity in the aquarium industry rather than anything unique to their biology (Orfinger and Goodding, 2018). According to Armbruster and Page (2006), *P. pardalis* has a spotted pattern on its ventral surface, while *P. disjunctivus* has a reticulate black pattern. However, sailfin catfish individuals with abdominal spots and patterns that are intermediate or coalescent between these two species have been reported frequently (Wu et al., 2011; Jumawan et al., 2011; Zworykin and Budaev, 2013), which suggest possibility of natural or artificial hybridization between these two species (Wu et al., 2011; Vargas-Rivas et al., 2023) (Tab. S2).

Sailfin catfishes are unique tropical fish that can live in warm lowland rivers, oxygen-poor stagnant water basins, and swift, relatively cool mountain streams. They are also capable of surviving mesohaline conditions (up to 10 ppt) for extended periods of time, and thus can use estuarine and coastal areas for dispersal (Capps et al., 2011). Like other Loricariids, *Pterygoplichthys* spp. have high tolerance for hypoxia and are often found in contaminated waters due to their large vascular stomach, which acts as an auxiliary respiratory organ (Chavez et al., 2006). According to Armbruster (1998), they may even live for up to 20 h without water. Their lower lethal temperature, which has been estimated to be between 8.8 and 11°C in several species, is the only factor that usually keeps populations in check (Gestring et al., 2010). General water-quality preferences for *Pterygoplichthys* spp. (though their abiotic ranges are broader) includes warmer temperatures (21–29 °C), neutral pH (7 ± 1), low water hardness (4–20 mg/L) and dissolved oxygen as low as 3 ppt (Fuller et al., 1999; Capps et al., 2011; Nico et al., 2012). Furthermore, these fishes are algivorous, have high breeding capacity and high level of parental care (Gibbs et al., 2017). During the breeding season, males construct horizontal burrows in banks and peripheral bottom sediments that are up to 120–150 cm deep. Female spawn in these burrows and male aggressively defend the nests against intruders until the free-swimming larvae leave (Hoover et al., 2014). Moreover, these fishes have capacity to adjust their reproductive tactics (Tab. S3) depending on the environmental condition and environmental constraints (Gibbs et al., 2017; Hussan et al., 2023). All these factors likely played a part in making the members of *Pterygoplichthys* as one of the most successful freshwater invaders, different species of which have been reported from 21 countries across five continents (Orfinger and Goodding, 2018).

The invasion of *Pterygoplichthys* species can lead to changes in food chains, disturbances in ecological balances, and competition with native species for resources (Fig. 1). Hence, invasive population of these fishes reported from large aquaculture systems and natural water bodies of India, is of serious concern (Krishnakumar et al., 2009; Kumar et al., 2018; Hussan et al., 2019). *P. pardalis*, *P. disjunctivus*,

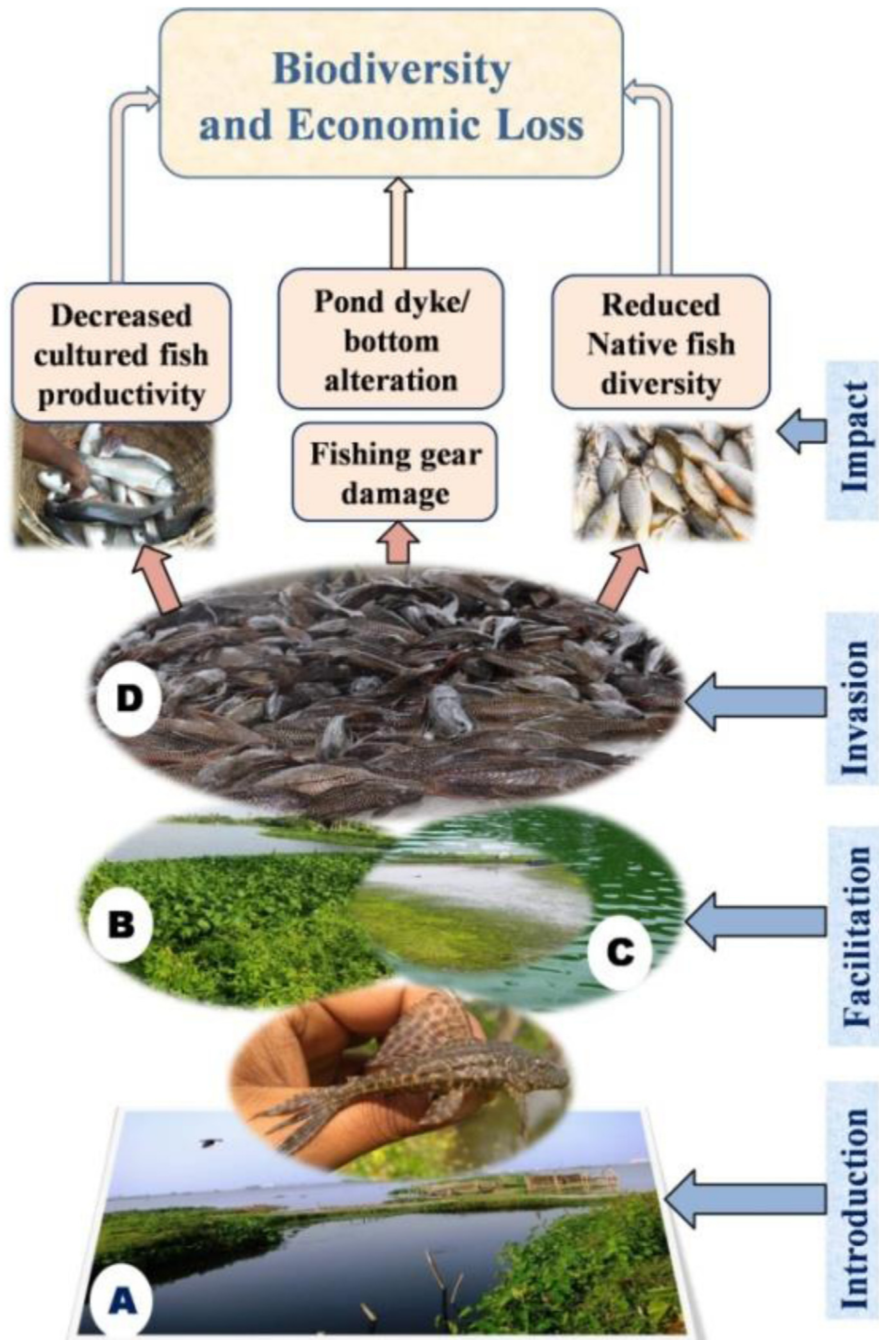

Fig. 1. Pathways and booster of *Pterygoplichthys pardalis* invasion in the East Kolkata Wetlands, India and their impacts on native fish population or community, and ecosystem. (A) Sewage distribution canals- the major pathway of *P. pardalis* spread and entry to the water bodies, (B) dense *Eichhornia crassipes* mats (spread: 2–3 m) along the periphery of the water bodies- use by the species as shelter in weak stages (young / mature fishes) or as hide-outs, (C) abundance of plankton population including detritus in EKW water bodies- the principal food of *P. pardalis*, (D) self-sustaining breeding population of *P. pardalis* in EKW.

P. anisitsi (synonym of P. ambrosettii), *P. multiradiatus*, and potential hybrids are among the sailfin catfish species reported from the country (e.g., *P. multiradiatus* from Krishnakumar et al., 2009; *P. anisitsi* from Sinha et al., 2010; *P. pardalis*, *P. disjunctivus* and *P. pardalis* x *P. disjunctivus* from Hussan et al., 2018). However, using mtDNA COI gene sequence analysis and BOLD data matching, Sahoo et al. (2022) confirmed that all the *Pterygoplichthys* specimens of East Kolkata Wetlands (EKW) of India, having variable abdominal spots and patterns (identified previously as diverse *Pterygoplichthys* species; Hussan et al., 2019) are in fact *Pterygoplichthys pardalis*. This species of sailfin catfish (*P. pardalis*) have overlapping food and feeding preference with many of the economically important food fishes of India, like catla

Labeo catla (Hamilton 1822), rohu *Labeo rohita* (Hamilton 1822), mrigal *Cirrhinus mrigala* (Hamilton 1822), magur *Clarias magur* (Hamilton 1822), and butter catfish *Ompok bimaculatus* (Bloch 1794), and thus a direct competition between *P. pardalis* and native fishes is most likely (Suresh et al., 2019; Hussan et al., 2019). Furthermore, *P. pardalis* can disrupt primary production by causing a net sink in phosphorus level and by grazing on benthic algae and detritus they can change the distribution and abundance of resources important to aquatic insects, eaten by many small native fishes (Page and Robbins, 2006; Hussan et al., 2019). However, there isn't much comprehensive research on how *P. pardalis* affects fish communities of invaded ecosystem and has not been done yet in India.

Hence, in this study, we conducted experiments to ascertain whether Amazon sailfin catfish (*Pterygoplichthys pardalis*) (Fig. 2) have any tendency to consume early life stages (eggs, hatchlings, and early fry) and whether their presence has an impact on the behavior and development of advanced life stages (fingerlings forth) of native fishes of India. We included two species of native fishes, *Labeo rohita*, one of the most preferred and commercially important aquaculture species of native carp, and *Ompok bimaculatus* (colloquially called as 'Pabda' in India), a highly priced species of native catfish for the study (Fig. 2). Both these native species have natural distribution in several of the Indian freshwater ecosystems reported to be invaded by the sailfin catfish (*P. pardalis* and *P. disjunctivus* from Hussan et al., 2019; *P. disjunctivus* from Das et al., 2020) and also share an overlapping feeding preference with the Amazon sailfin catfish (Tab. 1). Furthermore, according to Parvez et al. (2023) sailfin catfish (*P. disjunctivus*) have greater impact on midwater omnivore *Labeo rohita* in comparison to the pelagic planktivore *Lebeo catla*. Therefore, we kept limited the focus of this study to assessing the effects of invasive Amazon sailfin catfish on native mid-water omnivorous carp *Labeo rohita* and catfish *Ompok bimaculatus*.

2 Materials and methods

2.1 Experimental organisms

Rohu *Labeo rohita* and butter catfish *Ompok bimaculatus* brood fish (for producing prey items for experiment-1 and for indoor study of experiment-2) and their advanced life-stages (40g+ size of rohu and 10g+ size of butter catfish; for outdoor and mesocosm study of experiment-2) were collected from the pond raised stock of the Field Station located at Kalyani, West Bengal, India (22°57′43.9″ N, 88°26′30.8″ E) of the Regional Research Station-Rahara of Indian Council of Agricultural Research- Central Institute of Freshwater Aquaculture (ICAR-CIFA). The medium- (40–80 g) and large-sized (100–250 g) Amazon sailfin catfish were collected from three bheries ('bhery'- a local term used for the water bodies of East Kolkata Wetlands (EKW) and are generally in the size range of 5 – 30 ha each), *viz.* Narkeltala bhery (22°33′32″ N, 88°26′55″ E), Chacker bhery (22°33′11″ N, 88°26′37″ E) and Jhagrasirsha bhery (22°32′39″ N, 88°27′31″ E), of the EKW (22°27′00″ N, 88°27′00″ E) (Fig. 3) using drag net between May to August, 2022 and transported to the experimental site at Kalyani, West Bengal, India in well oxygenated containers (1000 L capacity).

Fig. 2. Images of studied fish species.

Before being used in the experiment, the above experimental fish were reared in well-fertilized earthen ponds (0.04 ha each) for 30 days. During this time, they were fed a commercial diet (Growfin, Growel Feeds Private Limited, India; 32% crude protein and 5% crude lipid; hereafter 'Growfin 32/5') at a rate of 3% body weight, twice a day. On the other hand, small size Amazon sailfin catfish (2-10 g) were bought from an ornamental store at Kalyani, West Bengal (which collects adult sailfin catfish from EKW to breed and produce seed), and reared in FRP (Fibre Reinforced Plastic) tanks for 15 days, feeding them commercial diet at a rate of 5% of their body weight twice a day. Live *Tubifex* worms utilized in this study were also acquired from the ornamental store, Kalyani, West Bengal.

Each fish specimen used in the studies were carefully selected to ensure that they were all healthy and of comparable

Table 1. Gut content analysis reports of *Pterygoplichthys pardalis, Labeo rohita* and *Ompok bimaculatus*.

Species	Authors	Location	Gut content
Pterygoplichthys pardalis	Samat et al. (2016)	Sungai Langat, Malaysia	*P. pardalis* feeds primarily on small size particles (<500 μm), mostly algae (84%) especially Bacillariophyta and Euglenophyta followed by pant-based fragments, and animal-based fragments including insects and fish larvae.
	Elfidasari et al. (2020)	Ciliwung River, Jakarta, Indonesia	Classified *P. pardalis* as herbivorous fish in the ecosystem of the Ciliwung River, with diet composition consisting of Bacillariophyta (78–86%), Chlorophyta (6–12%), Cyanophyta, Euglenophyta, Dinoflagellata, Amoebozoa, and detritus.
	Qasim and Jawad (2022)	Shatt al-Arab River, Basrah, Iraq	Fourty-one food items were recognized in the stomach contents, which were broadly categorized as algae (14.11%; includes Bacillariophyta, Charophyta, Chlorophyta, Ochrophyta and Rhodophyta), crustacean (14.12%; includes Anomopoda, Copepoda and Decapoda), insect larvae and pupae (15.53%; includes Diptera, Hemiptera, Ephemeroptera, Coleoptera and Odonata), meiofauna (4.24%), fish (7.06%), fish eggs and larvae (14.12%) and organic detritus and sediment (28%).
Labeo rohita	Bakhtiyar et al. (2017)	Gho-Manhasa fish farm, Jammu. India	Food items recorded in gut content analysis consisted of plant (algae and macrophytes) and animal matter (cladocerans, copepods, rotifers, protozoa, molluscs, annelids and insects) along with unidentified matter, sand/mud, and detritus.
	Kaur et al. (2018)	Harike wetland, Punjab, India	Gut content of *L. rohita* comprised of detritus (46%), phytoplankton (36.40%; includes members of Chlorophyceae such as *Chlorella* sp., *Zygnema* sp. etc. and Bacillariophyceae such as *Diatoma* sp., *Tabellaria* sp. etc.), zooplankton (5.75%; includes rotifera, cladocera and copepoda), insects, crustacean appendages, molluscan eggs and unidentified matter (some parts of leaves and roots).
Ompok bimaculatus	Hanjavanit and Sangpradub (2009)	Nong Han Kumphawapi Lake, Thailand	Gut content of *Ompok bimaculatus* includes zooplankton, aquatic insects, ostracods, fish, shrimps, algae and plant materials.
	Arthi et al. (2011)	River Amaravathy, Tamil Nadu, India	Gut content of *O. bimaculatus* comprised mainly of fish (30.04%), vegetable matter (22.69%), crustaceans larvae and adults (20.12%), insects (7.7%) and molluscs (5.58%). The other food items recorded includes zooplankton, tadpoles, annelid worms and organic detritus.

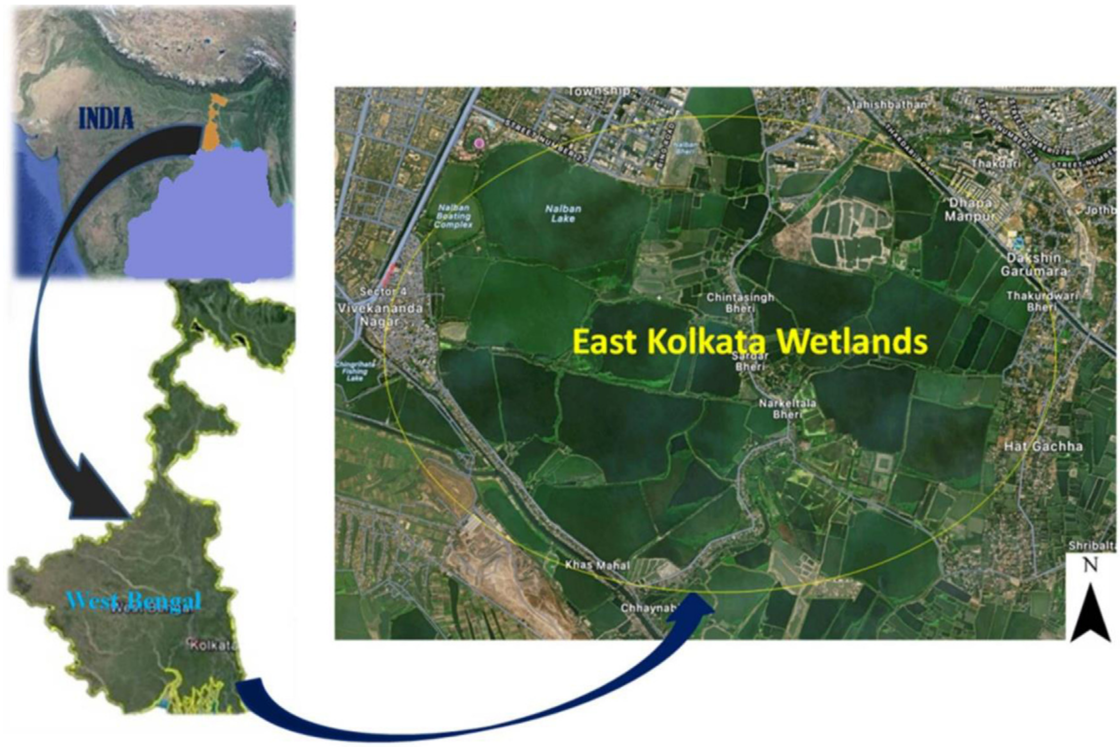

Fig. 3. *Pterygoplicthys pardalis* collection site: East Kolkata Wetlands (22°25′ − 22°40′N, 88°20′ − 88°35′E), West Bengal, India.

size to satisfy the experiment's requirements. Standard protocol of induced breeding and seed rearing (Chakrabarti et al., 2017; Hussan et al., 2020) was followed to produce eggs, hatchlings, first-feeding fry, and 10-day-old fry of native rohu and butter catfish. For rohu ($n = 8$), the body weight of the males and females employed for induced egg collection and induced seed production were 1537.50 ± 110.87 and 2087.50 ± 131.49 g, respectively, while for butter catfish ($n = 40$), it was 45.05 ± 3.28 and 53.9 ± 7.06 g, respectively. The fish and experimental protocols were managed in compliance with the established standards of the Institutional Animal Ethics Committee (IAEC), ICAR-CIFA, Bhubaneswar, India.

2.2 Analyze the impact on early life-stages of native fish

In aquaria (30 × 60 × 30 cm, $n = 48$) filled with 45 l of well oxygenated tap water with a temperature of 25.6 ± 0.07°C and pH of 7.43 ± 0.02, prey items (eggs, hatchlings, first-feeding fry, and 10-day-old fry) were released separately for each species (rohu and butter catfish) and each life-stage in four different stocking densities (@ 100, 200, 300, and 400 nos.) (Fig. 4). In order to reduce the rate of mortality from handling stress, hatchlings, first-feeding fry and 10-day-old fry were acclimatized in the experimental tanks for an hour following the introduction. Following that, the dead individuals were taken out and replaced with the living ones. After that, the Amazon sailfin catfish were introduced to the test aquariums.

Since Amazon sailfin catfish showed a high affinity for fish eggs in the preliminary study, further sets of experiments were carried out to determine whether Amazon sailfin catfish have any particular selectivity towards fish eggs. In these experiments, *Tubifex* (@ 0.5, 1.0, 1.5, and 2.0 g) were provided in addition to the eggs of rohu and butter catfish (individually) as prey items for the Amazon sailfin catfish. To ascertain the natural mortality or loss, a set of control (with prey items but without any Amazon sailfin catfish) was maintained in each case. All the experiments were carried out in triplicate.

To begin the experiment, three different size classes of Amazon sailfin catfish, small (TL: 9.95 ± 0.7 cm, W: 8.19 ± 1.53 g, $n = 30$), medium (TL: 21.74 ± 0.87 cm, W: 69.31 ± 7.82 g, $n = 30$), and large (TL: 30.81 ± 1.59 cm, W: 226.85 ± 21.92 g, $n = 30$), were taken from the pond and acclimatized in FRP tanks (3.0 × 1.0 × 0.6 m, 2000-L capacity) with aeration for 24 h. During that time, the fish weren't fed. First prey items (eggs, eggs with *Tubifex*, hatchlings, first-feeding fry, and 10-day-old fry) of each species were introduced into the aquarium after counting. After that, a single Amazon sailfin catfish of a given size- small, medium, or large- was placed into each aquarium (apart from the control) and kept undisturbed for a whole day under a natural photo regime (13/11 h, light/dark). Prey items that remained in the aquarium after 24 h were then collected and counted (except *Tubifex*, which was weighed).

2.3 Analyze the impact on native fish growth

Three sets of competition studies were carried out with varied size groups, combinations, and settings (Fig. 5) in order to quantify the interaction impacts of sailfin catfish on the growth and survival of native fish species (rohu and butter

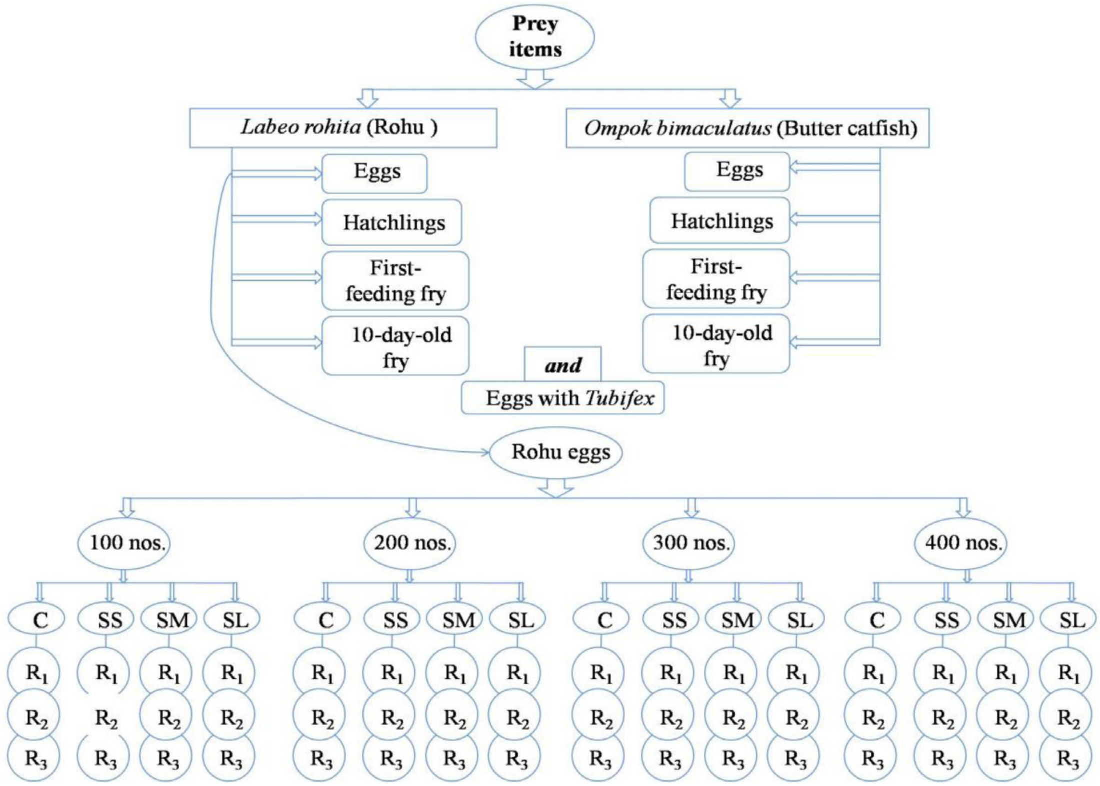

Fig. 4. Experimental set-up to analyze the impact of Amazon sailfin catfish on survival of early life-stages of native fish [C: Control (without any fish); SS: Amazon sailfin catfish (small size); SM: Amazon sailfin catfish (medium size); SL: Amazon sailfin catfish (large size); R_1, R_2 & R_3: replicates]. Each life-stage of each of the native fish is tested same way; the method of testing rohu eggs are presented in this figure.

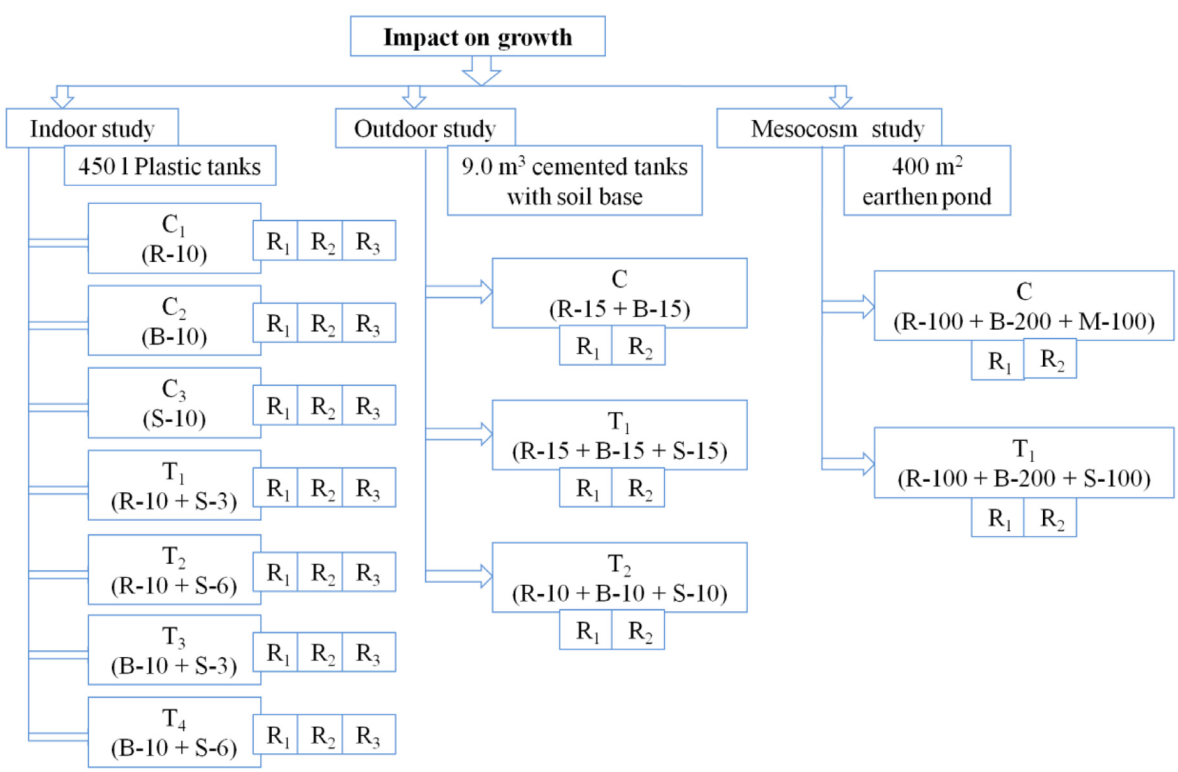

Fig. 5. Experimental set-up to study the impact of Amazon sailfin catfish on native fish growth [R: rohu; B: butter catfish; S: Amazon sailfin catfish; M: mrigal; R_1, R_2 & R_3: replicates].

catfish). Depending on the availability of resources, the number of treatments and replicates in different set of competition studies was adjusted. Moreover, feeding of the fishes were done in different combinations in different sets of competition studies to ascertain the impact of Amazon sailfin catfish on native fishes in natural water bodies and in fully or partially supplementary feed dependent aquaculture systems.

2.3.1 Indoor study

A randomized block design method with four treatments (T_1–T_4) and three controls (C_1, rohu control; C_2, butter catfish control; C_3, Amazon sailfin catfish control), each with three replicates (R_1–R_3), were employed to measure the interactive effects of Amazon sailfin catfish on native fish species growth and survival (Fig. 5). Amazon sailfin catfish fingerlings in different densities (low and high) were stocked with fixed numbers of rohu fingerlings (10 numbers) in treatments T_1 and T_2, and with fixed numbers of butter catfish fingerlings (10 numbers) in treatments T_3 and T_4. There were three Amazon sailfin catfish in the low density treatment (T_1 and T_3) and six in the high density treatment (T_2 and T_4). Stocking weights (Mean ± SD and range) of the experimental species were: rohu, 3.2 ± 0.51 g (2.1–3.9 g); butter catfish, 2.5 ± 0.3 g (2.1–3.3 g); and Amazon sailfin catfish, 2.7 ± 0.4 g (2.0–3.2 g). The study was conducted for 90 days (September–November 2022) in 450 l cylindrical plastic tanks filled with tap water and provided with continuous aeration. The fish were fed with commercial fish feed (Growfin 32/5) at a rate of 5% body weight, twice a day (in the early morning and evening).

2.3.2 Outdoor study

The study was carried out in 9.0 m^3 outdoor cement tanks provided with five centimeter soil base and filled with water from a well-fertilized farm pond. Using advanced fingerlings of the experimental fish two treatments (T_1–T_2) and one control (C) was set up, each with two replicates (R_1–R_2) (Fig. 5). In control rohu and butter catfish were stocked together at a rate of 15 each. While maintaining the same number of native fish as the control, in T_1 15 nos. of Amazon sailfin catfish was added. However in treatment T_2, densities of natives (rohu and butter catfish) as well as Amazon sailfin catfish were adjusted to 10 nos. each to make it proximate to the total biomass of control to test for any biomass effect. Stocking weights (Mean ± SD and range) of the experimental species were: rohu, 52.1 ± 3.7 g (45.3–58 g); butter catfish, 10.8 ± 0.85 g (9.1–12.4 g); and Amazon sailfin catfish, 57.8 ± 2.9 g (51–61.4 g). The tanks were fertilized initially and every one week interval with mustard oil cake (MOC) to encourage and maintain natural productivity. Additionally commercial feed (Growfin 32/5) was also provided at a rate of 2% body weight, once a day (evening). The study was conducted for 120 days (July–October 2022).

2.3.3 Mesocosm study

The study was conducted in four earthen ponds (400 m^2) of similar size and characteristics for a period of six-month (June–November 2022) utilizing sub-adult stages of experimental fish. One month prior to the fish being stocked, the ponds were totally dewatered and limed (calcium carbonate @ 500 kg ha^{-1}). Ponds were then filled with water from neighboring non-experimental pond and fertilized with both organic and inorganic fertilizers following standard procedure (Sundaray et al., 2019). The investigation was set-up with one treatment (with Amazon sailfin catfish) and one control (without Amazon sailfin catfish) in duplicates (Fig. 5). The number of native test fish was the same in the control (C) and treatment (T) ponds (C and T; 100 numbers rohu and 200 numbers butter catfish). In contrast, there were 100 Amazon sailfin catfish in the treatment pond and zero in the control pond. Furthermore, in order to bring the overall biomass of the control (C) closer to that of the treatment (T; natives + Amazon sailfin catfish), 100 numbers of mrigal *Cirrhinus mrigala* (a bottom feeder; not investigated for interaction study) fish with weights similar to Amazon sailfin catfish were stocked in the control. Surface feeder fishes, *viz*. catla and silver carp *Hypophthalmichthys molitrix* (Valenciennes 1844) having comparable size (128.3 ± 17.61 g) were also stocked in the control and test ponds in equal numbers (@ 20 nos. of each species) to maintain the ecological balance of the ponds, but they were not examined for the interaction study. Stocking weights (Mean ± SD and range) for the experimental species were: rohu, 119.5 ± 11.6 g (104–136 g); butter catfish, 20.75 ± 1.7 g (17.4–23 g); and Amazon sailfin catfish, 120.68 ± 13.08 g (101.5–142.2 g). The ponds received no external feeding. However, to sustain natural food production, the ponds were fertilized once a week with cow dungs, MOC and single super phosphate at appropriate dose depending on the trophic status of the pond. The water level was maintained at 1.20 m.

Fish growth was monitored monthly in terms of length and weight gain. All fish were counted, and randomly five fishes (except Amazon sailfin catfish of T_1 and T_3: indoor study) from each replicates were measured and weighed in each sampling in case of indoor and outdoor sets of study. In mesocosm study, fishes were caught using a seine net (mesh 30 × 30 mm) and random sample of 10 individuals of each test species from each replicates were measured and weighed each time.

2.3.4 Water quality parameters

Physicochemical properties such as temperature, pH, dissolved oxygen (DO), alkalinity, hardness, total ammonia nitrogen (TAN) and nitrate–nitrogen (NO_3–N) were analyzed monthly (indoor, outdoor and mesocosm competition studies) following the standard procedure (APHA, 2005).

2.4 Data analysis

Data in the text and figures are expressed as mean ± standard deviation or mean ± standard error. After confirming the homoscedasticity of variances (Levene's test) and the distributional normality of the data (Shapiro-Wilk test), statistical comparisons were performed. The means of the treatment groups were compared for significant differences ($p < 0.05$) using Student's *t*-test for paired data sets and one-way analysis of variance (ANOVA) in all other cases. Tukey's range test was used to compare the means of treatment pairings at the 5% level ($p < 0.05$) whenever ANOVA revealed a significant difference. A general linear model (GLM) was used to assess the effects of sailfin catfish size, stocking density of native fish life-stage, and their interactions on the mortality or destruction of the corresponding life-stages of the native fish. When the GLM showed a significant effect, Tukey's range test was used to examine the differences between treatments. All data analysis was performed using SPSS version 23 (IBM corporation).

3 Results

3.1 Impact on survival of early life-stages of native fish

All sizes of Amazon sailfin catfish extensively consumed and/or destroyed the eggs of rohu ($F = 1107.80$, $p < 0.001$; one-way ANOVA) and butter catfish ($F = 1912.37$, $p < 0.001$; one-way ANOVA) (Fig. 6). No correlation was seen between the size of Amazon sailfin catfish and the rate of feeding on native fish eggs (GLM: $F = 0.451$, $p = 0.642$ for rohu; and $F = 1.735$, $p = 0.198$ for butter catfish) (Tab. 2). Small, medium, and large Amazon sailfin catfish foraged / destroyed, on average, 91%, 93%, and 91% of rohu eggs and 94%, 96%, and 96% of butter catfish eggs, respectively (represented as the average percentage from the pooled duplicates of all stocking densities of the life stage). Even in presence of *Tubifex* (an aquatic macro-invertebrate), eggs of both native fish species were consistently consumed and/or destroyed (89–95%) by Amazon sailfin catfish. The species also appear to have greater affinity for fish eggs, as they consumed fish eggs first and in greater quantity than *Tubifex* (Fig. 7). Among native species, butter catfish eggs were found to be more susceptible to Amazon sailfin catfish foraging activities ($p < 0.001$) than rohu (Fig. 8). However, impact of Amazon sailfin catfish on the survival of motile life-stages (hatchlings, first-feeding fry, and 10-day-old fry) of both native fish species was found to be nominal (0.5–4% higher) and statistically insignificant ($p > 0.05$), except a significant impact of large size Amazon sailfin catfish on rohu hatchlings ($p = 0.018$) and first-feeding fry ($p = 0.012$) (Fig. 6). Overall the effects of Amazon sailfin catfish on the mortality and destruction of the early life stages of native fish were found to be largely unaffected by their size and the stocking density of the corresponding life stage of the native fish (GLM: all $p > 0.05$), with the exception of the stocking density effect of butter catfish eggs ($p < 0.001$) and rohu hatchlings ($p = 0.033$) (Tab. 2). Likewise, a noteworthy interaction impact between Amazon sailfin catfish size and native species stocking density was seen just for rohu hatchlings (GLM: $F = 3.564$, $p = 0.011$).

3.2 Impact on growth of advanced stages of native fish

In the indoor competition trial, where the fish were given only commercial fish feed, growth of butter catfish decreased by 12–17% with increasing density of Amazon sailfin catfish but rohu grew better (2–4%) in treatments compared to the control (Fig. 9). However, overall impacts of Amazon sailfin catfish on the growth of native species in the experiment was found insignificant (all $p > 0.05$; Tab. 3). Whereas in outdoor set-up of experiment, the impact of Amazon sailfin catfish on the growth of both the native species (rohu and butter catfish) was found to be highly significant (all $p < 0.05$; Tab. 3). When compared to a control group that included both native species but no Amazon sailfin catfish, the growth of native species in the high (T_1) and low (T_2) biomass Amazon sailfin catfish treatments was reduced by 23.4% and 18.8% for rohu and 36.7% and 28.9% for butter catfish, respectively (Fig. 10). Compared to rohu the effect of Amazon sailfin catfish on butter catfish was observed to be not only stronger, but also more rapid. A significant variation in growth was noted in the case of butter catfish starting at 30 days ($F = 6.201$, $p = 0.006$; one-way ANOVA), whereas in case of rohu it was observed at 60 days ($F = 3.537$, $p = 0.047$; one-way ANOVA). Likewise, the mesocosm investigation showed that Amazon sailfin catfish presence have significant impact on growth of both the native species (Tab. 3). The growth of rohu and butter catfish decreased by 29.7% and 32.2%, respectively, during the course of six months when Amazon sailfin catfish were present (Fig. 11). However, in all experimental settings (mesocosm study: no Amazon sailfin catfish control), Amazon sailfin catfish growth did not differed much among treatment groups (Tab. 3).

No mortality of any species occurred in the outdoor or mesocosm studies. However, mortality of all the species was recorded in the indoor study. The survival rate in low-density Amazon sailfin catfish treatment was 93.33% and 83.33% for rohu and butter catfish, respectively. Whereas, in the high-density Amazon sailfin catfish treatment, survival rate was much lower (86.67% for rohu and 70% for butter catfish). However, Amazon sailfin catfish survival rate was greater than 94% in all treatments.

3.3 Physico-chemical parameters in indoor, outdoor and mesocosm study

Though water temperature varied seasonally, no significant difference was observed among treatments within the experimental set-up. Other water quality parameters (pH, DO, alkalinity, hardness, TAN and NO_3–N) also did not varied significantly ($p > 0.05$) among the treatments within the experimental set-up over the study period (Tabs. 4 and 5).

4 Discussion

Results from our study clearly showed that invasive Amazon sailfin catfish have an influence on native fish species. Their effects, however, can differ based on the native species' developmental stage. The eggs of native fishes were easily devoured by the Amazon sailfin catfish of all sizes, and their survival throughout the motile early stages (hatchlings and first-feeding fry) was affected to some extent. Furthermore, the growth rate of advance life–stages (fingerlings, sub-adult and adult) of both the native species was found comparatively lower in the presence of Amazon sailfin catfish in all three sets of trials (indoor, outdoor, and mesocosm). This implies that the sailfin catfishes have potential to adversely affect the native fish diversity of freshwater habitats of India, where its distribution is already extensive (Hussan et al., 2019).

While debris, algae, macrophytes, and to a lesser extent crustaceans, insects, and other similar creatures make up the majority of the sailfin catfish's diet (Gestring et al., 2010), present study suggests that sailfin catfish can right away

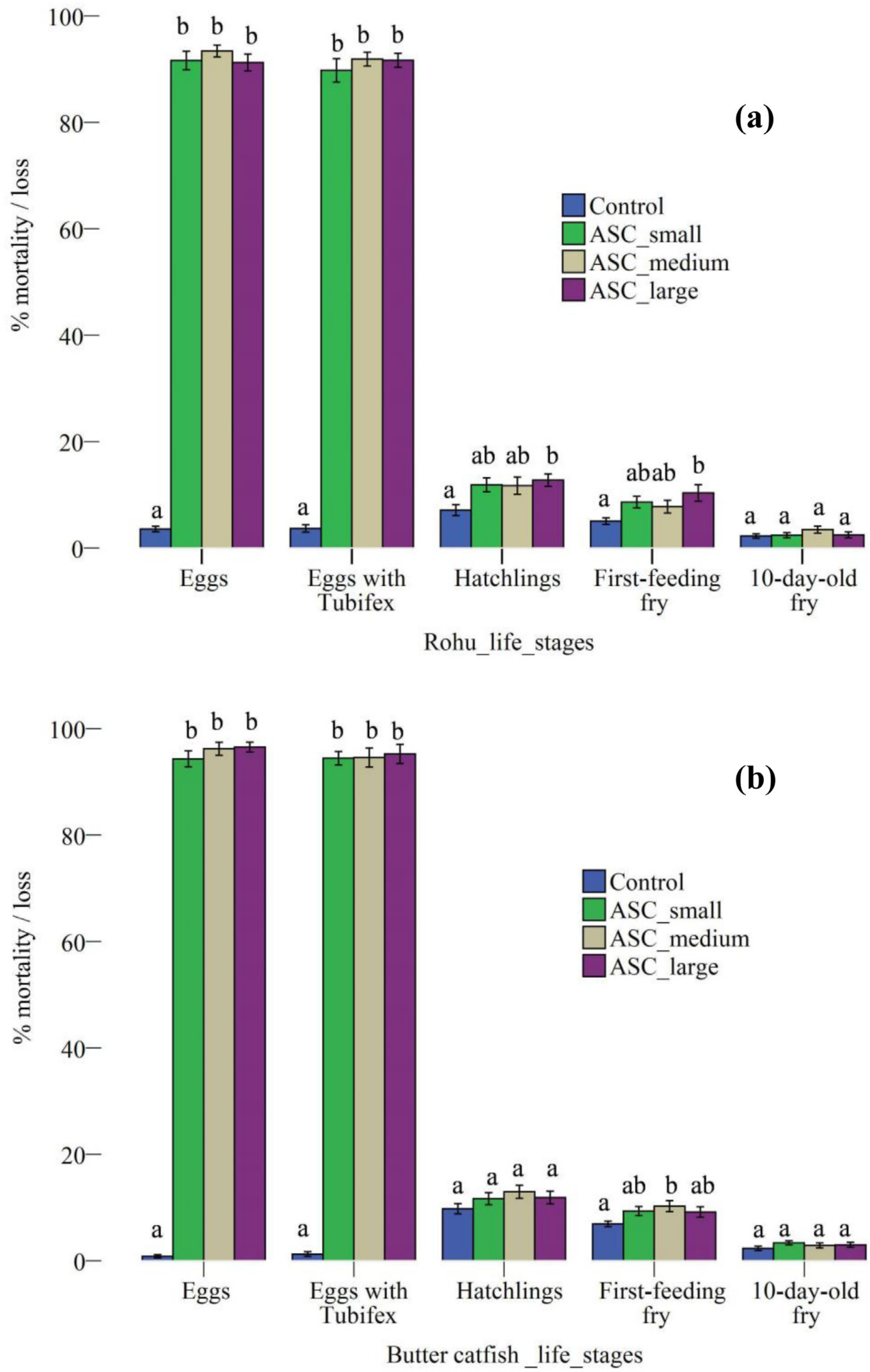

Fig. 6. Impacts of different size groups of Amazon sailfin catfish (ASC) on survivability of different early life-stages of rohu (a) and butter catfish (b) over the period of 24 h. Values are denoted as mean and standard error (mean ± SE) of mortality/loss in percentage (expressed as percentage of all stocking densities per treatment, from combined replicates; $n = 12$). Bars within panels having a different letter are significantly different ($p < 0.05$; one-way ANOVA followed by post hoc Tukey test).

Table 2. General linear model (GLM) results for the impact of Amazon sailfin catfish size (small, medium and large), stocking density (of respective life stage of native fish) and their interaction on mortality /destruction of rohu (R) and butter catfish (BC) eggs (E), eggs in presence of *Tubifex* (ET), hatchlings (H), first-feeding fry (FF) and 10-days old Fry (F10).

Variables	Amazon sailfin catfish size (SS)			Native fish stocking density (NSD)			SS x NSD		
	df	F	P	df	F	P	df	F	P
Rohu (*Labeo rohita*)									
RE	2	0.451	0.642	3	0.204	0.893	6	0.103	0.995
RET	2	0.410	0.668	3	0.454	0.717	6	0.367	0.893
RH	2	0.282	0.757	3	3.419	**0.033**	6	3.564	**0.011**
RFF	2	1.268	0.299	3	0.889	0.461	6	2.299	0.068
RF10	2	1.058	0.363	3	0.140	0.935	6	1.236	0.323
Butter catfish (*Ompok bimaculatus*)									
BCE	2	1.735	0.198	3	9.028	**<0.001**	6	1.677	0.170
BCET	2	0.119	0.888	3	7.556	**0.001**	6	1.772	0.148
BCH	2	0.323	0.727	3	0.035	0.991	6	1.126	0.377
BCFF	2	0.344	0.712	3	1.738	0.186	6	0.149	0.987
BCF10	2	0.264	0.770	3	0.086	0.967	6	0.280	0.941

Statistically significant values at a probability level of $p < 0.05$ are shown in bold.

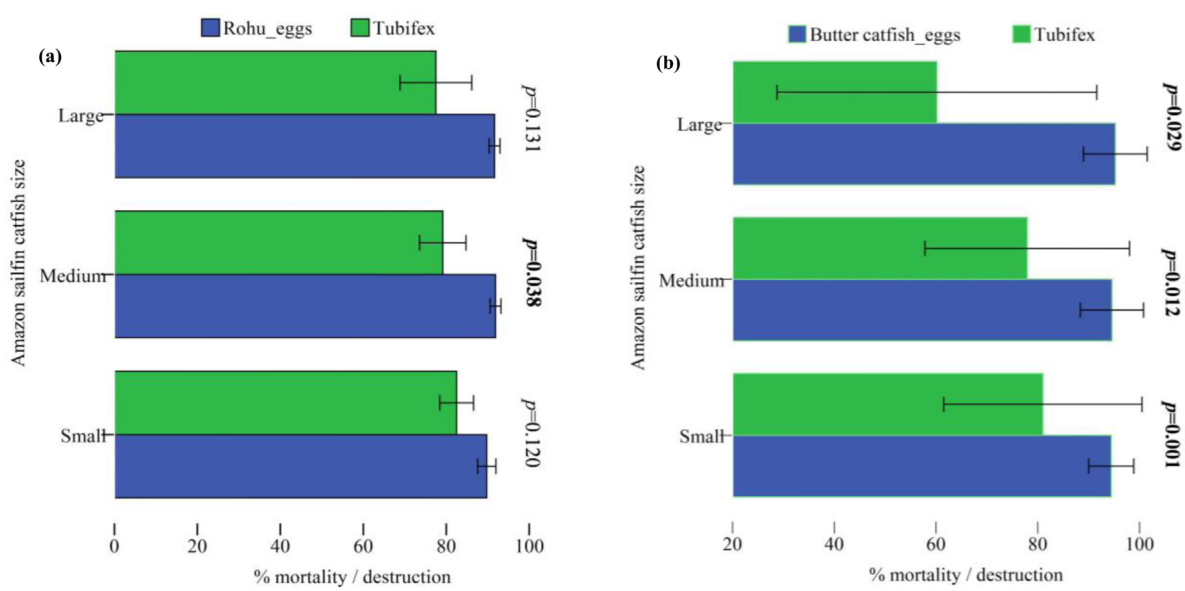

Fig. 7. Comparison between consumption / destruction of eggs of rohu (a) or butter catfish (b) and *Tubifex* by different size groups of Amazon sailfin catfish. Values are denoted as mean and standard error (mean ± SE) of loss in percentage (expressed as percentage of all stocking densities per treatment, from combined replicates; $n = 12$). Values above the bar indicate significance level (independent *t* test). Statistically significant differences ($p < 0.05$) are shown in bold.

consume the eggs of native fish. We found that Amazon sailfin catfishes consumed/destroyed 86–100% eggs of native fishes, which is nearly similar to the observation of Chaichana and Jongphadungkiet (2012) who reported 100% destruction of Nile tilapia *Oreochromis niloticus* (Linnaeus 1758) eggs by all size classes of *P. pardalis*, irrespective of the stocking density of the eggs. About 97.5% predation/ destruction of eggs of the endangered fountain darter *Etheostoma fonticola* (Jordan & Gilbert 1886), endemic to the San Marcos River in Hays County and the Comal River in Comal County, USA) by the loricariid catfish of the genus *Hypostomus* (closely related to *Pterygoplichthys* spp.) was also reported (Cook-Hildreth, 2009). Hoover et al. (2004) periphrastically linked the egg consumption by loricariid catfishes, more particularly by sailfin catfishes, with their benthic and sucking feeding behavior. They explained that, as sailfin catfishes grazes on the bottom and surfaces of the objects to scrap algae and detritus, it is probable that they might consume the eggs of the native species laying eggs on those grounds. Furthermore, according to Pound et al. (2011), armoured catfishes in the Texas River did not feed on macrophytes, macroinvertebrates, or fish eggs rather they primarily eat detritus, filamentous red algae and

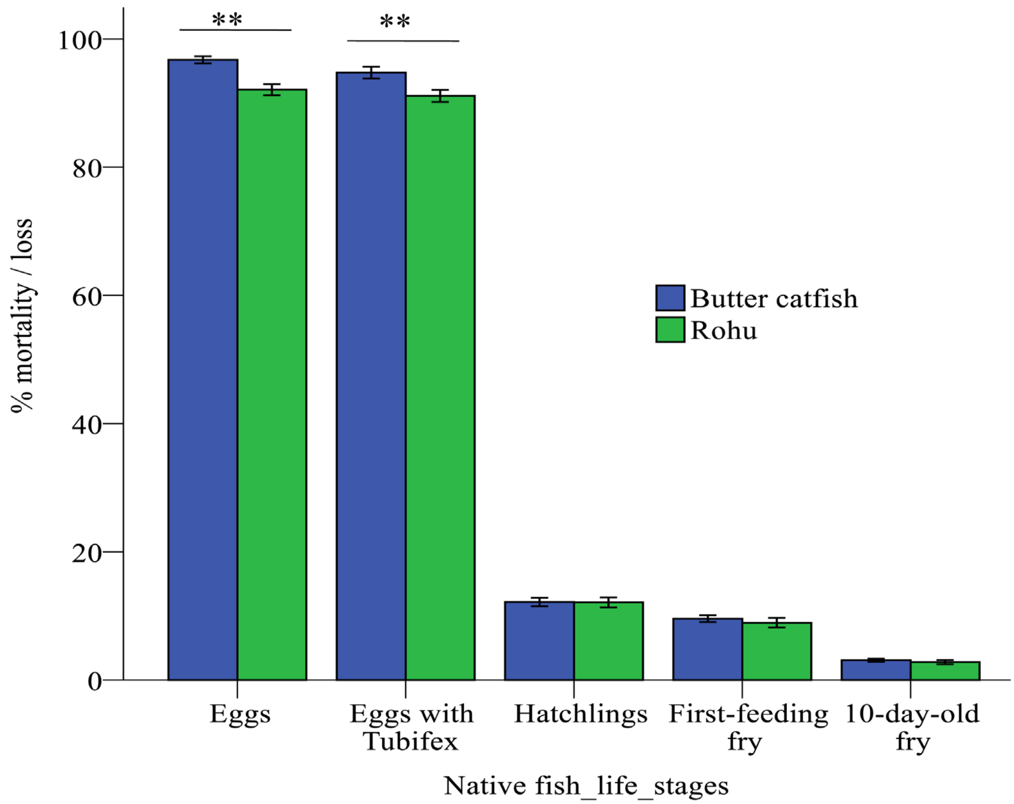

Fig. 8. Comparison of impacts on survivability of different early life-stages of rohu and butter catfish by Amazon sailfin catfish (all size groups polled together). Values are denoted as mean and standard error (mean ± SE) of mortality/loss in percentage (expressed as percentage of all stocking densities and all size classes of Amazon sailfin catfish against a native species, from combined replicates; $n = 36$). **indicate significant difference at 1% level (independent t test).

picoplankton. In contrast to these views, we found that Amazon sailfin catfish ate or destroyed >80% of the rohu and butter catfish eggs and showed a clear preference for these native fishes eggs, even when given the choice between fish eggs and *Tubifex*. They also ingested fish eggs first and in larger quantities than *Tubifex*. This suggests that, sailfin catfishes have potential to reduce the breeding success of the native fishes by consuming native fish eggs (Chaichana and Jongphadungkiet, 2012). Fishes which lay demersal and substratum attached eggs are likely more vulnerable, as sailfin catfish graze on benthic surfaces and swim close to the benthos (Power et al., 1989). Eggs of fountain darters, a phytolithophilic spawner which deposit adhesive eggs on filamentous algae (Schenck and Whiteside, 1977), was reported more assailable to foraging activities of *Hypostomus*, compare to eggs of Devils River minnow *Dionda diabolic*, which spawns over gravel with the eggs sinking down to just below the surface (Gibson et al., 2003; Cook-Hildreth, 2009). The increased consumption of butter catfish eggs (demersal and adhesive) compared to rohu eggs (demersal but non-sticky) that we found in our study may be explained by this.

The survival rate of motile life-stages (hatchlings, first-feeding fry, and 10-day-old fry) of both native fishes was not significantly impacted by the presence of Amazon sailfin catfish, with a few minor exceptions (large size Amazon sailfin catfish caused significant mortality of rohu hatchlings and first-feeding fry, though no noticeable consumption of the same was recorded). This suggests that, Amazon sailfin catfish prefer more easily accessible stationary food items over the moveable ones like fish hatchlings and fry. Findings of Gestring et al. (2010) might be connected to our findings, where they observed detritus and algae as the principal food for Orinoco sailfin catfish, with insects, crustaceans, mollusks, and arachnids, each contributing <1% of the food volume. However, our present findings contradicts the observation of Chaichana and Jongphadungkiet (2012), where they observed 25–40% consumption of first feeding fry of Nile tilapia by different size groups of Amazon sailfin catfish.

In the indoor competition trial using artificial feed, growth of butter catfish reduced slightly due to presence of Amazon sailfin catfish, but rohu growth was found unaffected. This might be due to the superior feeding efficiency of the rohu on artificial feed, as observed during the study. However, in partially and fully natural food dependent trials (outdoor and mesocosm experiments), presence of Amazon sailfin catfish significantly reduced the growth of both rohu (18.8–29.7%) and butter catfish (28.9–36.7%). These findings are in line with those of Parvez et al. (2023), who found that a high density of vermiculated sailfin catfish reduced rohu growth by 21.4% and suggested a strong competition between native rohu with sailfin catfish for the same foods. Suresh et al. (2019) reported

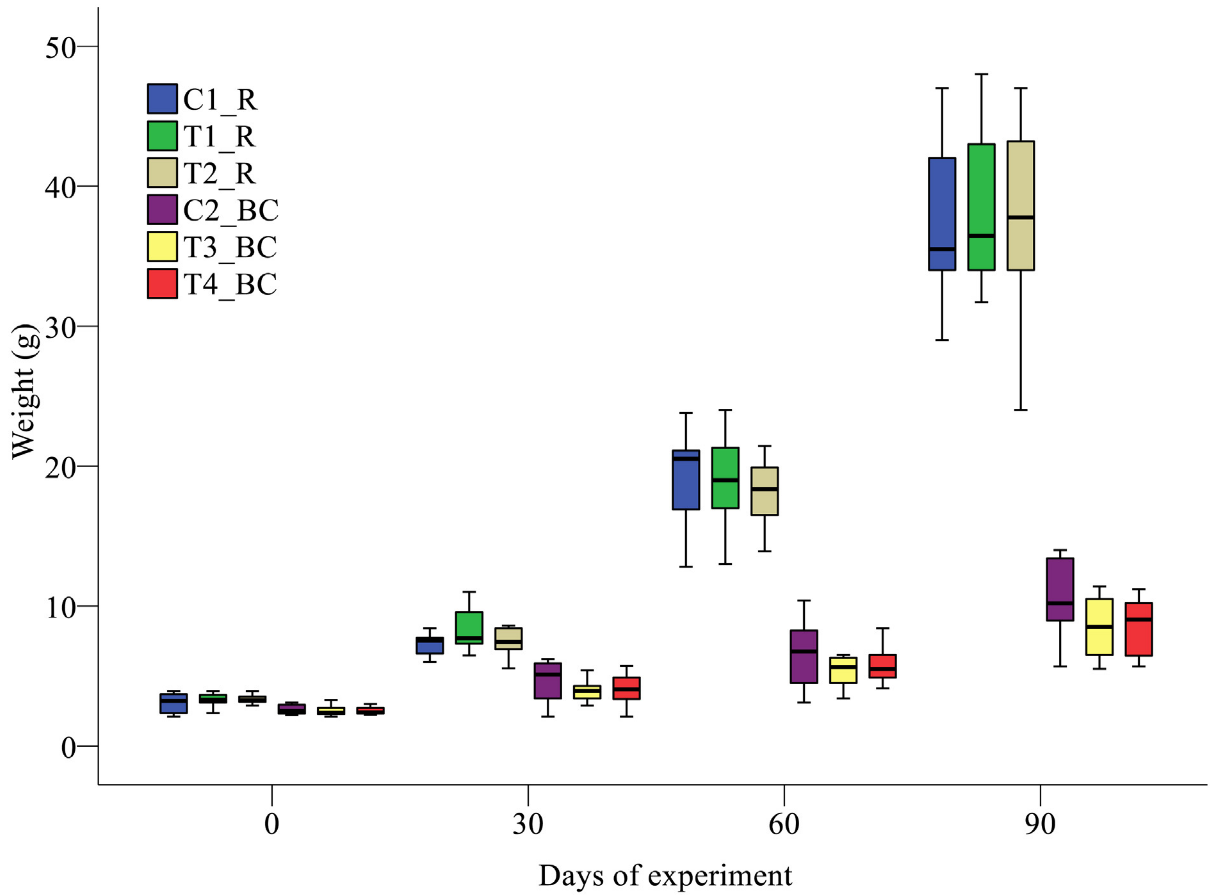

Fig. 9. Boxplots showing the weight of native species in different treatment groups under indoor experiment (C1_R, rohu control; T1_R and T2_R are low- and high-Amazon sailfin catfish density treatment on rohu; C2_BC, butter catfish control; T3_BC and T4_BC are low- and high-Amazon sailfin catfish density treatment on butter catfish) over 90 days. Midline within the box is the median; upper and lower limits of the box represent the third and first quartile (75th and 25th percentile) respectively.

Table 3. Changes in mean body mass of the studied species (different life-stages under different experimental conditions) in relation to presence of non-native Amazon sailfin catfish obtained through One-way ANOVA and independent t test ($^{\lambda}$).

Test species	Growth (in terms of weight)					
	Indoor study		Outdoor study		Mesocosm study	
	F value	p value	F value	p value	t value	p value
Labeo rohita	0.142	0.868	30.459	**<0.001**	5.62^{λ}	**<0.001**
Ompok bimaculatus	1.909	0.168	36.348	**<0.001**	5.179^{λ}	**<0.001**
Pterygoplichthys pardalis	2.342	0.085	$t = -1.664^{\lambda}$	0.113	–	–

Statistically significant values at a probability level of $p < 0.05$ are shown in bold.

greater than 60% resemblance between the food items of the invasive vermiculated sailfin catfish and those of the native mrigal, magur, Indian spiny eel *Macrognathus pancalus* (Hamilton 1822), spotted snakehead *Channa punctatus* (Bloch 1793) and climbing perch *Anabas testudineus* (Bloch 1792) of India. Despite feeding mostly on the bottom (Nico et al., 2012), Amazon sailfin catfish can spread out across the receptor habitat and eat anything they come across (Nico et al., 2009a; Pound et al., 2011; Qasim and Jawad, 2022) and thus can significantly interfere even with the mid-water and surface-feeder fishes having dietary similarities (Parvez et al., 2023). Furthermore, according to Parvez et al. (2023), native fishes of different food habits, from herbivorous to carnivorous will be in direct competition with sailfin catfishes for the food sources and habitat when these fishes invade a body of water. In the San Marcos River and drainages in central Texas, USA, native herbivorous fishes, such as the algivorous Devils River minnow are thought to have been displaced by invasive armoured catfish (*H. plecostomus*) through competitive exclusion for resources (food and space) (Lopez-Fernandez and Winemiller, 2005;

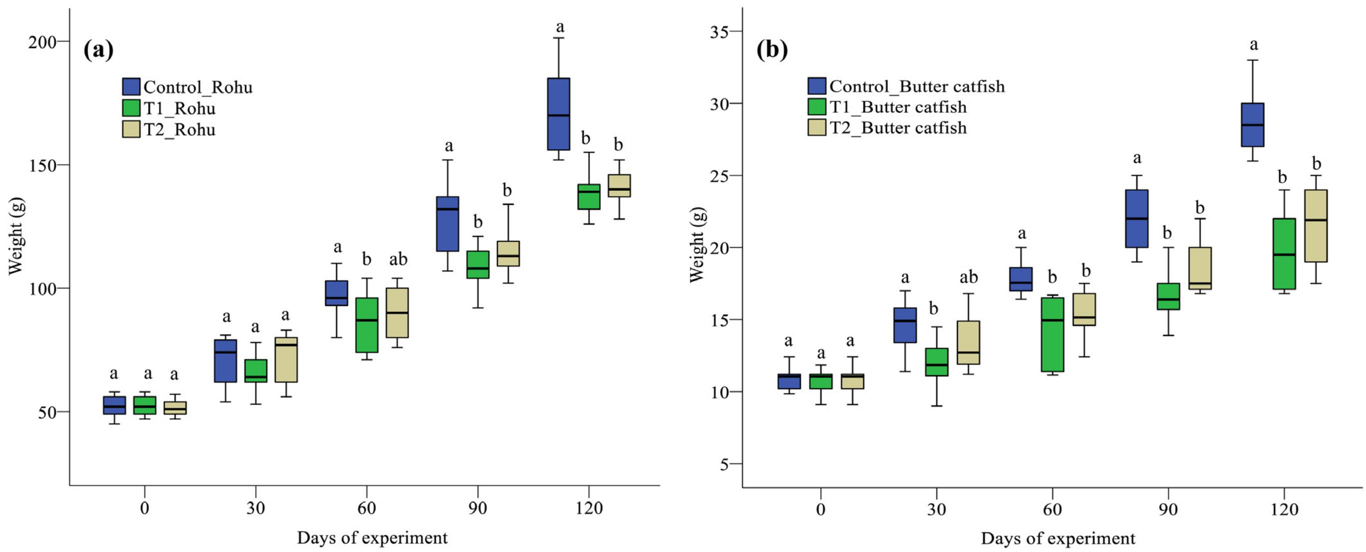

Fig. 10. Boxplots showing the weight of the native carp rohu (a) and native butter catfish (b) in different treatment groups under outdoor experiment (T1 and T2, high- and low-Amazon sailfin catfish density treatment groups respectively) over 120 days. Midline within the box is the median; upper and lower limits of the box represent the third and first quartile (75th and 25th percentile) respectively. Different letters on the top of the boxplot represent significant difference ($p < 0.05$; one-way ANOVA followed by post hoc Tukey test) between treatments at different time points.

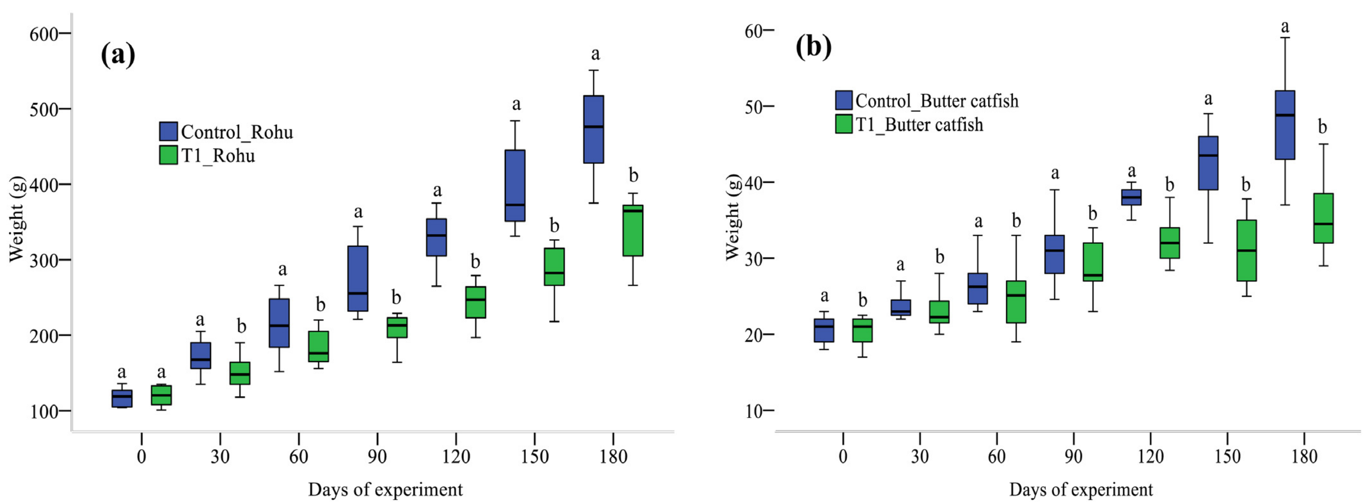

Fig. 11. Boxplots showing the weight of the native rohu (a) and butter catfish (b) in different treatment groups under pond/mesocosm experiment (T1, Amazon sailfin catfish treatment group) over 180 days. Midline within the box is the median; upper and lower limits of the box represent the third and first quartile (75th and 25th percentile) respectively. Different letters on the top of the boxplot represent significant difference ($p < 0.05$; independent *t* test) between treatments at different time points.

Hoover et al., 2014). Interactions with sailfin catfish were implicated in the declining abundance and limited occurrences of many herbi-omnivorous native fishes, particularly small (<15 cm) minnows or minnow-like fishes, such as swamp barb *Puntius chola* (Hamilton 1822) and ticto barb *Pethia ticto* (Hamilton 1822) in East Kolkata Wetlands, West Bengal, India (Hussan et al., 2019). Even population of carnivorous elongate glassy perchlet *Chanda nama* (Hamilton 1822) has been displaced in East Kolkata wetlands (Hussan et al., 2019) by sailfin catfishes, might be through alteration of distribution and abundance of resources like aquatic insects through destruction of insects breeding grounds while grazing (Hoover et al., 2014).

Thus, sailfin catfishes have potential to significantly harm a variety of fish and other aquatic animals (e.g., snails, Hoover et al., 2014; manatees, Nico et al., 2009b) in invaded ecosystems, either directly or indirectly. Reduction of food resources such as aquatic insects and vegetation, destruction of spawning and shelter ground, and direct habitat competition due to high biomass of populations are reported as the prime reason of native fish decline in sailfin catfish invaded systems

Table 4. Mean (± SE) values of water quality parameters of 30-day samples over the 3-month indoor competition experiment (September-November, 2022).

Parameters	C_1	C_2	C_3	T_1	T_2	T_3	T_4
Temperature (°C)	26.66 ± 0.26^a	26.65 ± 0.31^a	26.72 ± 0.29^a	26.81 ± 0.21^a	26.69 ± 0.23^a	26.68 ± 0.28^a	26.71 ± 0.27^a
pH	7.62 ± 0.07^a	7.73 ± 0.09^a	7.68 ± 0.05^a	7.65 ± 0.11^a	7.74 ± 0.09^a	7.78 ± 0.10^a	7.59 ± 0.08^a
DO ($mg\,L^{-1}$)	6.44 ± 0.13^a	6.39 ± 0.16^a	6.15 ± 0.20^a	6.35 ± 0.14^a	6.23 ± 0.13^a	6.38 ± 0.15^a	6.40 ± 0.11^a
Alkalinity ($mg\,L^{-1}$)	149.87 ± 1.98^a	153.76 ± 3.04^a	152.50 ± 2.96^a	150.37 ± 3.15^a	153.83 ± 2.27^a	151.75 ± 2.17^a	155.62 ± 1.74^a
Hardness ($mg\,L^{-1}$)	162.51 ± 2.44^a	165.12 ± 2.93^a	165.25 ± 1.99^a	168.62 ± 1.94^a	162.73 ± 1.67^a	166.19 ± 2.03^a	164.34 ± 2.79^a
TAN ($mg\,L^{-1}$)	0.053 ± 0.004^a	0.041 ± 0.003^a	0.046 ± 0.005^a	0.038 ± 0.004^a	0.035 ± 0.005^a	0.042 ± 0.002^a	0.041 ± 0.003^a
NO_3–N ($mg\,L^{-1}$)	0.09 ± 0.007^a	0.11 ± 0.008^a	0.10 ± 0.008^a	0.13 ± 0.005^a	0.09 ± 0.004^a	0.13 ± 0.005^a	0.10 ± 0.007^a

None of the parameter varied significantly between treatment ($p > 0.05$; One-way ANOVA). Abbreviations: DO, dissolved oxygen; TAN, total ammonia nitrogen; NO_3–N, nitrate–nitrogen.

Table 5. Mean (± SE) values of water quality parameters of 30-day samples over the experimental period in outdoor and mesocosm competition experiment.

Parameters	Outdoor competition experiment			Mesocosm competition experiment	
	C	T_1	T_2	C	T_1
Temperature (°C)	27.12 ± 0.28^a	26.96 ± 0.23^a	27.03 ± 0.36^a	27.48 ± 0.41^a	27.72 ± 0.34^a
pH	7.56 ± 0.06^a	7.69 ± 0.09^a	7.62 ± 0.08^a	7.54 ± 0.15^a	7.48 ± 0.19^a
DO ($mg\,L^{-1}$)	6.13 ± 0.22^a	6.41 ± 0.17^a	6.32 ± 0.25^a	5.96 ± 0.27^a	6.02 ± 0.22^a
Alkalinity ($mg\,L^{-1}$)	147.87 ± 1.96^a	144.25 ± 2.28^a	149.12 ± 2.05^a	141.76 ± 1.84^a	143.07 ± 1.49^a
Hardness ($mg\,L^{-1}$)	140.12 ± 1.94^a	138.12 ± 2.17^a	141.23 ± 1.55^a	136.76 ± 2.75^a	137.69 ± 2.61^a
TAN ($mg\,L^{-1}$)	0.062 ± 0.004^a	0.075 ± 0.007^a	0.069 ± 0.003^a	0.093 ± 0.014^a	0.107 ± 0.019^a
NO_3–N ($mg\,L^{-1}$)	0.14 ± 0.01^a	0.21 ± 0.015^a	0.18 ± 0.012^a	0.22 ± 0.013^a	0.24 ± 0.012^a

None of the parameter varied significantly between treatment in outdoor ($p > 0.05$; One-way ANOVA) and mesocosm ($p > 0.05$; independent *t* test) competition experiment. Abbreviations: DO, dissolved oxygen; TAN, total ammonia nitrogen; NO_3–N, nitrate–nitrogen.

(Hoover et al., 2004; Hossain et al., 2018; Hussan et al., 2019). However, they can also affect native aquatic biodiversity through reduced periphyton biomass, altered periphyton nutrient ratios, altered organic matter availability, altered invertebrate community composition (Jones et al., 1994; Scott et al., 2012), and mechanical modification of benthic habitat (Capps and Flecker, 2013; Hoover et al., 2014). By bed-plowing these fishes can uproot native aquatic macrophytes, which can reduce native-plant abundances in beds of submersed aquatic vegetation that are vital to native-phytophylic fishes (Ludlow and Walsh, 2014). At high densities, these fishes can even change the nutrient proportionality in invaded habitats by retaining and/or accelerating the re-mineralization of important nutrients like phosphorus and nitrogen (Capps and Flecker, 2013). Consequently, the quantity of algal standing crops may decline, which may affect secondary production and the development of invertebrate standing crops, ultimately affecting native fish communities (Pound et al., 2011; Scott et al., 2012). Besides biodiversity loss, numerous studies have reported loss of capital and livelihood due to decreased yield of desirable food fishes and shrimp, and damage and loss of fisheries gears (Chavez et al., 2006; Krishnakumar et al., 2009; Sumanasinghe and Amarasinghe, 2013; Hussan et al., 2019). Sumanasinghe and Amarasinghe (2013) reported 21% replacement of commercial fishes in Polgolla Reservoir of Sri Lanka by accidently introduced Amazon sailfin catfish. Hussan et al. (2019) reported direct and indirect financial losses due to sailfin catfish invasion in EKW as 0.092 lakh ha^{-1} yr^{-1}. Economic losses to fishermen by Orinoco sailfin catfish by damaging equipment such as cast and gillnets and displacing native fishes in India (Krishnakumar et al., 2009); by vermiculated sailfin catfish and Amazon sailfin catfish by damaging cages and nets and reducing availability of more desirable fish in Laguna de Bay, Philippines (Chavez et al., 2006) were also reported.

Sailfin catfishes are hardy macrohabitat generalists that can tolerate harsh weather and polluted water (Nico et al., 2009a; Capps et al., 2011; Nico et al., 2012). They are generalized demersal feeder, feed widely on algae, detritus, and various benthic invertebrates (Pound et al., 2011; Qasim and Jawad, 2022). Many of the species like *P. pardalis* are multi-spawner, highly fecund and have female-biased sex ratios (Samat et al., 2016; Hussan et al., 2019). All these factors probably contribute to the explosive population growth of these fishes upon introduction. Moreover, they have several anti-predatory adaptations, like external bony plates and defensive erection of their dorsal and pectoral spines (Hoover et al., 2004;

Hussan et al., 2016; Hossain et al., 2018). Thus, if these exotic fishes have had time to colonize and expand their ranges, eradication often becomes difficult (Hill and Sowards, 2015; Hussan et al., 2021). Though younger sailfin catfishes are reported somewhat vulnerable to predation because of their thinner armor and smaller body sizes, such reports are very limited from their invasion range. Chaichana and Jongphadungkiet (2012), in laboratory experiments observed predation of smaller size (0.6–10 cm total length) Amazon sailfin catfish by two native fishes of Thailand, the bagrid catfish *Hemibagrus wyckioides* (Fang & Chaux 1949) and the marbled sleeper *Oxyeleotris marmorata* (Bleeker 1852). However, in natural habitats, adult male sailfin catfish aggressively guard the eggs and young ones in excavated burrows (Hussan et al., 2021), and thus it might be difficult for piscivorous fish to eradicate young sailfin catfish. In their natural range, sailfin catfishes and other loricariids were reported to be preyed upon by certain animals, like olivacious cormorants (*Phalacrocorax olivaceus*), great blue heron (*Area herodius*), otters (*Lontra longicaudis*, *Pteronura brasiliensis*, and *Lutra canadensis*), and alligators (*Alligator mississippiensis*), which helps to maintain biological control over these fishes (Nico, 2010). But, our country like many other countries invaded by these sailfin catfishes, lacks an efficient predator of this kind, and therefore the best way out is to strictly control the pathways of introduction and dispersal to halt the spread of this invasive fish species and lessen its negative impacts.

5 Conclusion

Findings of this study suggests that, Amazon sailfin catfish can readily consume the eggs of native rohu and butter catfish, and have preference for fish eggs over aquatic macro-invertebrate like Tubifex. Amazon sailfin catfish were also found to have a detrimental effect on native fish growth, reducing native fish growth by 18.8–36.7%, particularly in instances where fish feeding was either fully or partially dependent on natural fish food organisms. Because of the controlled experimental setups and space constraints, the results obtained here may be of higher order, but they do shed insight on the potential harm that sailfin catfish may pose in the wild. In open natural environments, the negative effects of sailfin catfish may not be noticeable until their density reaches a particular level, as more space is available there to restrict interspecies interaction. Nonetheless, given the effects of Amazon sailfin catfish on indigenous fish species in India, as this study shows, the nation must promptly establish effective management plans to stop both deliberate and unintentional releases of these fish into the wild. Additionally, it is essential to educate traders, hobbyists, fish breeders, fishermen, and other stakeholders about the detrimental effects of introducing such invasive fish into natural waters, as human facilitate the majority of transfers between catchments.

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Data availability statement

The data used to support the findings of this study are available from the corresponding author upon reasonable request.

Supplementary materials

Table S1. List of recognized species in the genus *Pterygoplichthys*.
Table S2. Possible hybridization cases of *Pterygoplichthys* in its native and invasion range.
Table S3. Reproductive biology of the invasive *Pterygoplicthys pardalis* and its closest congener *P. disjunctivus*.

The Supplementary Material is available at https://www.alr-journal.org/10.1051/alr/2025002/olm.

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