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RESEARCH PAPER

The Ecological and Socio-economic Impacts of the Aquarium Sailfin Catfish Invasion: Fate of Fisherfolk at Major Inland Water Bodies, Tamil Nadu, South India

Mohan Raj Rajasekaran*, Indhar Saidanyan Ravichandran**, Parthiban Balasingam***, and Chandrasekaran Sivagnanam****

Abstract: Keeping pets has been part of human life since the earliest civilizations. Today, exotic animals are sold online and shipped globally to enthusiasts. However, pet sellers and keepers sometimes release exotic pets into nearby natural ecosystems, leading to biological invasion. This paper examines the invasion by sailfin catfish (*Pterygoplichthys* spp.) of the Cauvery and Vaigai river basins and its ecological and socio-economic impacts. We assessed the ecological impacts by comparing the total abundance and biomass of the invasive fish species (IFS), *Pterygoplichthys* spp., with those of comparator fish species (CFS) and various physicochemical parameters. We used semi-structured interviews and case studies of IFS mechanical removal programmes to assess the socio-economic impacts. The abundance and biomass of the IFS were significantly higher than those of the CFS in most lentic and lotic ecosystems. Interviews revealed significant sociological impacts on fisherfolk, including a push from fishing (a familial profession) to non-fishing vocations. The input–cost–outcome assessment of mechanical removal programmes revealed that the expenditure incurred could not prevent further invasion of the IFS. This study advocates for increasing awareness among stakeholders to devise effective control measures and implement policy-level changes to curb the sailfin catfish invasion in India's inland water bodies.

Keywords: *Pterygoplichthys* spp., Biological Invasion, Ecological and Socio-economic Impacts, Fishing Communities, Cauvery River Basin, Vaigai River Basin.

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* Department of Plant Sciences (DPSc), School of Biological Sciences (SBS), Madurai Kamaraj University, Madurai - 625021, India (MKU); santhamoorthy92@gmail.com

** DPSc, SBS, MKU; saidanyan@gmail.com

*** DPSc, SBS, MKU; parthibanpana@gmail.com

**** DPSc, SBS, MKU; csekaran.biological@mkuniversity.ac.in.✉

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1. INTRODUCTION

Humans have been fascinated with pet-keeping since time immemorial (Herzog 2014; Gee and Mueller 2019). Recent reports show that nearly 50% of households in the US, Australia, and the UK keep at least one pet in their homes for recreational purposes (Lockwood *et al.* 2019). The COVID-19 pandemic lockdowns also led to an increase in the adoption of exotic pets as a means of alleviating stress (May 2021; Hoffman *et al.* 2021; Shoesmith *et al.* 2021). The pet and aquarium trade has become a multibillion-dollar industry worldwide. For instance, the US reptile industry generated nearly $1.4 billion in annual revenues in under two decades since 1990 (Collis and Fenili 2011). Similarly, the global trade in ornamental fish, fish feed, and accessories is estimated to exceed $15 billion, with significant year-over-year growth (Borges *et al.* 2021).

In the past, conventional retail pet and aquarium shops were the primary pathway for acquiring exotic pets, including small animals, birds, aquatic plants, and ornamental fish. Subsequently, these organisms were released into freshwater and marine ecosystems globally, either intentionally or accidentally (Krishnakumar *et al.* 2009; Lockwood *et al.* 2019). Currently, the online pet or aquarium trade, facilitated by online pet shops, e-commerce sites (Soundararajan *et al.* 2015), and social media platforms (Borges *et al.* 2021), has become a novel pathway for acquiring exotic pets. This has accelerated the introduction of a vast variety of exotic organisms, especially freshwater and marine fish, at an unprecedented rate in the global pet market. For instance, Soundararajan *et al.* (2015) report that almost 1,000 varieties of exotic ornamental fish were already being traded online in India a decade ago. Similarly, Borges *et al.* (2021) report that approximately 600 species of marine and freshwater ornamental fish are sold online through Facebook in Brazil.

In the global ornamental fish trade, freshwater fish are the dominant species, accounting for approximately 90% of the total traded volume, primarily due to their popularity and widespread use as aquarium pets, compared to marine fish and invertebrates (King 2019; Valdez and Mandrekar 2019). Due to the aquarium trade, ornamental fish comprise one-third of the world's worst aquatic invasive species. The aquarium fish invasion occurs through the release of unwanted fish and accidental escapes from tanks, breeding farms, and public aquariums into nearby drainage systems connected to natural aquatic habitats (Padilla and Williams 2004; Soundararajan *et al.* 2015). Sometimes, fish are intentionally released in temple ponds as part of religious rituals (Severinghaus and Chi 1999). From the public's perspective, aquarium pets have become an integral part of life.

However, aquarium keepers often encounter challenges in relocating these exotic organisms when they move for jobs, education, business reasons, vacations, or medical treatments. In such cases, aquarium keepers attempt to give their exotic pets to relatives or friends or release them into nearby natural ecosystems (Duggan *et al.* 2006; Stringham and Lockwood 2018). These repeated introductions ultimately result in bioinvasion, which leads to substantial environmental and economic losses worldwide. For instance, Diagne *et al.* (2021) estimated that the global economic losses associated with bioinvasion were a minimum of $1.288 trillion over the period 1970–2017. Exotic fish species, such as *Oreochromis mossambicus* (Mozambique tilapia), *Gambusia affinis* (mosquitofish), *Osphronemus goramy* (giant gourami), *Xiphophorus maculatus* (southern platyfish), and *Poecilia reticulata* (guppy), have invaded Indian rivers due to the aquarium trade and subsequent multiple introduction events (Raghavan *et al.* 2008).

Pterygoplichthys spp. (sailfin catfish) are one such popular freshwater aquarium fish. Commonly called tank cleaners, these fish are native to South America, especially the Amazon River Basin, and have been introduced into local ecosystems in many parts of the world. These are reported as an invasive species in over 20 countries, including India (Krishnakumar *et al.* 2009; Sinha *et al.* 2010; Global Invasive Species Database 2025). In India, four species, including *Pterygoplichthys anisitsi*, *P. disjunctivus*, *P. multiradiatus*, and *P. pardalis*, have been observed in various freshwater habitats, including rivers, lakes, ponds, and canals (Singh and Lakra 2011; Sarkar *et al.* 2012; Soundararajan *et al.* 2015; Ganguly and Umapathy 2024; Verma *et al.* 2024; Wanjari *et al.* 2024). These invasive fish species are problematic because they occupy typical fishing habitats, resulting in low yields and destroying fishing nets (Chavez *et al.* 2006; Wakida-Kusunoki *et al.* 2007), which ultimately affects the revenue and protein intake of inland fishing communities. Though scattered news reports and literature (Sinha *et al.* 2010; Bijukumar *et al.* 2015; Muralidharan *et al.* 2015; Raj *et al.* 2021; Daniel *et al.* 2022; Wanjari *et al.* 2024; Hussan *et al.* 2025) are available on the invasion and subsequent impact of *Pterygoplichthys* spp., comprehensive studies about their habitat characteristics and ecological and socio-economic impacts are limited in the Indian context. Therefore, in this study, we examine the ecological and socio-economic impacts of the *Pterygoplichthys* spp. invasion in two major river basins, the Cauvery and Vaigai of Tamil Nadu, with the following objectives: i) to study the distribution of the invasive fish species (IFS) *Pterygoplichthys* spp.; ii) to assess the ecological impacts of the IFS; iii) to investigate the influence of water physicochemical characteristics on the abundance and biomass of

IFS; and iv) to reveal the socio-economic impacts faced by fisherfolk due to the *Pterygoplichthys* spp. invasion.

2. MATERIALS AND METHODS

The materials used and methodology followed for the field survey, measurement of water physicochemical characteristics, ecological and socio-economic impact assessments of the *Pterygoplichthys* spp. invasion in the Cauvery and Vaigai river basins, and the statistical data analysis is detailed in the following subsections.

2.1. Study Site and Field Survey

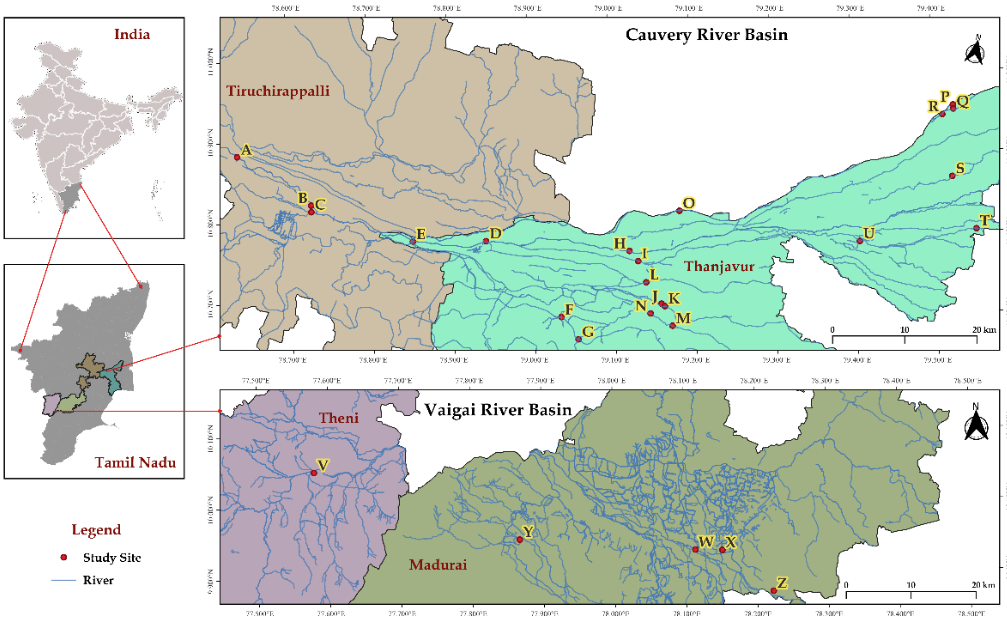
Initially, extensive field surveys were conducted at several inland water bodies around the Cauvery River Basin (CRB) and Vaigai River Basin (VRB), Tamil Nadu, South India, to record the presence of invasive *Pterygoplichthys* spp. The Cauvery River is the fourth-largest river in India, spanning four states and covering a total area of 81,155 km^2. It has several tributaries and is a significant freshwater resource, harbouring a vast diversity of South Indian freshwater fish that support inland fisheries. The Vaigai River is another important river basin that flows through five districts of Tamil Nadu, spanning a length of 258 km. It supports the inland fisheries of the southern part of the state. In total, we surveyed 41 sites in the Cauvery (21 sites) and Vaigai (20 sites) river basins, covering four districts of Tamil Nadu—Tiruchirappalli, Thanjavur, Madurai, and Theni—between April 2016 and March 2017. Based on their ecosystem type, the sites were classified as either lotic (characterised by flowing waters, such as rivers) or lentic (characterised by still waters, such as lakes). In the CRB, the lentic ecosystems include the Upper Anicut, the Grand Anicut, the Lower Anicut, and a few others; the Cauvery River, Kudamurutti River, Kollidam River, and others were classified as lotic ecosystems. Due to the lack of perennial water flow, a few sites generally classified as lotic were considered lentic ecosystems in the present study. For instance, Vadavar River sites 1 and 2 were considered lentic ecosystems because there was no continuous water flow due to shortages in seasonal rainfall, poor water release from dams, habitat modifications, and water utilization. In the VRB, except the Vaigai River (lotic), we classified the remaining sites—Vaigai Dam, Vandiyur Lake, Valandur Lake, Sakkudi Lake, Odankundu Lake, Ananchiyur Lake, and Thenur Lake—as lentic ecosystems.

In all the CRB and VRB study sites, the presence and absence of *Pterygoplichthys* spp. were recorded (sampling size, $N = 48$) along with the corresponding geographic coordinates in DMS (degrees, minutes, and seconds) format using a GPS device (eTrex® 20x, Garmin). This data was converted to decimal degrees format, and the study site map (Figure 1) was created using QGIS software (version: 3.34.10-Prizren). The presence of *Pterygoplichthys* spp. was confirmed by fishing using cast nets (mesh size range: 10 mm^2–50 mm^2; weight: ~ 4 kg) and seine nets (mesh size range: 50 mm^2–90 mm^2; weight: ~8 kg) with the help of local fishermen. Based on morphological keys, we identified the genus of this invasive fish species, and, based on abdominal patterns, identified the species (Armbruster and Page 2006; Wu *et al.* 2011; Bijukumar *et al.* 2015). However, for hybridized or intergrade populations of *Pterygoplichthys* species (such as *P. pardalis* and *P. disjunctivus*), species identification was found to be complex and inaccurate. Hence, the sailfin catfish group is uniformly referred to as the invasive fish species (IFS) *Pterygoplichthys* spp. throughout the study. Furthermore, we evaluated the physicochemical characteristics of the sites and the ecological and socio-economic impacts of the IFS in relation to comparator fish species (CFS). Here, CFS refers to the fish species group consisting of all native species and all commercially important fish species (including exotic taxa). Physicochemical characteristics, including pH, temperature, electrical conductivity, total dissolved solids (TDS), and salinity, were measured in the *Pterygoplichthys* spp. occurring sites using a handheld water quality tester (PCSTestr 35™, Eutech Instruments) to understand their relationship with the population sustenance of the IFS and CFS. The unique habitats, land-use activities, and nesting tunnels in the lotic and lentic ecosystems featuring *Pterygoplichthys* spp. were also recorded through in-field surveys and interviews with local people.

2.2. Assessment of Ecological Impacts

One important ecological impact of the *Pterygoplichthys* spp. invasion is the disruption of the CFS population in the inland water bodies of the CRB and VRB. Hence, we evaluated the abundance and biomass of the IFS in comparison to that of the CFS present in the fish harvest during the entire study period. The abundance was calculated by counting the number of IFS and CFS fish (species-wise) that were caught in each fish sampling. We estimated the biomass by separately measuring the total wet weight of the IFS and CFS (by species) caught in each sampling (Supplementary Figures S1 and S2). Then, we calculated the total abundance percentage and total biomass percentage to investigate the spread of the IFS compared to CFS in the surveyed sites. However, a few sites were excluded from the calculation due to inaccessibility resulting from a lack of water flow and

Figure 1. Overall Distribution Map of *Pterygoplichthys* spp. Along Several Inland Water Bodies of the Cauvery and Vaigai River Basins, Tamil Nadu.



Identifiers:
Cauvery River Basin: Upper Anicut* (A), Kambarasampettai Check Dam* (B), *Kudamurutti River Site 1*** (C), Cauvery River Site 1** (D), The Grand Anicut* (E), The Grand Anicut Canal Pit 1* (F), The Grand Anicut Canal Pit 2* (G), Cauvery River Site 2** (H), *Kudamurutti River Site 2*** (I), Vennar River Site 1** (J), Vennar River Site 2** (K), Vettar River** (L), *Vadavar River Site 1** (M), *Vadavar River Site 2** (N), Kollidam River** (O), Lower Anicut Site 1* (P), Lower Anicut Site 2* (Q), Lower Anicut Site 3* (R), Palavar River** (S), Nattar River** (T), and *Arasalar River*** (U). Vaigai River Basin: Vaigai Dam* (V), *Vaigai River*** (W), *Vandiyur Lake** (X), Valandur Lake* (Y), and Sakkudi Lake* (Z)

Source: Authors' compilation
Note: * and ** represent the sites that belong to the lentic and lotic ecosystem types, respectively. Sewage-contaminated study sites are formatted in italics.

other habitat modifications. From the overall sampling (N = 48) data, the relative occurrence (RO) of every CFS was calculated as the ratio of the number of individual samples of a particular CFS to the total number of samples. We measured the fecundity of *Pterygoplichthys* spp. by dissecting the ovaries of the gravid female fish captured during fish sampling. This was accomplished by counting a pre-weighed sub-sample of eggs in a sliced portion of the ovary. We then combined this data with the overall weight of the egg population to estimate the total number of eggs using the gravimetric method (Miller and Kendall 2009).

2.3. Assessment of Socio-economic Impacts

Pterygoplichthys spp. cause several socio-economic impacts in every ecosystem they invade. They can reduce CFS yields, affecting local communities' revenue and protein intake. They can also make fish harvesting a strenuous, laborious, and tedious process and cause damage to fishing nets, leading fisherfolk to abandon their familial profession. These impacts are relatively unexplored. Hence, the socio-economic impacts of the *Pterygoplichthys* spp. invasion for common fishermen, lake leaseholders, and local people around the CRB and VRB were recorded using semi-structured interviews and case studies of mechanical IFS removal programmes. We conducted these semi-structured interviews using a questionnaire that captured data on the livelihood-related impacts of the *Pterygoplichthys* spp. invasion. After obtaining informed consent, participants (N = 3) were randomly selected and individually interviewed in the regional language (Tamil) at each study site; we recorded the audio for documentation. The informed consent form and questionnaire for the semi-structured interview are given in the Supplementary Material.

The mechanical removal programmes and the economic losses incurred by the fisherfolk were recorded at the Grand Anicut Canal Pits 1 and 2, and the Vandiyur Lake Pit, of the CRB and VRB during May 2016 and November 2016, respectively. The Grand Anicut Canal Pit 1 (10.7758°N, 79.0227°E), with a dimension of 125×175×25 ft (l×b×d), and the Grand Anicut Canal Pit 2 (10.7528°N, 79.0498°E), with a dimension of 125×175×15 ft, are located along the flow path of the Grand Anicut Canal (one of the tributaries of the Cauvery River), Thanjavur district, to aid water storage and aquaculture. These pits are massively infested with *Pterygoplichthys* spp., the stock population of which originated from the Grand Anicut and reached the pits through water releases.

The Vandiyur Lake (9.9318°N, 78.1514°E) is a mesotrophic lake with a total surface area of 231.58 ha and a depth range of 2 m to 12 m. It is located in Madurai (suburban stretch) and is commercially used for aquaculture. Due to seasonal effects, the available water is usually dispersed into several isolated water pits, which become infested by *Pterygoplichthys* spp. These fish proliferate throughout the lake once the water level returns to normal.

Mechanical removal programmes are usually conducted before the CFS fingerling release season by leaseholders and fishing communities around the lakes, ponds, and canals invaded by *Pterygoplichthys* spp. to reduce competition from this invasive fish. We assessed the socio-economic impacts of *Pterygoplichthys* spp. removal programmes based on input–cost–outcome parameters. Here, input refers to resources such as labour (fisherfolk), time (working days), and material (fishing net and equipment). Cost represents labour and equipment hiring charges as well as fishing net replacement charges. Outcome refers to the mass of invasive fish eliminated at the end of the programme.

2.4. Statistical Analysis

All the data formatting and descriptive statistics analysis were performed using Microsoft Excel 2021. We analysed site-level variations in the physicochemical characteristics of the invaded sites using the Kruskal-Wallis test. The statistical significance of the difference between the abundance and biomass of the IFS and CFS in both river basins was tested using the Wilcoxon rank-sum test, visualized through boxplots, and assessed using *p*-values. Further, the degree of flow regulation; land-use activities, such as sewage disposal and cattle or cloth washing; the presence of invasive aquatic vegetation; and the existence of dams and bridges were assigned on a rank scale to the study sites (predictor variable) and compared against the IFS (biomass) percentage (response variable) through simple linear regression models. The effect of physicochemical parameter variations on the abundance and biomass of IFS and CFS was tested using Spearman's rank correlation test, visualized through a multi-way correlation plot, and inferred through r_s-values and *p*-values. To understand the site-level random effects of the physicochemical parameters and CFS abundance (CFSA) and biomass (CFSB) on the IFS abundance (IFSA) in both river basins, generalized linear mixed-effects models were developed. All data analysis and visualizations were performed using R software version 4.4.1 (RStudio Team 2025) with the following packages: "ggplot2", "ggpubr", "tidyverse", "reshape2", "patchwork", and "glmmTMB".

3. RESULTS

This section describes i) the characteristics of the *Pterygoplichthys* spp. invaded sites; ii) ecological impacts with respect to CFSA and CFSB; iii) the relationship between the physicochemical characteristics and the abundance and biomass of IFS and CFS; and iv) the socio-economic impacts of the studied *Pterygoplichthys* spp. invasion.

3.1. Habitat Characteristics

During the study period, various land-use activities, including aquaculture, cattle washing, clothes washing, fishing, grazing, irrigation, sewage disposal, and others, were observed at the CRB and VRB sites (Table 1). Apart from regular water flow paths and open waters, certain unique habitats were predominantly occupied by IFS rather than CFS, and such instances varied by site. For instance, in the Kudamurutti River, *Pterygoplichthys* spp. were predominantly found in portions covered with invasive aquatic vegetation (*Pontederia crassipes*) and sewage-contaminated stretches of the river. In the Grand Anicut, *Pterygoplichthys* spp. were mostly found near the dam's wall and shutters. In the Vennar River, *Pterygoplichthys* spp. were predominantly found in areas that contained abandoned break wall wreckage.

Similarly, in the Vaigai Dam, *Pterygoplichthys* spp. were found in abundance in the rocky regions of the dam (Table 1). In comparison to the open waters of the Vaigai River, the stagnant water pools along the river, contaminated with domestic sewage, had a higher density of IFS than CFS. During the study period, we also identified IFS nesting tunnels along the banks of the sites. For instance, in the CRB, out of 21 sites, we observed nesting tunnels in three sites: Kudamurutti River, Vettar River, and Arasalar River. In the VRB, the Vaigai River and Vandiyur Lake had nesting tunnels (Table 1).

Table 2 shows the physicochemical characteristics of the CRB and VRB sites invaded by *Pterygoplichthys* spp. In the CRB, all sites had an alkaline pH, with the highest pH value found in the Vettar River. The sites where domestic sewage was disposed of, such as the Kudamurutti River, had the highest conductivity, TDS, and salinity, followed by the Vadavar River and Arasalar River. However, we observed that the Upper Anicut had the lowest conductivity, TDS, and salinity. Likewise, in the VRB, the sewage-contaminated Vandiyur Lake had the highest conductivity, TDS, and salinity. In contrast, Vaigai Dam had the lowest conductivity, TDS, and salinity (Table 2). However, the statistical analysis revealed that all the physicochemical parameters differ significantly ($p < 0.01$) across the *Pterygoplichthys* spp. invaded sites (Table 3).

Table 1. Habitat Characteristics of *Pterygoplichthys* spp. Invaded Sites of the Cauvery and Vaigai River Basins

Habitat characteristics	**Cauvery River Basin**							**Vaigai River Basin**		
	Upper Anicut	Kuda-murutti River	The Grand Anicut	Vennar River	Vettar River	Vadavar River	Arasalar River	Vaigai Dam	Vaigai River	Vandiyur Lake
Land-use activities	Fishing, irrigation, and water storage	Fishing and sewage disposal	Fishing, irrigation, and water storage	Fishing and cattle washing	Fishing and cattle washing	Fishing, grazing, cattle washing, and sewage disposal	Fishing and sewage disposal	Fishing, irrigation, and water storage	Fishing, clothes washing, grazing, and sewage disposal	Aqua-culture, fishing, grazing, and sewage disposal
Habitats predo-minantly occupied	Rocky regions	Sewage-conta-minated and aquatic vegetation–covered portions	Regions near the dam's wall and shutters	Abandoned break wall wreckages	Isolated water pools and aquatic vege-tation–covered portions	Sewage-conta-minated and aquatic vegetation–covered portions	Sewage-conta-minated regions	Rocky regions	Sewage-contaminated isolated water pools and aquatic vegetation–covered portions	Isolated water pools and aquatic vegetation–covered portions
Nesting tunnels along the banks	Not recorded	Recorded	Not recorded	Not recorded	Recorded	Not recorded	Recorded	Not recorded	Recorded	Recorded

Source: Authors' compilation

Table 2. Physicochemical Characteristics of *Pterygoplichthys* spp. Invaded Sites of the Cauvery and Vaigai River Basins

Study Sites	Cauvery River Basin								Vaigai River Basin			
	Upper Anicut	Kuda-murutti River	The Grand Anicut	Vennar River	Vettar River	Vadavar River	Arasalar River	Overall Value	Vaigai Dam	Vaigai River	Vandiyur Lake	Overall Value
pH	8.80 (0.10)	8.25 (0.37)	8.99 (0.35)	9.02 (0.08)	9.05 (0.08)	8.99 (0.43)	8.89 (0.54)	8.85 (0.42)	8.61 (0.21)	8.37 (0.14)	8.89 (0.44)	8.62 (0.36)
Temperature (°C)	28.08 (1.36)	32.65 (0.89)	32.36 (1.10)	30.87 (1.02)	31.57 (0.80)	31.36 (0.96)	33.35 (1.18)	31.46 (1.91)	26.19 (0.28)	29.83 (1.82)	34.29 (1.30)	30.10 (3.57)
Conductivity (µS)	727.50 (14.05)	1497.50 (45.42)	802.11 (36.03)	843.94 (25.87)	973.67 (7.43)	1215.61 (175.95)	1026.81 (243.84)	1012.45 (274.22)	260.22 (5.10)	1824.72 (126.40)	2326.67 (216.81)	1470.54 (894.73)
TDS (ppm)	544.33 (41.68)	1057.96 (36.54)	573.39 (15.35)	598.94 (10.03)	694.00 (8.77)	833.18 (129.55)	738.93 (158.81)	720.10 (185.29)	185.11 (4.69)	1117.50 (50.87)	1647.78 (154.73)	983.46 (613.87)
Salinity (ppm)	339.50 (18.78)	716.21 (16.95)	372.94 (11.03)	395.61 (3.08)	461.00 (7.47)	576.72 (131.65)	494.78 (121.40)	479.54 (139.73)	119.72 (3.24)	1012.94 (192.76)	1148.00 (137.07)	760.22 (477.50)

Source: Authors' compilation

Note: Values of the water physicochemical parameters are given as Mean and Standard Deviation in parentheses. TDS: Total dissolved solids.

Table 3. Statistical Analysis of Physicochemical Parameter Variations in the *Pterygoplichthys* spp. Invaded Sites of the Cauvery and Vaigai River Basins Using the Kruskal-Wallis Test

Physicochemical parameter	**Cauvery River Basin**			**Vaigai River Basin**		
	p-value	df	H-value	*p*-value	df	H-value
pH	0.000**	6	125.52	0.000**	2	41.74
Temperature (°C)	0.000**		204.47	0.000**		124.55
Conductivity (µS)	0.000**		281.27	0.000**		125.86
TDS (ppm)	0.000**		265.13	0.000**		127.12
Salinity (ppm)	0.000**		270.81	0.000**		102.56

Source: Authors' analysis

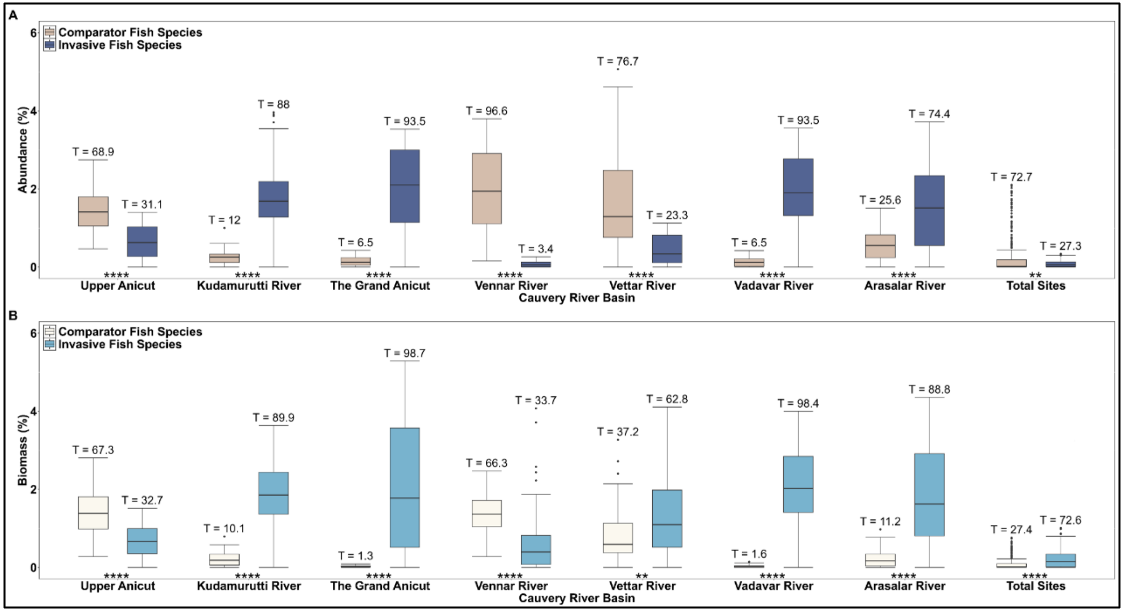
Note: ** denotes the significantly different *p*-values at 1% significance level. TDS: Total dissolved solids.

3.2. Ecological Impacts

As a whole, the total abundance of IFS across all CRB sites was significantly lower ($p < 0.01$) than that of the CFS (Figure 2A). However, the total biomass of IFS was significantly higher ($p < 0.0001$) (Figure 2B). Further, individual site-wise data revealed that sewage-contaminated lotic ecosystems, such as the Kudamurutti and Arasalar Rivers, had a significantly higher ($p < 0.0001$) total abundance of IFS compared to CFS (Figures 1 and 2A). Similarly, in lentic ecosystems, the aquatic vegetation–covered and sewage-contaminated Vadavar River, followed by the Grand Anicut, were found to have a significantly higher ($p < 0.0001$) total abundance of IFS than CFS. However, the Upper Anicut (lentic ecosystem) had a significantly lower ($p < 0.0001$) total abundance of IFS than CFS; lotic ecosystems, such as the Vennar River and Vettar River, had a significantly higher ($p < 0.0001$) total abundance of CFS than IFS (Figures 1 and 2A). The total biomass of IFS was significantly higher ($p < 0.0001$) in all lotic ecosystems except the Vennar River (Figures 1 and 2B). In lentic ecosystems, except Upper Anicut, the total biomass of IFS was significantly higher than that of CFS (Figures 1 and 2B).

The total abundance and biomass of IFS were lower than those of CFS in the VRB when the sites were combined; however, the difference in biomass was non-significant ($p > 0.05$) (Figure 3A and B). From the individual site-wise data, we found that the total abundance of CFS in the Vaigai River (lotic) was significantly higher ($p < 0.001$) than that of IFS (Figures 1 and 3A).

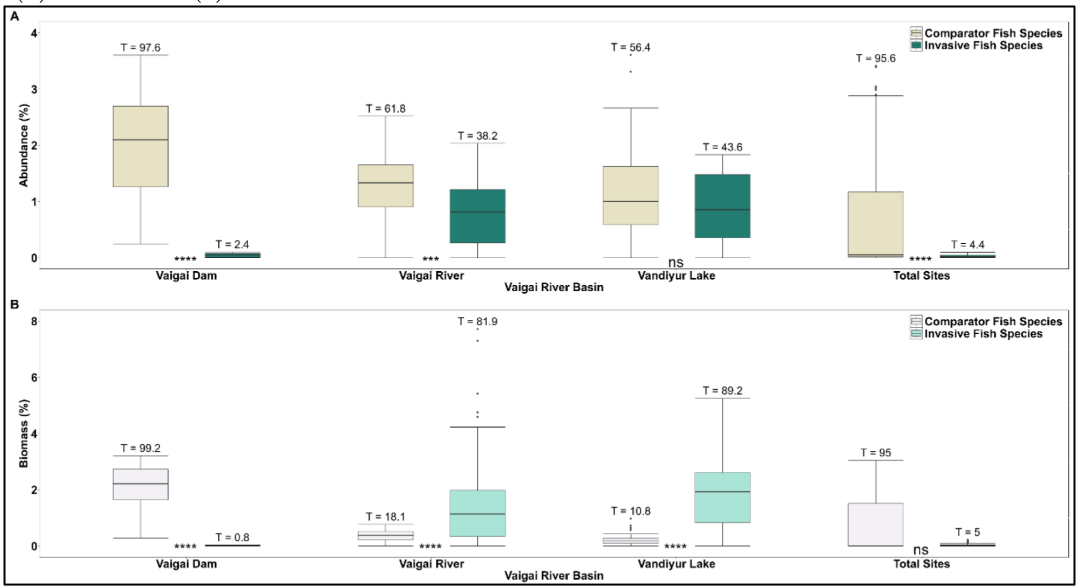
Figure 2. Boxplot Representing the Individual and Total Sites' Abundance (%) and Biomass (%) of Comparator Fish Species and Invasive Fish Species, *Pterygoplichthys* spp. in the Cauvery River Basin, with Statistical Analysis using Wilcoxon Rank-Sum Test. Abundance (A) and Biomass (B).



Source: Authors' analysis

Note: ** and **** denote the significant difference at $p < 0.01$ and $p < 0.0001$, respectively.

Figure 3. Boxplot Representing the Individual and Total Sites' Abundance (%) and Biomass (%) of Comparator Fish Species and Invasive Fish Species, *Pterygoplichthys* spp. in the Vaigai River Basin, with Statistical Analysis Using Wilcoxon Rank-Sum Test. Abundance (A) and Biomass (B).



Source: Authors' analysis

Note: ***, ****, and 'ns' denote the significant difference at $p < 0.001$, $p < 0.0001$, and non-significant difference at $p > 0.05$, respectively.

Figure 4. Ecological Impact Assessment of *Pterygoplichthys* spp. in the Cauvery and Vaigai River Basins. Abundant *Pterygoplichthys* spp. Appeared in a Fish Catch at the Grand Anicut (A), Asian Needlefish at Vennar River (B), *Pterygoplichthys* spp. Individual at Vandiyur Lake (C), Nesting Tunnels of *Pterygoplichthys* spp. at Vettar River (D), Gravid Female *Pterygoplichthys* spp. Individual with Extruded Eggs at Vaigai River (E), and (F), Domestic Sewage Mixed Sites of Vadavar River (G), and a Large Population of *Pterygoplichthys* spp. Present in a Catch at Vadavar River (H)

Source: Authors' compilation

In contrast, the total biomass of IFS was significantly higher ($p < 0.0001$) than that of CFS at the same site (Figures 1 and 3B). In lentic ecosystems such as Vaigai Dam, the total abundance of IFS was significantly lower ($p < 0.0001$) than that of CFS. In contrast, the total biomass of IFS was significantly higher ($p < 0.0001$) than that of CFS at Vandiyur Lake, but lower at Vaigai Dam. Site-wise flow alterations (such as invasive aquatic vegetation domination) and human impacts (such as sewage disposal) had a statistically significant positive influence on the IFS' biomass percentage in both the CRB ($R^2 = 0.79$; $p < 0.001$) and VRB ($R^2 = 0.99$; $p < 0.001$).

In the CRB, CFS were recorded at sites where *Pterygoplichthys* spp. were present, such as the Grand Anicut (Figure 4A), the Kudamurutti River, the Upper Anicut, the Vennar River, and others. The species included *Channa striata* (snakehead murrel), *Etroplus suratensis* (pearlspot cichlid), *Macrobrachium* sp. (freshwater prawn), *Xenentodon cancila* (Asian needle fish) (Figure 4B), and so on (Table 4). In the overall sampling ($N = 48$), the RO of each CFS varied between the study sites. For instance, *Mystus cavasius* (Gangestic mystus) had the highest RO at the Vennar River, followed by the Vettar River and Vadavar River; the Kudamurutti River had the lowest RO of 10.42%. Among the CFS in all sites, *Oreochromis niloticus* (Nile tilapia) accounted for the highest RO at Upper Anicut. Furthermore, several CFS were present only in the CRB, and those particular study sites recorded minimal RO. For instance, *Neolissochilus bovanicus* (Bowany barb) at Kudamurutti River had an RO of 6.25% (Table 4).

In the VRB, the recorded CFS included *Channa punctata* (spotted snakehead), *Cirrhinus cirrhosus* (mrigal carp), *Mystus vittatus* (striped dwarf catfish), and so on (Table 4). Similar to the CRB, the RO of the CFS varied across the VRB sites. For instance, *Labeo rohita* (rohu) had an RO of 45.83% at Vaigai Dam and 33.33% at Vandiyur Lake. *O. niloticus* in Vandiyur Lake had the highest RO among the CFS. In contrast, *M. vittatus* had the lowest RO compared to other CFS. Several CFS were present only in one of the VRB study sites with different levels of RO. For instance, *C. cirrhosus* was recorded only at Vaigai Dam with an RO of 64.48%. Some CFS, such as *C. punctata*, *C. striata* and *Cyprinus carpio* (common carp), were common to both the CRB and VRB. In contrast, CFS such as *Catla catla* (catla), *Clarias gariepinus* (North African catfish), and *Heteropneustes fossilis* (Asian stinging catfish) were present only in the VRB (Table 4).

Table 4. Relative Occurrence Percentage of Comparator Fish Species Recorded during the Sampling (*N* = 48) in the Cauvery and Vaigai River Basins

Scientific name	Common name	Cauvery River Basin							Vaigai River Basin		
		Upper Anicut	Kuda-murutti River	The Grand Anicut	Vennar River	Vettar River	Vadavar River	Arasalar River	Vaigai Dam	Vaigai River	Vandiyur Lake
Ambassis ambassis	Commerson's glassy	-	-	-	-	12.50	-	-	-	-	-
Catla catla	Catla	-	-	-	-	-	-	-	33.33	-	-
Channa punctata	Spotted snakehead	-	20.83	-	18.75	-	-	-	-	62.50	22.92
Channa striata	Snakehead murrel	16.67	29.17	-	-	-	-	-	50.00	-	-
Cirrhinus cirrhosus	Mrigal carp	-	-	-	-	-	-	-	64.58	-	-
Cirrhinus reba	Reba carp	-	10.42	-	85.42	31.25	31.25	-	-	-	-
Clarias gariepinus	North African catfish	-	-	-	-	-	-	-	31.25	-	-
Cyprinus carpio	Common carp	72.92	29.17	20.83	72.92	-	-	45.83	-	31.25	-
Etroplus suratensis	Pearlspot cichlid	64.58	29.17	-	-	-	-	-	-	-	-
Glossogobius giuris	Tank goby	16.67	14.58	20.83	18.75	-	-	-	41.67	-	-
Heteropneustes fossilis	Asian stinging catfish	-	-	-	-	-	-	-	-	-	18.75
Hyporhamphus xanthopterus	Red-tipped halfbeak	-	-	-	10.42	-	-	-	-	-	-
Hypselobarbus jerdoni	Jerdon's carp	-	-	-	-	-	-	-	-	27.08	43.75

Labeo rohita	Rohu	-	-	10.42	-	-	-	-	45.83	-	33.33
Macrobrachium sp.	Freshwater prawn	25.00	27.08	31.25	12.50	25.00	-	-	-	-	-
Mastacembelus armatus	Zig-zag eel	20.83	10.42	16.67	-	-	-	-	18.75	-	-
Mystus cavasius	Gangetic mystus	-	10.42	-	83.33	22.92	22.92	-	-	-	-
Mystus vittatus	Striped dwarf catfish	35.42	22.92	-	52.08	20.83	27.08	50.00	-	47.92	12.50
Neolissochilus bovanicus	Bowany barb	-	06.25	-	-	-	-	-	-	-	-
Ompok bimaculatus	Butter catfish	-	14.58	-	-	-	-	-	66.67	-	-
Oreochromis mossambicus	Mozambique tilapia	-	-	-	56.25	29.17	27.08	31.25	-	-	-
Oreochromis niloticus	Nile tilapia	95.83	47.92	12.50	-	-	-	-	58.33	75.00	56.25
Puntius sophore	Pool barb	-	08.33	-	18.75	31.25	31.25	14.58	-	-	-
Trichogaster lalius	Dwarf gourami	-	08.33	-	12.50	-	-	-	-	-	54.17
Wallago attu	Helicopter catfish	-	-	-	-	-	-	-	20.83	-	-
Xenentodon cancila	Asian needlefish	16.67	06.25	-	37.50	-	-	-	-	-	-

Source: Authors' analysis

Note: '-' denotes the non-occurrence of the species in the respective study site

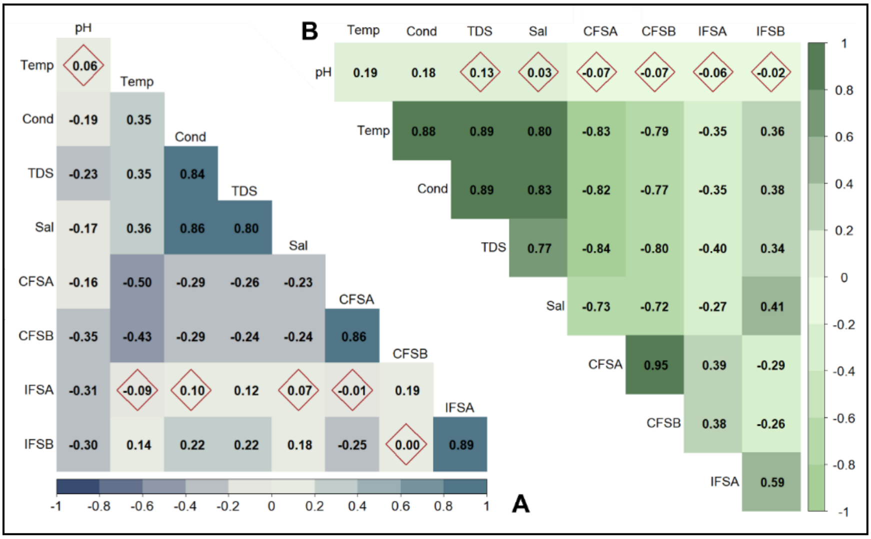
During the study period, horizontal nesting tunnels of *Pterygoplichthys* spp. (Figure 4C) were observed along the banks of lotic sites such as the Kudamurutti River, Vettar River (Figure 4D), and Arasalar River in the CRB, followed by Vaigai River and Vandiyur Lake in the VRB. We calculated the fecundity of the gravid female *Pterygoplichthys* spp. individuals (Figure 4E and F) in the sample and found 7543.66 ± 688.72 eggs. The sites where domestic sewage water had mixed into the water bodies, including the Vaigai River and Vandiyur Lake of the VRB, as well as the Kudamurutti River, Arasalar River, and Vadavar River (Figure 4G) of the CRB, had an abundant population of IFS (Figure 4H).

3.3. Physicochemical Parameters' Effect

We performed Spearman's rank correlation analysis to determine the effects of physicochemical parameter variations on the abundance and biomass of invasive *Pterygoplichthys* spp. (IFSA and IFSB) and comparator fish species (CFSA and CFSB). The multi-way correlation plots are shown in Figure 5A and B. In the CRB, pH exhibited a statistically significant, albeit weak, negative correlation with IFSA and IFSB (Figure 5A). We observed a similar relationship with CFSA and CFSB. However, temperature had a negligible correlation with IFSA and a weak but statistically significant positive correlation with IFSB. In contrast, temperature exhibited a moderate yet significant negative correlation with CFSA and CFSB (Figure 5A). The correlation coefficients of other physicochemical parameters, such as conductivity, TDS, and salinity, exhibited a statistically significant, albeit weak, negative correlation with the total abundance and biomass of CFS. In contrast, conductivity had a non-significant correlation, TDS had a significant but weak positive correlation, and salinity had a negligible correlation with IFSA. Yet, conductivity, TDS, and salinity exhibited a significant, albeit weak, positive correlation with the IFSB (Figure 5A). All the statistical differences were significant at the $p < 0.05$ level.

In the VRB, pH had a statistically negligible correlation with IFSA and IFSB, as well as with CFSA and CFSB (Figure 5B). However, temperature and conductivity were found to have a weak negative correlation to IFSA and IFSB. On the contrary, the same parameters had a strong negative correlation with CFSA and CFSB, respectively. TDS had a moderate negative correlation with IFSA and a weak positive correlation with IFSB. In contrast, TDS had a strong negative correlation with CFSA and CFSB. The correlation coefficients of salinity showed a strong negative correlation with CFSA and CFSB, whereas there was a weak negative correlation and a moderate positive correlation with IFSA and IFSB, respectively. However, except for pH ($p > 0.05$), all the other physicochemical parameters had a statistically significant relationship between the abundance and biomass of CFS and IFS at the level $p < 0.05$ (Figure 5B).

Figure 5. Spearman's Rank Correlation Coefficients between Physicochemical Parameters and Abundance and Biomass of Comparator Fish Species and Invasive *Pterygoplichthys* spp. at Cauvery River Basin (A) and Vaigai River Basin (B)



Source: Authors' compilation

Note: Values in the marked cells denote the correlation coefficients r_s having a p-value > 0.05 (non-significant). Temp: temperature; Cond: conductivity; TDS: total dissolved solids; Sal: salinity; CFSA: comparator fish species' abundance; CFSB: comparator fish species' biomass; IFSA: invasive fish species' abundance; and IFSB: invasive fish species' biomass.

3.4. Generalized Linear Mixed Models with Site-level Random Effects

Generalized linear mixed models (GLMMs) were developed by recursively adding and removing physicochemical parameters and CFSA and CFSB as fixed effects, with IFSA as the response variable, while accounting for study site–level variations (i.e., random effects). The models used the maximum likelihood estimation method, and the likelihood of random effects on the GLMMs was approximated using the Laplace approximation method. Through the recursive approach, the final model was developed based on improved comparative statistics, including Akaike Information Criterion and Bayesian Information Criterion values, as well as the statistical significance (p-value) of the independent variables. In the GLMM of the

CRB, among the physicochemical parameters, salinity showed a statistically non-significant ($p > 0.05$) positive association with IFSA with a statistically significant ($p < 0.05$) intercept. CFSA had a statistically significant ($p < 0.01$) negative association, and CFSB had a highly significant ($p < 0.001$) positive association with IFSA (Table 5). On the other hand, in the GLMM of the VRB, TDS had a statistically significant ($p < 0.001$) negative association with IFSA with a statistically significant intercept (Table 5).

Table 5. Generalized Linear Mixed Model with Site-Level Random Effects to Determine the Relationship between Physicochemical Parameters, the Abundance and Biomass of Comparator Fish Species, and Invasive *Pterygoplichthys* spp. Abundance

GLMM characteristics	**Cauvery River Basin**		**Vaigai River Basin**	
Comparative statistics				
Akaike information criterion (AIC)	3219.00		1383.60	
Bayesian information criterion (BIC)	3241.90		1398.50	
Log-likelihood	–1603.50		–686.80	
Parameter estimates	**Fixed effects**	***p*-value**	**Fixed effects**	***p*-value**
Intercepts	34.8578	0.0120*	55.6080	0.0000***
Total dissolved solids	-	-	–0.0220	0.0007***
Salinity	0.0039	0.8550	-	-
CFSA	–0.0384	0.0036**	0.0027	0.4109
CFSB	3.7857	0.0000***	-	-

Source: Authors' analysis

Note: *, **, and *** denote the significantly different *p*-values at the 5%, 1%, and 0.1% significance levels, respectively. CFSA: comparator fish species' abundance; CFSB: comparator fish species' biomass.

3.5. Socio-economic Impacts

In addition to the ecological impacts, the invasion of *Pterygoplichthys* spp. in parts of the CRB and VRB has adversely affected the livelihoods of fishing communities. This section describes the most common IFS-related livelihood problems faced by fishing communities, as reported during our semi-structured interviews and case studies of mechanical removal programmes. Since *Pterygoplichthys* spp. have widely occupied fishing habitats along the CRB and VRB, nearly all the interviewees noted that these invasive fish were trapped in fishing nets almost every time they fished (Figure 6A). The spiny nature of this fish causes it to become heavily entangled in fishing nets, requiring considerable time and effort to remove it without damaging the net (Figure 6B). During the removal process, fishermen's palms often get scratched and bleed. The fishermen also emphasised that they often had to cut off portions or discard fishing nets that were entangled with these fish. This reduced the durability and usage of fishing nets, ultimately forcing fisherfolk to purchase new nets, which caused additional economic distress. The time-consuming removal process also resulted in fisherfolk returning late to the selling point with their poor CFS yields, resulting in a low income and ultimately diminishing their livelihoods.

The interviewed fishermen also explained that they routinely made additional efforts to capture IFS to minimize their population. Lacking alternatives, fishermen discard the IFS in nearby areas or landfills. These disposals create a foul smell, resulting in an uncomfortable and nauseating environment for the local population. The interviewees also revealed that some members of fishing communities, which had been fishing for several generations, had to quit and take up daily wage jobs, such as painting or civil work. With no other options available, only older fishermen and those who had made fishing their profession continued fishing. According to a few of them, the daily and annual income they could earn from fishing had reduced threefold following the invasion of tank cleaner fish. The fishermen, dependent solely on fishing, highlighted their reduced protein intake due to poor CFS yields.

Similarly, leaseholders involved in aquaculture reported that their revenue losses were mainly due to increased expenditure on labour for removing IFS. However, their efforts were unsuccessful, as even a small population of IFS, owing to their high fecundity rate, could generate a large population in a few months by consuming the food supplied for the CFS. This, in turn, led to reduced resources for CFS, resulting in poor abundance and biomass, which eventually led to lower market value. Given these circumstances, people were unwilling to lease the sailfin catfish–infested lakes and ponds, leading to unemployment for many dependent fishermen. The problems encountered by these fishing communities were not accurately reported to the concerned governing bodies. Overall, the *Pterygoplichthys* spp. invasion had adversely affected the livelihoods of thousands of fisherfolk.

As discussed in the methodology, this study also examined the socio-economic impacts on leaseholders and fishermen arising from the need to implement mechanical removal programmes. We analysed removal programmes at the Grand Anicut Canal Pits 1 and 2 and Vandiyur Lake Pit using the input–cost–outcome associated parameters (Table 6 and Figure 6C–G). Before releasing commercial fish fingerlings for aquaculture, leaseholders conduct mechanical removal programmes. We analysed these programmes through i) the resource inputs in terms of labour, time, and materials, ii) the associated costs, and iii) the resulting outcomes of the IFS removal. During the programme at the Grand Anicut Canal Pits 1 and 2, the efforts of 22 workers over seven days, using seven fishing nets, incurred a total expenditure of ₹1,16,900 and resulted in the removal of five tonnes of IFS (Table 6). Though a significant proportion of the IFS in the pits was removed, the pits became infested with IFS again following water release from the Grand Anicut. Hence, the mechanical removal programme resulted in a considerable loss for the leaseholders.

Table 6. Overall Resource Inputs, Associated Costs, and the Resulting Outcomes of the Mechanical Removal Programmes of *Pterygoplichthys* spp. in the Grand Anicut Canal Pits 1 and 2 and Vandiyur Lake Pit

Field site	**The Grand Anicut Canal Pit 1**	**The Grand Anicut Canal Pit 2**	**Vandiyur Lake Pit**
Input			
No. of labourers hired	10	12	15
No. of working days	7	7	1
No. of fishing nets (size)	3 (10 mm)	4 (10 mm)	2 (10 mm)
Equipment hired	-	-	Water suction pump
Cost			
Individual labour charges/day (in INR)	600	600	550
Total labour charges (in INR)	42,000	50,400	8,250
Equipment hiring charges/day (in INR)	-	-	1,000
Total cost of fishing net (in INR)	10,500	14,000	7,000
Total expenditure (in INR)	52,500	64,400	16,250
Outcome			
Total biomass of *Pterygoplichthys* spp. eliminated (in kg)	1,500	3,500	300

Source: Authors' compilation

Figure 6. Assessment of the Socio-economic Impacts of the *Pterygoplichthys* spp. Invasion in the Cauvery and Vaigai River Basins: (A) Fisherman Showing a Large Number of *Pterygoplichthys* spp. Trapped in the Fishing Net, (B) Complexly Entangled Sailfin Catfish, (C) Fishermen Involved in the Mechanical Removal of Invasive Sailfin Catfish at the Grand Anicut Canal Pit 1, (D) and (E) Huge Population of *Pterygoplichthys* spp. Removed During the Programme, (F) Fishermen Discarding the Trapped Fishing Net at the Grand Anicut Canal Pit 2, and (G) Preventing Fish from Entering the Suction Hose during the Mechanical Removal Programme at Vandiyur Lake Pit.

Source: Authors' compilation

Similarly, at Vandiyur Lake, the leaseholder employed 15 fishermen for the mechanical removal programme and provided them with wages and food. The fishermen identified a pit with minimal water and a large number of IFS along with a sparse population of CFS. They used a water suction pump to remove the water, placing a net in front of the suction hose to prevent fish from entering it (Figure 6G). The IFS were discarded on nearby land. The fishermen also collected juvenile CFS, such as Nile tilapia (*Oreochromis niloticus*), Asian stinging catfish (*Heteropneustes fossilis*), and spotted snakehead catfish (*Channa punctata*). The mechanical removal programme took place over one day, incurred a total expenditure of approximately ₹16,250, and resulted in the removal of 300 kg of *Pterygoplichthys* spp. (Table 6). However, the fishermen were unable to remove the entire population of *Pterygoplichthys* spp., as a few juveniles were partially buried in the mud, and several pits were still infested with *Pterygoplichthys* spp. This outcome significantly distressed the workers and the leaseholder, leading to the suspension of the removal programme.

4. DISCUSSION

Pterygoplichthys spp. can occupy various habitats, including cool to warm water and fast- to slow-flowing streams. They can survive in oxygen-rich water and stagnant pools and live in a broad range of water conditions, from acidic to alkaline (Mendoza *et al.* 2009). In the present study, the *Pterygoplichthys* spp. were mostly found in alkaline water conditions in both the CRB and VRB. Similar to the results found in Nico and Martin (2001) and Chavez *et al.* (2006), the *Pterygoplichthys* spp. populations recorded in the present study were able to tolerate low water quality. They were predominantly found in sewage-contaminated sites such as the Kudamurutti River, Vadavar River, and Arasalar River of the CRB, as well as the Vaigai River and Vandiyur Lake of the VRB. The correlation analysis revealed that these sewage-contaminated sites have higher values of conductivity, TDS, and salinity; however, they showed weak to moderate correlations with the abundance and biomass of invasive *Pterygoplichthys* spp. Although these water quality parameters may not have a direct effect, they lead to algal blooms (Ayele and Atlabachew 2021), which serve as a food resource for tank cleaner fishes.

In addition, we found that the sewage-contaminated sites were dominated by invasive *Pontederia crassipes* (formerly *Eichhornia crassipes* - water hyacinth), native to South America, which helps support a sustainable population of *Pterygoplichthys* spp. The dense mat of *P. crassipes* provided a predator-free environment for the juveniles of *Pterygoplichthys* spp. (Tran *et al.* 2021). It also provided a healthy breeding site for the adults (Hussan *et al.* 2019) by increasing phytoplankton densities and supporting detritus accumulation under their bushy root structure (Tran *et al.* 2021). These conditions ensure a reliable food supply for the IFS. From this, we can infer that the beneficial association between the two worst invasive species (*Pterygoplichthys* spp. and *P. crassipes*) is evident in their wide dispersal (Tran *et al.* 2021) in the inland water bodies of the CRB and VRB. Furthermore, the continuous discharge of sewage water at these sites during drought conditions ultimately supports these IFS populations throughout the year.

Similar to the findings of Wang *et al.* (2021) and Monico *et al.* (2022), we found that alterations in the flow regimes of inland water bodies, through the construction of dams and bridges; the spread of invasive aquatic vegetation such as *P. crassipes*; and anthropogenic disturbances such as sewage disposal, favours the sustenance of IFS over CFS. However, there were a few study sites in both the river basins, including the Kambarasampettai Check Dam, Cauvery River Sites 1 and 2, Palavar River, Nattar River, Valandur Lake, and Sakkudi Lake, where there was no stable maintenance population of either CFS or IFS due to irregular water availability resulting from both natural and anthropogenic activities. One possible reason for this discontinuous water availability is the poor 2016 north-eastern monsoons in Tamil Nadu, particularly, in the districts where the Cauvery and Vaigai rivers faced deficient (–20% to –59%) to significant deficient rainfall (–60% to –99%) compared to the average rainfall (Balachandran 2016).

Disruption of the aquatic food chain, reduction in the abundance of native organisms, mortality of shorebirds, changes in aquatic plant populations, and bank erosion were some of the reported ecological consequences of the *Pterygoplichthys* spp. invasion (Orfinger and Gooding 2018). For instance, *P. multiradiatus* has been linked to a decline in carp and tilapia fisheries, as well as damage to fishing gear, in El Infiernillo Reservoir, Mexico (Rueda-Jasso *et al.* 2013). Similarly, in the present study, due to the presence of IFS in the CRB and VRB, the abundance and biomass of CFS such as *Xenentodon cancila* (Asian needlefish), *Cirrhinus cirrhosus* (Mrigal carp), *Channa striata* (snakehead murrel), and *Glossogobius giuris* (tank goby) were observed to be reduced in fish catches in several study sites. Nevertheless, in the lotic ecosystems of the CRB, the total abundance of CFS was higher than that of IFS, mainly due to the presence of *Mystus cavasius* (Gangetic mystus, weighing less than 10 g) in the fish catches made in the Vennar River. In the VRB, the total CFSA was higher primarily due to the use of several sites for commercial aquaculture, where several thousand CFS fingerlings are released each year. Other than Vaigai Dam, CFSB was lower than IFSB in the VRB due to the occurrence of abnormally large IFS individuals. The IFS compete for food and living space, resulting in a lower yield of CFS compared to previous years.

Pterygoplichthys spp. reproduce via sexual reproduction and throughout the year with a high fecundity rate. On average, a single female individual in a spawning season can lay between 3,600 and 6,900 eggs, with the number varying by size and species (Gibbs *et al.* 2008). In the natural drainages of Thiruvananthapuram, Kerala, Raj *et al.* (2021) reported the absolute fecundity of different-sized individuals of *P. pardalis* to be in the range of 923–14,777 eggs. However, in the present study, up to 7,500 eggs were recorded for the gravid female *Pterygoplichthys* spp. individuals caught in the study sites. This higher fecundity can be attributed to the absence of natural enemies and the increased availability of food resources due to algal blooms in sewage-contaminated sites. Seasonal effects also influence the fecundity of *Pterygoplichthys* spp. (Gibbs *et al.* 2017). In this species, an interesting parental behaviour exists, where male individuals construct horizontal burrows 30–140 cm deep along the banks of rivers, lakes, and ponds that serve as nesting tunnels for females to lay eggs (Lienart *et al.* 2013). Once the eggs have been laid, the males guard the eggs until they hatch, releasing larvae (Mendoza *et al.* 2009). In the present study, we observed horizontal nesting tunnels along the banks at water-depleted portions of the study sites, including the Kudamurutti River, Vettar River, Arasalar River, Vaigai River, and Vandiyur Lake. Such burrows have previously been reported to weaken the bank structure, ultimately leading to siltation problems in several invaded regions, including Hawaii and Florida (Nico *et al.* 2009).

The sociological problems faced by fishing communities due to the *Pterygoplichthys* spp. invasion extends beyond economic losses; it is a life-or-death situation. Drawing a net full of *Pterygoplichthys* spp. rather than CFS has a severe psychological impact on fishermen. Besides the damage to fishing gear (Global Invasive Species Database 2025), the laborious process of removing spiny *Pterygoplichthys* spp. often injures the fishermen's hands and delays the effective fishing of CFS, subsequently impacting the time at which the poor yields of CFS are sold. This severely affects their daily incomes and poses significant constraints on the day-to-day lives of fishing communities. These situations have even prompted fishermen to abandon their familial profession for employment in other sectors. However, the unskilled average fisherfolk who depend on fishing to meet their protein needs have no alternative.

The mechanical removal programmes reported in this study offer deep insights into the socio-economic impact of the *Pterygoplichthys* spp. invasion.

Mechanical removal programmes are generally considered the preferred control method due to the problems associated with non-specific chemical control methods and biocontrol methods, which can introduce new exotic organisms (Messing and Wright 2006). Furthermore, mechanical removal programmes require a significant amount of manpower and money to cover wages, food, damage to fishing equipment, and other additional expenses. In this study, mechanical removal programmes could only partially remove the *Pterygoplichthys* spp., as subsequent water releases from the associated dams and monsoon rainfall led to the proliferation of *Pterygoplichthys* spp. again. An important point to note here is that the cost of mechanical removal was approximately ₹1,50,000 for just a few days of work at each pit. Hence, the total expenditure required to completely remove *Pterygoplichthys* spp. from the CRB and VRB would be staggering.

The present study attempted to describe the ecological and socio-economic impacts of the *Pterygoplichthys* spp. invasion in major inland water bodies in the Cauvery and Vaigai River Basins. The findings underscore the urgent need to increase awareness among ecologists, academics, politicians, policymakers, and the general public regarding the seriousness of the issue. Further, it emphasizes the need to develop novel or alternative management strategies to curb the invasion of *Pterygoplichthys* spp. and similar exotic pets in Indian ecosystems. Additionally, promoting native ornamental freshwater and marine fish, as well as other small pet animals for aquariums and petting purposes, through extensive outreach programmes targeting younger and older generations can aid in the prevention of future invasion episodes.

5. CONCLUSION

Based on this study, the following conclusions can be drawn: i) the biomass of IFS is comparatively higher than that of CFS at most sites in the Cauvery and Vaigai river basins; ii) mechanical control measures undertaken by the fishing communities for the removal of invasive *Pterygoplichthys* spp. are not effective; iii) strict regulations are required to monitor the transactions of sellers, buyers, and keepers of exotic pets or aquarium species; and iv) innovative management and control strategies are needed to eradicate invasive *Pterygoplichthys* spp.

Supplementary Material: The site-wise specifics of the abundance (nos.) and biomass (kg) of IFS and CFS in the CRB and VRB are detailed in Supplementary Figures S1 and S2. The informed consent form and questionnaire used for the semi-structured interview to record the socio-economic impacts on fishing communities are provided in the Supplementary Material.

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Ethics approval: Not applicable.

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RESEARCH PAPER (Supplementary material)

The Ecological and Socio-economic Impacts of the Aquarium Sailfin Catfish Invasion: Fate of Fisherfolk at Major Inland Water Bodies, Tamil Nadu, South India

Mohan Raj Rajasekaran*, Indhar Saidanyan Ravichandran**, Parthiban Balasingam***, and Chandrasekaran Sivagnanam****

Abstract: Keeping pets has been part of human life since the earliest civilizations. Today, exotic animals are sold online and shipped globally to enthusiasts. However, pet sellers and keepers sometimes release exotic pets into nearby natural ecosystems, leading to biological invasion. This paper examines the invasion by sailfin catfish (*Pterygoplichthys* spp.) of Cauvery and Vaigai river basins, and its ecological and socio-economic impacts. We assessed the ecological impacts by comparing the total abundance and biomass of the invasive fish species (IFS), *Pterygoplichthys* spp., with those of comparator fish species (CFS) and various physicochemical parameters. We used semi-structured interviews and case studies of IFS mechanical removal programmes to assess the socio-economic impacts. The abundance and biomass of the IFS were significantly higher than those of the CFS in most lentic and lotic ecosystems. Interviews revealed significant sociological impacts on fisherfolk, including a push from fishing (a familial profession) to non-fishing vocations. The input–cost–outcome assessment of mechanical removal programmes revealed that the expenditure incurred could not prevent further invasion of the IFS. This study advocates for increasing awareness among stakeholders to devise effective control measures and implement policy-level changes to curb the sailfin catfish invasion in India's inland water bodies.

Keywords: *Pterygoplichthys* spp., Biological Invasion, Ecological and Socio-economic Impacts, Fishing Communities, Cauvery River Basin, Vaigai River Basin.

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* Department of Plant Sciences (DPSc), School of Biological Sciences (SBS), Madurai Kamaraj University, Madurai - 625021, India (MKU); santhamoorthy92@gmail.com

** DPSc, SBS, MKU; saidanyan@gmail.com

*** DPSc, SBS, MKU; parthibanpana@gmail.com

**** DPSc, SBS, MKU; csekaran.biological@mkuniversity.ac.in.✉

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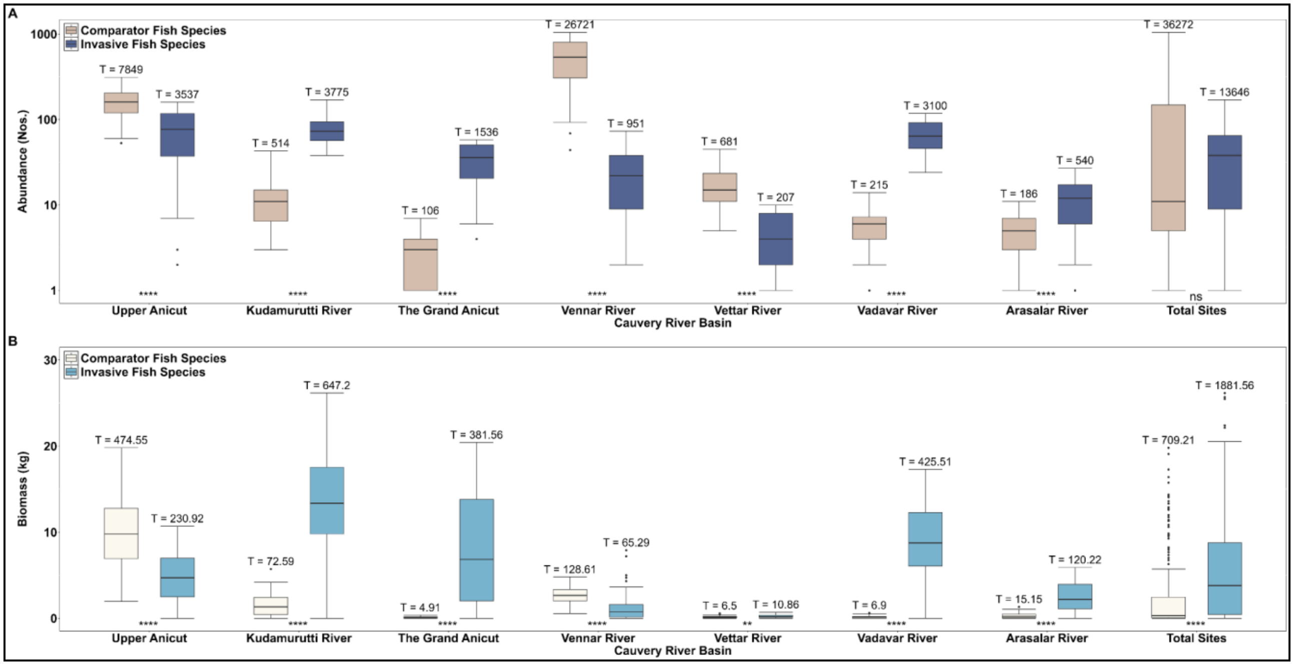
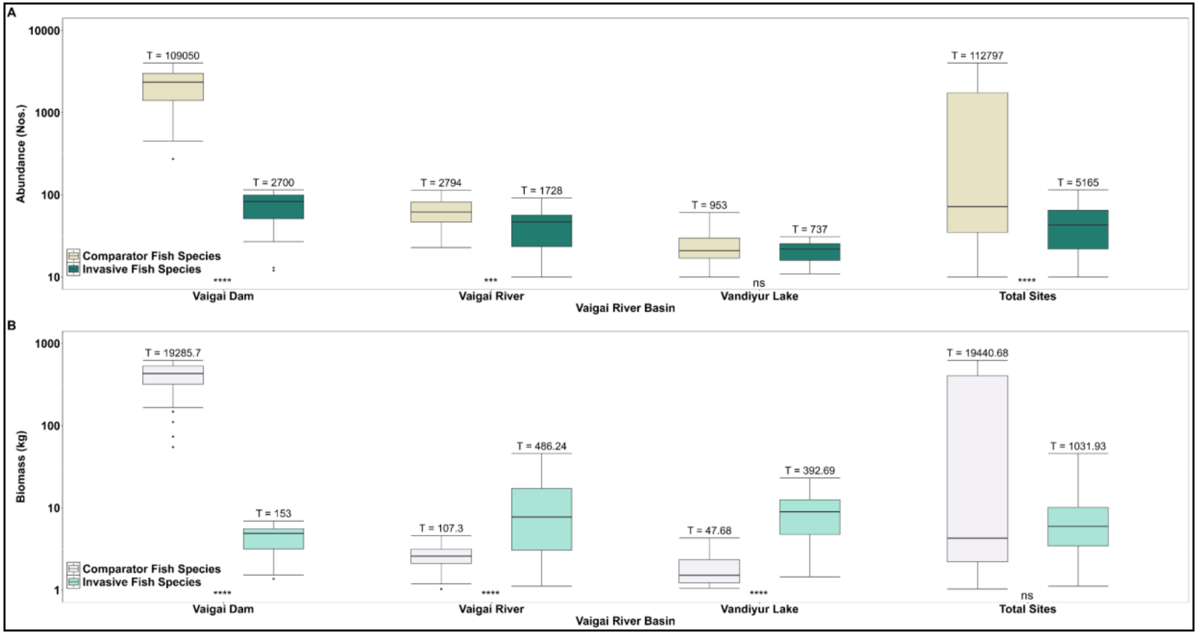
Figure S1. Boxplot Representing the Individual and Total Sites' Abundance (No.) and Biomass (kg) of Comparator Fish Species and Invasive Fish Species, *Pterygoplichthys* spp. in the Cauvery River Basin and with Statistical Analysis Using Wilcoxon Rank-Sum Test. Abundance (A) and Biomass (B).



Source: Authors' analysis

Note: **, ****, and 'ns' denote the significant difference at $p < 0.01$, $p < 0.0001$, and non-significant difference at $p > 0.05$, respectively.

Figure S2. Boxplot Representing the Individual Site's and Total Sites' Abundance (No.) and Biomass (kg) of Comparator Fish Species and Invasive Fish Species, *Pterygoplichthys* spp. in the Vaigai River Basin and with Statistical Analysis Using Wilcoxon Rank-Sum Test. Abundance (A) and Biomass (B).



Source: Authors' analysis

Note: ***, ****, and 'ns' denote the significant difference at $p < 0.001$, $p < 0.0001$, and non-significant difference at $p > 0.05$, respectively

Informed Consent Form for the Semi-Structured Interview

Project Title: Studies on the Ecological, Economical, and Sociological Impacts of Invasive Species in Tamil Nadu

Funding Agency: Tamil Nadu State Land Use Research Board (TNSLURB), State Planning Commission, Tamil Nadu (Ref. No. 535/SPC/LUD/2016)

Project Context: To study the various problems caused by invasive species, particularly *Pterygoplichthys* spp. (hereafter tank cleaner fish), in relation to the natural ecosystem and the local people in the Cauvery and Vaigai river basins

Conditions:

I agree to participate in this project through this interview with the following conditions:

- The project studies the ecological, economic, and sociological impacts of invasive species in Tamil Nadu. For this purpose, semi-structured interviews will be conducted with key informants (leaseholders of a particular water body, fishermen, local people, etc.).
- Interviews will last for about one hour, and questions will deal with the ecological, sociological, and economic problems encountered by the people in the study area due to invasive species.
- The interview I give and the information it contains will be used solely for the purposes defined by the project.
- At any time, I can refuse to answer certain questions, discuss certain topics, or even put an end to the interview without prejudice to myself.
- To facilitate the interviewer's job, the interview can be recorded. However, the recording will be deleted as soon as it has been transcribed.
- All interview data will be handled carefully to protect the interviewees' confidentiality. Therefore, no names will be mentioned, and the information will be coded.

For any information about the project, contact Prof. S. Chandrasekaran, Principal Investigator (TNSLURB Project), Head, Department of Plant Sciences, School of Biological Sciences, Madurai Kamaraj University, Madurai 625021.

Respondent's signature   Interviewer's signature

Semi-Structured Interview Questionnaire

i) Introduction

1. Introduction of the Interviewer
2. Purpose of the Interview
3. Introduction of the Interviewee (asking the following details)

   Name:

   Native place:

   Occupation:

   How long have they been working in the fishing profession?

ii) Main Portion of the Interview

Focusing Theme: Economic and Sociological Impacts of *Pterygoplichthys* spp. in Cauvery and Vaigai River Basin

1. When did you notice the tank cleaner fish for the first time in this area?
2. How did it occur?
3. When did the tank cleaner fish first start troubling you? What are the problems with it?
4. What are all the fish species affected by the tank cleaner fish? How are they affected by it?
5. Which portion of the water body has the highest population of tank cleaner fish?
6. Comparatively, which year/month has the highest recorded number of tank cleaner fish in the catch?
7. Has it reduced or increased after it was caught to the maximum?
8. At what time are the tank cleaner fish active?
9. Have there been any changes in the water quality of the water body due to tank cleaner fish invasion?
10. Have there been any damages caused to your fishing equipment?
11. Did this fish invasion affect your decision to take a lease of a particular lake/pond?
12. Did this fish invasion require more labour, work, and money to eliminate the fish in the leased water body?
13. How much did you spend on eliminating this fish from the leased water body at one time? How many times did you attempt to eliminate this fish?

14. Is your total annual income affected by the tank cleaner fish invasion?
15. Is anyone interested in buying this fish? For what purpose do they buy it?
16. At what size and for what price are they buying the fish?
17. How often do they buy the tank cleaner fish?
18. Have you made a profit from this fish? Did you gain any valuable amount from this fish?
19. Is anyone or any farm nearby cultivating this fish?
20. Has this fish invasion affected your time spent catching comparator fish species?
21. Did this fish invasion make you stressed and quit based on the poor yield of valuable comparator fish species?
22. Has this fish invasion affected your food demand or daily family income generated from selling the comparator fish?
23. Have you eaten this fish? How do you prepare it?
24. Has this situation led you to quit fishing and search for an alternative?
25. Does the new job provide more benefits than your previous one? How?
26. What are the steps you are following to tackle these problems? Will it give a positive result?
27. How are you managing the situation as you face these problems?
28. What are all the other places affected by this fish invasion, and who are all the victims of the tank cleaner fish invasion?
29. Did you file any complaints regarding these problems with any officials?
30. Did they take any actions?
31. Similar to this fish species, are there any other fish or other organisms causing problems to your people?

iii) Conclusion Portion of the Interview

1. Is there anything more you want to tell us?
2. Do you have any questions for us?