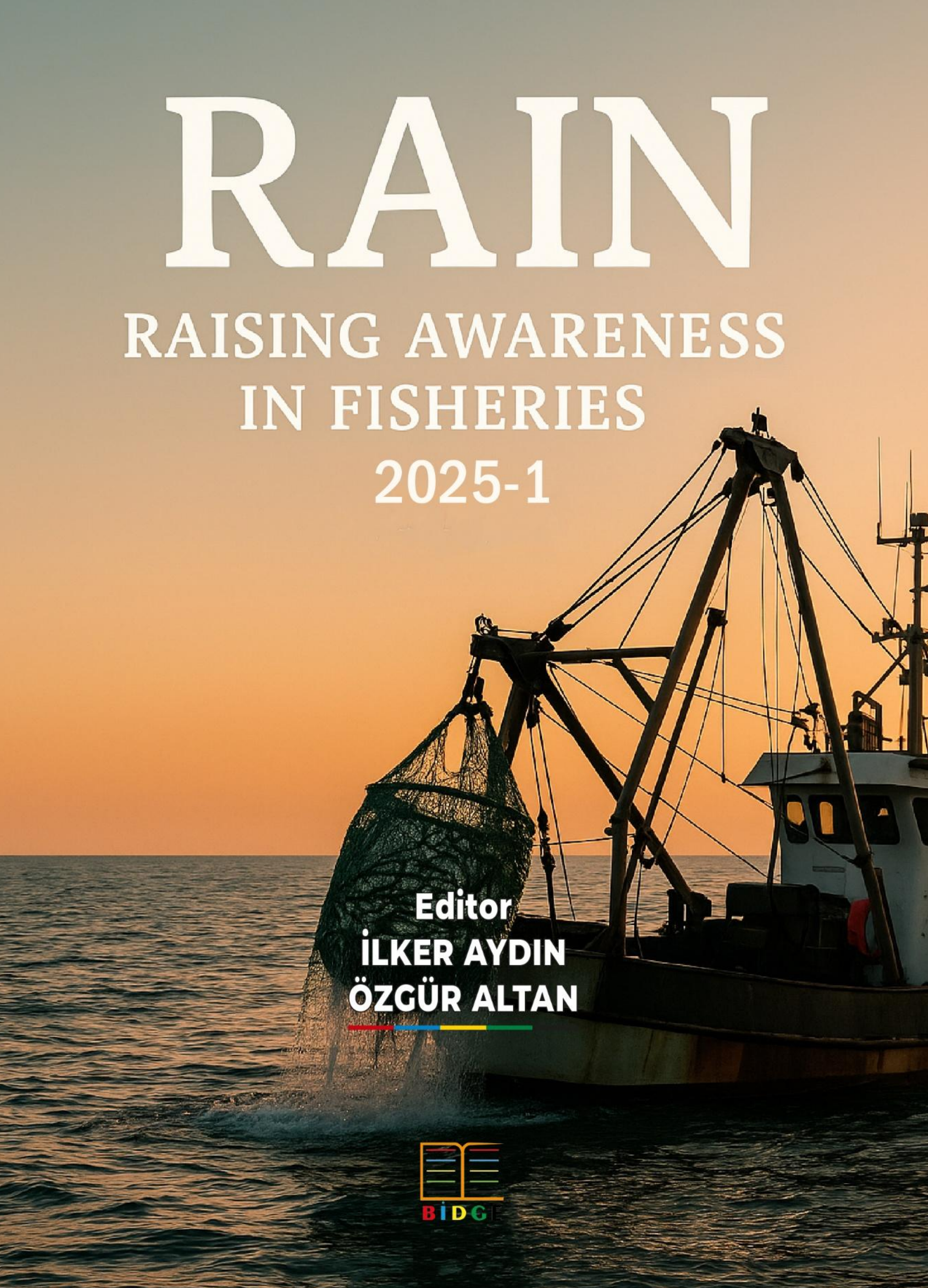

RAIN

RAISING AWARENESS IN FISHERIES

2025-1

Editor

İLKER AYDIN

ÖZGÜR ALTAN

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Contents

HYDROMETRIC, ANTHROPOGENIC, AND HYDROPOWER IMPACTS ON THE LITHUANIAN FISH INDEX AND SURFACE WATER ECOLOGICAL STATUS

LAİMA ČESONIENĖ

1.Introduction

The European fisheries sector operates in a constantly to protect people and ecosystems, the European Commission has adopted a zero-pollution action plan to prevent air, water and soil pollution. The European Commission encourages sustainability in agriculture and rural areas across the EU through the common agricultural policy, by which agriculture is environmentally sustainable, protects natural resources and enhances biodiversity. Despite the introduction of legislation such as the EU Nitrates and Water Framework Directives (OJEC…, 1991, OJEC…, 2000) agricultural practices are often still regarded as a major influencing factor on poor water quality across many EU member states (Harrison at al., 2019), and agricultural systems and activities will put pressure on freshwater resources (Lahlou at al., 2021). A scientific evaluation of the suitability and cost-effectiveness of options to reduce nutrient loss from rural areas to surface waters at the catchment scale, including the feasibility of the options under different climatic and geographical conditions, was conducted in different EU countries (Schoumans at al., 2014). Agricultural catchments are where farm and landscape management interact with policy and science, especially regarding the implementation and evaluation of agro-environmental regulation (Wall at al., 2011). The increasing rate of water resource usage results in its contamination by wastewater from domestic, industrial and agricultural sectors. The opinions of different researchers confirm that agricultural pollution poses a considerable challenge to grain security and human health, especially in economically developed areas (Jiang at al., 2020). Various studies show that the excessive use of chemical fertilizers and pesticides has caused serious nonpoint-source water pollution (Xiao at al., 20212). Diffuse water pollution and other water pollution problems are a major problem in many agroecosystems, especially in irrigated areas linked to ecosystems of high ecological value (Alcon at al., 2020). Requirements for high-quality water bodies are different, but identifying the spatiotemporal characteristics of water quality and related driving factors is essential for lake water quality management (Geng at al., 2020). The quality of water and nature is determined for ground and surface water by first measuring their N and P contents and, for natural areas, by measuring N deposition (Boruma, 2016). Lakes are one of the most important water resources and are used as a source of water for human consumption, and, in general, they account for approximately 0.3% of total surface water body sources. The quality of lake water (or other surface sources) is evaluated using various physicochemical and biological parameters selected based on the designated best use (DBU) of the water body (lake) for various purposes (Vasistha and Ganguly, 2020). The quality of lake water is dependent on the geological structure of the earth and on the anthropogenic activities surrounding it, such as construction, waste disposal, agriculture and other associated activities (Mahananda at al., 2010).

Changes in water quality indicators are much slower in large water bodies. The larger and deeper the water body is, the better the conditions for spontaneous water purification, slower hydrobiological processes, and slower accumulation of sediment. If the water body is shallow, hydrobiological and hydrochemical processes occur more intensely, organic sediments accumulate intensively, and the water body becomes overwhelmed and begins to disappear. The faster the water exchange, the lower the phosphorus concentration in the water and sludge (Sondergaard at al., 2001). Polish researchers have found that lakes with higher water temperatures have higher mean depth, maximum depth, and water transparency (V at al., 2019).

Water depth has an impact on the abundance and diversity of fish. Recent studies have shown that fish abundance and alpha diversity were positively correlated with wetland water depth. A. Garunkštis showed the remains of dead plankton, along with $CaCO_3$ crystals, slowly sinking into deeper layers. Lake cleaning can be continuous or partial. Cleaning the entire lake alters the average lake depth, whereby the type of lake is determined accordingly and should be evaluated before deciding to clean the lake because the ecological balance of the lake is damaged after the treatment and the indicators temporarily deteriorate. The impact on the ecosystem is lower when using partial cleaning; nonetheless, the impact on water quality is lower as phosphorus emancipation occurs from the remaining uncleaned sediments (Reddy at al., 2002). Depending of the 1 ha/1 meter depth of a shallow lake to 4 meters would create conditions for self-cleaning of the water and a decrease in phosphorus concentration from 0.0784 mg/L to 0.0565 mg/L (0.0219 mg/L).

2. Relationship between the Lithuanian fish index (LFI) values and the Hydrometric Parameters and Influence of Anthropogenic Loads on Surface Water Status

Poor surface water status can be affected by natural and anthropogenic factors. NATURAL - such as climate change, average depth, maximum depth, water exchange per year, area, pool area. ANTHROPOGENIC – total phosphorus (P) and total nitrogen (N) from arable land; meadows; from cities; from forests; from households not connected to sewage networks; from municipal wastewater; from surface wastewater; from organic farms; current number of organic farms, percent; current area of organic farms; conditional number of livestock; agricultural land; arable land area; number of farms in the basin.

The larger and deeper lakes and ponds are, the better the conditions for spontaneous water purification, slower hydrobiological processes and slower accumulation of sediment.

Multiple studies were conducted on 29 lakes and 10 ponds located throughout Lithuania in 2014–2020. It was found that the total N values in 50% of the surveyed water bodies did not correspond to the good and very good ecological status class values: 7.5% corresponded to the moderate ecological status class value, 22.5% to the poor status class value and 17.5% to the very poor status class value. Twenty percent of the tested water bodies had P total values that did not correspond to the good and very good ecological status class values. Of these, 7.5% corresponded to the moderate ecological status class value, 5% to the poor status class value and 7.5% to the very poor status class value. The study proved that higher maxima and average depths of lakes correlate with lower P total, N total and ichthyofauna taxonomic composition indicator for Lithuanian fish index (LFI) (Česonienė, Šileikienė & Dapkienė, 2020).

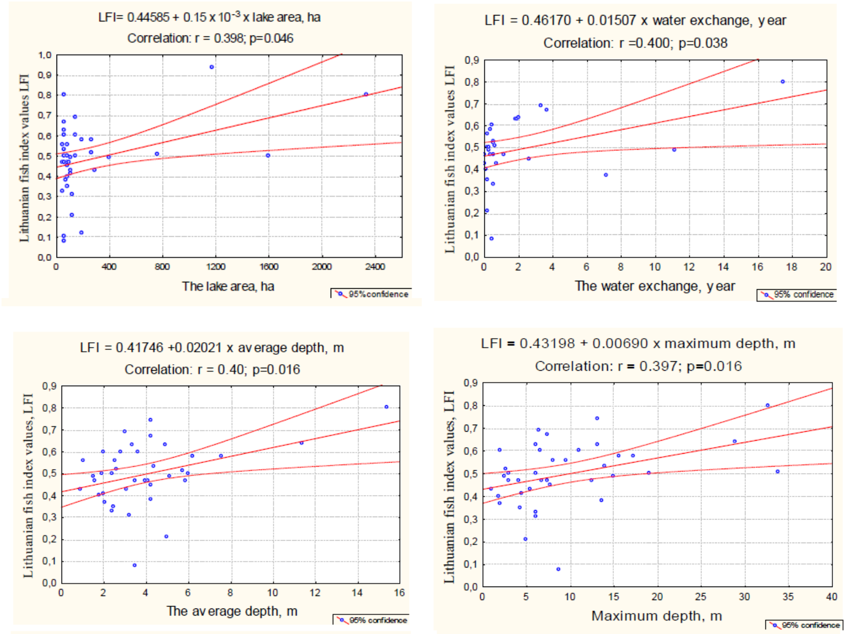

Figure 1. Water quality indicator - ichthyophaune taxonomic composition Lithuanian fish index (LFI) and water area, water exchange and their mean and maximum depths in the lakes assessed.

Larger lake areas contain smaller amounts of P total and N total, indicating better ecological status class, higher ichthyophane taxonomic composition in LFI, indicate better ecological status class. Rapid water exchange improves the condition of the lake in addition to nitrogen, phosphorus. The faster the water exchange in the lake is, the lower the P total and N total values. However, slower water exchange indicates better ecological status of the ichthyofauna taxonomic composition.

3. Influence of Anthropogenic Loads on Surface Water Status

Human agricultural activities and their development have an inevitable negative impact on the environment. One of the largest ecological issues today is the intensive anthropogenic activity in throughout the catchment, resulting in eutrophication. Anthropogenic loads were assessed according to pollution sources in individual water catchment basins. The lake basins and ponds received the largest amounts of pollution from agricultural sources with total nitrogen at 1554.13 t/year and phosphorus at 1.94 t/year, and from meadows and pastures with total nitrogen at 9.50 t/year and phosphorus at 0.20 t/year. The highest annual load of total nitrogen for lake basins on average per year was from agricultural pollution from arable land (98.85%), and the highest total phosphorus load was also from agricultural pollution from arable land (60%). (Česonienė at al., 2021).

Table 1. Influence of anthropogenic loads in basins on the taxonomic composition, abundance and age of ichthyofauna, LFI (lake fish index), in the water.

Environmental Factor	Unstandardized Coefficients		Standardized Coefficients	t	Significance Level $p < 0.05$
	B	Std. Error	Beta		
Constant	0.540	0.056		9.586	0.000
*Current number of organic farms %	0.044	0.020	0.531	2.250	0.047
Current area of organic farms, ha	0.000	0.000	0.317	0.979	0.341
Basin area, ha	0.002	0.002	0.676	1.130	0.273
Conditional number of livestock	-1.558×10^{-5}	0.000	−0.093	−0.171	0.867
Agricultural land area, ha	-3.697×10^{-5}	−0.000	−0.362	−0.248	0.807
Arable land area, ha	-8.631×10^{-5}	0.000	−0.052	−0.088	0.931
Number of farms in the basin, units	0.000	0.001	0.094	0.101	0.920

a. Dependent Variable: LFI (lake fish index)s; * Significance factor, $p < 0.05$.

A multiple regression analysis of the influence of anthropogenic loads in basins on the taxonomic composition, abundance and age of ichthyofauna in the water showed that the LFI values were affected by the current percentage of organic farms in the basin ($p < 0.05$). The higher the percentage of organic farms in the basin was, the higher the taxonomic composition, abundance and age of ichthyofauna in the water and the better the water status (positive function).

4. Assessment of the Impact of Small Hydropower Plants (SHPs) on the Ecological Status Indicators of Water Bodies

Lithuania is a low-lying country; therefore, the country's small hydropower plants are mostly low-head (up to 5 m) or medium-head (between 5 and 15 m). These plants op-erate on a run-of-the-river basis but involve relatively large water storage. Hydropower schemes consist of an impoundment with an earth-fill dam and integral or separated in-take, with a powerhouse located at the dam toe. Traditional diversion schemes are quite rare. Due to the flat topography and low terrain gradient, their reservoir surface areas are also quite large, sometimes exceeding 1 or 2 km^2 with corresponding water storage of a few millions m^3 or more. Consequently, backwater stretches far behind the dam, some-times up to 10 km or more.

To determine the impact of SHPs on the status of water bodies, studies were per-formed on water bodies above the hydroelectric reservoir (in the riverbed upstream from the SHPs, where the hydrological regime has not changed due to the impact of the SHP reservoir) and downstream from the SHP reservoir.

Surveys of physico-chemical quality indicators and suspended solids were per-formed in January-December 2020, while benthic macroinvertebrates and fish studies were performed in August-September 2020. Ten small hydropower plants were selected in different parts of Lithuania.

To assess the impact of small hydropower plants on water status, water samples were taken upstream and downstream from the SHPs. The physico-chemical and biolog-ical indicators of water quality were then assessed.

The significance of the effect was determined according to the determined values of LFI upstream and downstream from the SHP. The data are presented in Figures 2-3, which summarize all investigated SHPs. The representativeness of these data is outlined in Table 2. The data on the figures are described later in this section.

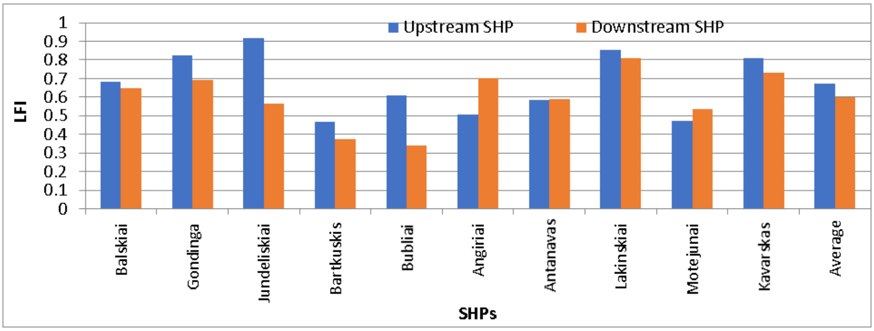

Figure 2. Lithuanian fish index (LFI) values upstream and downstream SHP dams.

In 7 out of 10 SHPs, the ecological status according to the LFI upstream from the SHP was found to be worse than that downstream (Balskai, Gondinga, Jundeliškės, Bartkuškis, Bubliai, Kavarskas and Lakinskai. Mean LFI values also were higher upstream than downstream of SHPs.

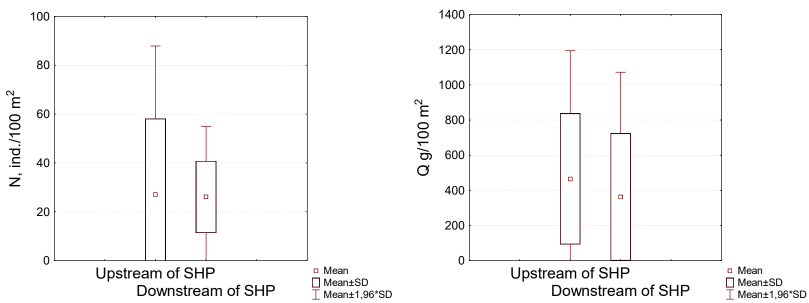

Figure 3. Fish abundance (N,ind./100 m^2)(individuals/100m2) and biomass (Q, g/100m^2) upstream and downstream from the SHPs.

By calculating the differences between fish abundance (N, ind./100 m^2) and biomass (Q, g / 100m^2) below hydroelectric power plants and above hydroelectric power plants, it was found that the biomass upstream from the SHP is significantly higher than that downstream. This difference is statistically significant (p-<0.05) for the Jundeliškės and Kavarskas SHPs. Fish abundance upstream from the SHP was found to be significantly higher than that downstream; this difference was found to be statistically significant (t<0.05) for the Lakinskai SHP and Kavarskas SHP.

The impact of hydroelectric and chemical water quality indicators on the Lithuanian Fish Index LFI (Y) and fish abundance (Y) was calculated by a multiple regression analy-sis. The results are presented in Table 2 and Table 3.

Table 2. Influence of small hydroelectric power plant and chemical water quality indicators on the Lithuanian Fish Index (LFI) downstream from the SHP.

Environmental factor	Non-standardized coefficients		Standardized coefficient	t	Significance level
	B	Standard error	Beta		p <0.05
Constant	-0.117	0.382		-0.307	0.767
BOD_7, mg/l **(x_1)**	0.000	0.035	-0.002	-0.006	0.995
N_{total}, mg/l **(x_2)**	0.019	0.027	0.156	0.695	0.510
P_{total}, mg/l **(x_3)**	-0.801	1.543	-0.161	-0.519	0.620
Suspended solids, mg/l **(x_4)**	0.002	0.004	0.159	0.499	0.633
Turbine power, kW **(x_5)**	3.644E-5	0.000	0.100	0.511	0.625
Q_0 m^3/s **(x_6)**	0,020	0.010	1.047	1.898	0.100
* The average depth of the river, m **(x_7)**	1.538	0.484	1.040	3.180	0.015
Vegetation, percentage of riverbed cover **(x_8)**	-0.074	0.129	-0.111	-0.576	0.583
Reservoir retention time, D **(x_9)**	-0.004	0.005	-0.250	-0.717	0.497
River area, m **(x_{10})**	-0.023	0.010	-1.406	-2.328	0.053
Flow rate, m/s **(x_{11})**	-0.145	0.156	-0.226	-.926	0.385

Table 3. Influence of small hydroelectric power plants and chemical water quality indicators on total fish abundance downstream from the SHP.

Environmental factor	Non-standardized coefficients		Standardized coefficient	t	Significance level
	B	Standard error	Beta		p <0.05
Constant	10.078	96.397		0.105	0.920
BOD_7, mg/l **(x_1)**	-2.488	8.813	-0.137	-0.282	0.786
N_{total}, mg/l **(x_2)**	-1.210	6.865	-0.070	-0.176	0.865
P_{total}, mg/l **(x_3)**	37.373	389.786	0.053	0.096	0.926
Suspended solids, mg/l **(x_4)**	-0.479	1.030	-0.264	-0.464	0.656
Turbine power, kW **(x_5)**	-0.009	0.018	-0.170	-0.489	0.640
Q_0 m^3/s **(x_6)**	1.089	2.611	0.409	0.417	0.689
The average depth of the river, m **(x_7)**	-41.854	122.226	-0.199	-0.342	0.742
Vegetation, percentage of riverbed cover **(x_8)**	-15.672	32.572	-0.165	-0.481	0.645
Reservoir retention time, D **(x_9)**	1.347	1.342	0.624	1.004	0.349
River area, m **(x_{10})**	0.473	2.546	0.200	0.186	0.858
Flow rate, m/s **(x_{11})**	27.413	39.535	0.301	0.693	0.510

A multiple regression analysis of the influence of hydroelectric and chemical water quality indicators on the Lithuanian Fish Index for the LFI showed that the value of the LFI is influenced by the average depth and area of the river (the higher the average depth of the river, the higher the LFI).

The performed multiplier regression analysis of the impact of hydroelectric and chemical water quality indicators on the total fish abundance showed that the studied in-dicators do not have a significant impact on the total fish abundance.

5.Conclusion

Natural factors (lake area, depth, water exchange) have a significant influence on the ecological status of surface waters. Larger and deeper lakes provide better conditions for natural self-purification, slower hydrobiological processes, and reduced accumulation of phosphorus (P) and nitrogen (N). These conditions are reflected in the Lithuanian Fish Index (LFI), where higher values indicate better ichthyofauna taxonomic composition and ecological status.

Anthropogenic factors, particularly agricultural runoff from arable land, represent the largest source of nitrogen (98.85%) and phosphorus (60%) entering the basins. These inputs are the main drivers of eutrophication, negatively affecting the ecological status of water bodies and the structure of fish communities.

The proportion of organic farms within a basin is positively correlated with LFI values. A higher share of organic farms leads to greater species diversity, abundance, and age structure of ichthyofauna, thus improving water quality and ecological status.

The impact of small hydropower plants (SHPs) is complex:

In 7 out of 10 SHPs, LFI values upstream were worse than those downstream, indicating disruption of natural fish communities.

Fish biomass and abundance were generally higher upstream than downstream, with statistically significant differences in some cases.

Multiple regression analysis showed that LFI values are mainly influenced by river depth and area, while overall fish abundance was not significantly affected by SHP operation.

6. Recommendations

Water quality management:

Reduce nitrogen and phosphorus inputs from agriculture, especially arable land.

Promote organic farming as a sustainable measure to mitigate nutrient pollution and improve water body status.

Monitoring:

Broaden the application of LFI as an integrated ecological assessment tool that combines hydrometric parameters with anthropogenic pressure indicators.

Ensure that monitoring includes both chemical and biological indicators (fish communities, macroinvertebrates).

Small hydropower regulation:

Introduce environmentally friendly technologies that minimize the negative impacts of SHPs on fish communities.

Conduct regular monitoring of SHP impacts, with emphasis on fish migration and biodiversity.

Require comprehensive ecological impact assessments, including effects on LFI, before constructing new SHPs.

Policy and strategy:

Integrate measures for reducing agricultural intensity, expanding organic farming, and controlling hydropower impacts into river basin management plans.

Strengthen ecological protection strategies through integrated basin-level management, balancing environmental, agricultural, and energy interests.

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THE ROLE OF RABBİTFİSHES (SİGANUS SPP.) İN SUSTAİNABLE AQUACULTURE

SERHAT ENGİN

1. INTRODUCTION

Rabbitfishes (Siganus spp.) represent a monophyletic genus within Siganidae, comprising 28 valid species distributed across the Indo-Pacific, from the Red Sea and Arabian Gulf to French Polynesia, and latitudinally from southern Japan to northern Australia (FAO, 2004; Lam, 1974). Morphological and ecological traits divide the genus into fusiform schooling species (*S. argenteus, S. canaliculatus, S. spinus*) and reef-associated, vividly pigmented species that often occur in pairs (*S. doliatus, S. corallinus, S. vulpinus*) (Lam, 1974). Molecular studies further delineate a third clade uniting S. argenteus with the morphologically divergent S. woodlandi (Babiak et al., 2019).

Rabbitfishes are characterized by laterally compressed, deep bodies, XIII dorsal spines, VII anal spines, and II ventral spines. Some species exhibit elongated snouts and distinct facial markings reminiscent of fox-like features, historically classified under the genus Lo (Lam, 1974).

Their herbivorous diet makes them culturally and nutritionally significant in many Indo-Pacific and Mediterranean communities (Bariche, 2006; FAO, 2023). Despite their widespread consumption, aquaculture development remains limited compared with carnivorous finfish, largely due to lower market value (CIHEAM, 2000). However, concerns over the sustainability of fishmeal-dependent aquaculture systems have stimulated renewed interest in rabbitfish, given their potential role in integrated and sustainable production (Ahn et al., 2020).

Biological Features

The family Siganidae comprises 28 valid species within the genus Siganus, collectively known as rabbitfishes (Woodland, 1990; Randall, 2001). These species are widely distributed across the Indo-Pacific region, extending westward from the Red Sea and the Arabian Gulf to French Polynesia, and southward from Japan to northern Australia (Figure 1). (Allen, 1991; Woodland, 2001). Based on morphological and ecological characteristics, rabbitfishes have traditionally been divided into two principal assemblages: (1) drab-coloured, fusiform species that form large schools within macroalgal-dominated habitats (e.g., S. argenteus, S. canaliculatus, S. spinus), and (2) brightly coloured, reef-associated species that typically occur in pairs (e.g., S. doliatus, S. corallinus, S. vulpinus) (Woodland, 1990; Fox & Bellwood, 2013).

Molecular phylogenetic analyses have subsequently revealed a third lineage comprising the fusiform schooling S. argenteus and the deep-bodied S. woodlandi, suggesting that genetic diversification within the genus is greater than previously recognized (Kuriiwa et al., 2007). Morphologically, rabbitfishes exhibit a deep, laterally compressed body with a rounded, blunt snout, although certain species possess a distinct tubular snout and conspicuous facial markings reminiscent of a fox—traits that historically warranted their placement within the former genus Lo (Woodland, 1990).

Fin morphology is defined by the presence of 13 dorsal spines, 7 anal spines, and 2 pelvic spines (Randall, 2001). Body colouration varies from olive-green to brown, and the integument is covered with small, smooth cycloid scales (Woodland, 2001; Kimura et al., 2003). These morphological and chromatic features are considered adaptive responses to the ecological diversity of coral reef and seagrass habitats inhabited by rabbitfishes across tropical and subtropical marine ecosystems (Fox & Bellwood, 2013).

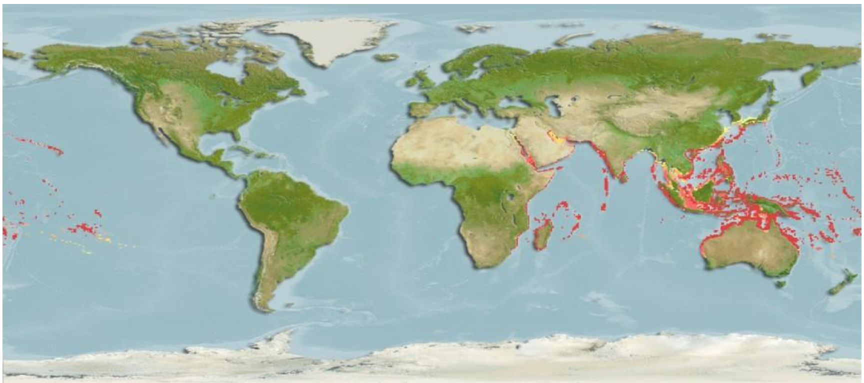

Figure 1. Distribution of Siganus spp.

Figure 2. Siganus caniculatus (A), S. rivilatus (B), S. fuscencens (C), S. argenteus (D), S. luridus

Why Rabbitfish Culture?

Rabbitfish aquaculture has gained prominence in the Philippines, particularly in mariculture operations utilizing floating net cages. The species can also be cultured either in monoculture or in polyculture systems with milkfish (Chanos chanos) and crabs within brackishwater ponds. As herbivorous fishes, rabbitfish require relatively low feed inputs during the grow-out phase; however, they can readily adapt to formulated diets when reared under captive conditions. Owing to their favorable market value—often higher than that of milkfish—rabbitfishes represent a profitable and sustainable alternative species for commercial grow-out aquaculture in coastal and estuarine environments.

2. SPECIES OF AQUACULTURE INTEREST

Culture practices vary by region. In Southeast Asia, S. canaliculatus, S. guttatus, S. virgatus, S. spinus, S. punctatus, S. fuscescens, and S. javus are reared (Duray, 1990). In the Middle East and Mediterranean, S. rivulatus dominates aquaculture efforts

(CIHEAM, 2000; Saoud et al., 2007). In the Pacific, S. randalli, S. lineatus, and S. fuscescens are utilized (Luong et al., 2014). In China, S. canaliculatus, S. fuscescens, and S. guttatus are well established in farming systems (Juario et al., 1985). (Figure 2).

3. SEED COLLECTION and NURSERY

Juveniles (1–7 cm) are typically collected from reef habitats one month post-spawning using nets, traps, light, or bait (Delmendo, 1969; Duray, 1990). Transport is conducted in oxygenated tanks, often with anesthetics such as MS-222 or clove oil. Although dedicated nursery protocols are limited, nursery phases are likely to improve survival and growth rates, based on analogies with other finfish species (figure 3).

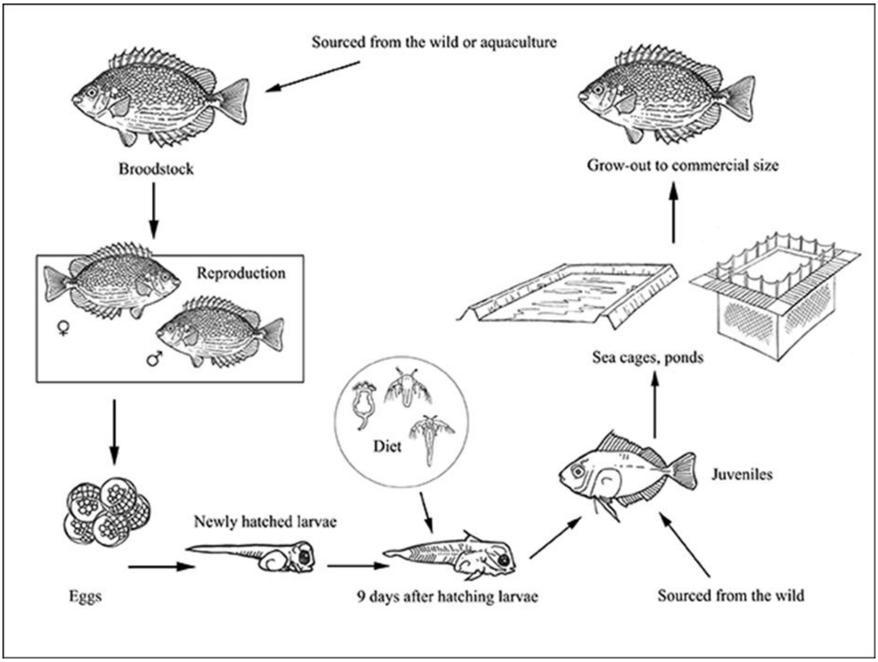

Figure 3. Production cycle

Nursery Operation in Net Cages

Rabbitfish fry should be reared in pond-based nursery net cages until they attain an average body weight of approximately 40–50 g, which is considered the ideal size for transfer to grow-out culture (SEAFDEC, 2015). Nursery facilities should be shaded using recycled or black polyethylene nets to minimize direct exposure to sunlight, as rabbitfish fry are highly sensitive to ultraviolet (UV) radiation. Adequate shading during this phase improves survival, reduces stress, and promotes uniform growth (Ragaza et al., 2017). (Figure 4).

Prior to stocking, nursery cages with a mesh size of 5 mm should be installed. Recommended dimensions are 4 m × 3 m × 1.5 m or 5 m × 5 m × 1.5 m, depending on pond size and management practices (Figures 4 and 5). The use of net cages facilitates easier harvesting of juveniles, improved feeding control, and efficient monitoring of growth and water quality (SEAFDEC, 2015).

Stocking Procedure

Fry measuring approximately 1 inch in total length should be stocked at a density of 150 individuals per cubic meter, preferably during the cooler part of the day to minimize handling stress. Prior to release, fish should be acclimatized for 20–30 minutes by floating the transport bag in the pond water and gradually adding pond water to the bag. This process equilibrates temperature and salinity between the transport medium and the pond, thereby preventing shock and mortality (FAO, 2016). (Figure 6).

Feeding Management

During the nursery phase, juveniles should be fed commercial diets containing 35–37 % crude protein and 7–8 % crude fat, administered three times daily—at 9:00 a.m., 12:00 p.m., and 5:00 p.m. (Ragaza et al., 2017; SEAFDEC, 2015). The daily feeding ration (DFR) is calculated using the following formula and adjusted monthly according to the average body weight (ABW) obtained from routine sampling:

Daily Feeding Ration (g/day)=Number of fish×Average Bod y Weight (g)×Feeding rate (%)

Daily Feeding Ration (g/day)=Number of fish×Average Bod y Weight (g)×Feeding rate (%)

Example:900 fish × 0.5g × 12% = 54 g/day 900 fish×0.5g×12% = 54g/day

When natural macrophytes such as Gracilaria spp. or filamentous algae are available (Figure 10), rabbitfish (Siganus spp.) may be fed a 50 % combination of natural algae and commercial feed. The corresponding ration for algal feed ("gulaman") can be computed as follows (SEAFDEC, 2015):

Daily Feeding Ration (gulaman, g/day)=Number of fish×A BW (g)×Feeding rate (%)×Algal

proportion (%)Dry weight (16% constant)Daily Feeding Rat ion (gulaman, g/day)=

Dry weight (16% constant)Number of fish×ABW (g)×Feedi ng rate (%)×Algal proportion(%)

Example: 900 × 0.5 × 12 % × 50 % 16% = 169g/day 16% 900×0.5 × 12% × 50% = 169g/day

Figure 4. Pond-based nursery setup at SEAFDEC/AQD's Dumangas Brackishwater Station.

Figure 5. Black polyethylene net cage (4 m × 3 m × 1.5 m).

Figure 6. Stocking procedure for rabbitfish fry in net cages.

Figure 7. Gracilaria spp. (“gulaman”) as a natural feed source.

4. HATCHERY PRODUCTION

Spawning in rabbitfishes often follows lunar cycles. Induced spawning has been achieved through hormonal injections (hCG, LHRHa), environmental cues, and dietary manipulations (Juario et al., 1985; Babiak et al., 2019). Fertilized eggs are adhesive, 0.42–0.70 mm in diameter, and hatch within 18–35 hours at 22–30 °C (Duray, 1990).

Larval survival is highly variable (0.2–38%) (CIHEAM, 2000). Salinity tolerance differs among species, e.g., S. canaliculatus tolerates 15.8–32.2 ppt (Saoud et al., 2007). Hatchery feeding protocols involve rotifers, Artemia nauplii, and formulated microdiets (Juario et al., 1985). Broodstock diets of ~42% protein sustain spawning but reduce egg quality over time (El-Dakar et al., 2011). Male spermiation remains insufficiently studied.

5. GROW-OUT and ONGROWING TECHNIQUES

The metamorphosis period differs among species: 45 days in S. guttatus (22 mm), 21 days in S. canaliculatus (20–24 mm), and 11 days in S. fuscescens (9.5 mm) (Duray, 1990). Grow-out is feasible in ponds, cages, and tanks, with species-specific tolerance. S. canaliculatus thrives at 10 ppt salinity, whereas S. rivulatus tolerates 10–50 ppt and 17–32 °C (Saoud et al., 2007; Babikian et al., 2017). (Figure 8).

Nutritional trials suggest protein requirements between 35–46% for S. javus (Parazo, 1989), while diets of 25% protein with sunflower oil support fry growth in S. canaliculatus (Monzer et al., 2017). Harvest is carried out by netting, with fish iced for transport. Venomous dorsal spines pose handling risks (Foo et al., 1985).

Figure 8. Marine cages with Siganus rivulatus in Cyprus. Courtesy of George Anastasiades, 2007.

6. DISCUSSION

Rabbitfish aquaculture lags behind carnivorous finfish due to technological and economic constraints. Primary challenges include low larval survival, lack of standardized hatchery protocols, gaps in broodstock nutrition research, and market limitations. Nonetheless, their herbivorous diet reduces reliance on fishmeal, aligning with sustainable aquaculture objectives (Ahn et al., 2020). Wide salinity and temperature tolerance make species like S. rivulatus and S. canaliculatus resilient to climate variability (Saoud et al., 2008). Compatibility with polyculture systems, such as integration with shrimp or carnivorous fish, enhances their potential for sustainable production (Luong et al., 2014; Soto, 2009).

7. CONCLUSION

Rabbitfishes are promising candidates for sustainable aquaculture in Indo-Pacific and Mediterranean regions. Their herbivory, environmental tolerance, and polyculture compatibility highlight their importance. Future research should prioritize broodstock management, larval rearing, hatchery diet formulation, and market development to unlock their commercial potential.

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PFAS FUNDAMENTALS AND TREATMENT INNOVATIONS IN AQUATIC SYSTEMS

SIBEL BARISCI

1. PFAS CHARACTERISTICS AND AQUATIC PATHWAYS

1.1 Chemical Properties

Per- and polyfluoroalkyl substances (PFAS) are widely used in the manufacturing of plastics, firefighting foams, water and stain repellents, paper coatings for food packaging, and numerous other applications. PFAS are not relatively soluble in water and might have a high affinity to sludge and sediments, resulting in the widespread dispersal in water bodies (Barisci & Suri 2021). Since the 1950s, numerous products widely utilized by consumers and industries have been produced with or contain PFAS. The distinctive physical and chemical properties of PFAS confer properties such as oil, water, and stain repellency, as well as chemical and thermal stability across a variety of applications. These substances find utility in multiple sectors, including aerospace, semiconductor manufacturing, healthcare, automotive, construction, electronics, and aviation. They are also prevalent in consumer goods, such as carpets, apparel, furniture, outdoor equipment, and food packaging, as well as in firefighting applications.

PFAS refers to a broad class of chemicals described by fully fluorinated carbon atoms of various chain lengths (i.e., $CF_3[CF_2]_n^-$). Among the most prominent examples of PFAS are perfluorocarboxylic acids (PFCAs; $C_nF_{2n+1}COOH$) and perfluorooctane sulfonate (PFOS; $C_8F_{17}SO_3^-$). These compounds are notably recognized due to their extensive detection in the global environment, as well as their presence in measurable concentrations within wildlife and human populations across both industrialized areas and regions known for PFAS emissions.

PFAS can be classified into polymer and non-polymer families. Each of these families encompasses various subgroups. Non-polymer PFAS are most frequently detected in environmental settings. However, certain PFAS, due to their stability and insolubility, have been shown to pose a lower risk to human and ecological health.

1.2 Entry Routes

PFAS have been identified universally in numerous water samples, such as drinking water (Hu et al. 2016, Sun et al. 2016), rivers (Scott et al. 2009, Kovarova et al. 2012), lakes (Giesy et al. 2006, Kim & Kannan 2007), rain (Kim & Kannan 2007, Sammut et al. 2017, Yeung et al. 2017), snow (Young et al. 2007, Kwok et al. 2013), groundwater (Backe et al. 2013, Sharma et al. 2016), coastal and offshore seawaters (Yamashita et al. 2008, Kwok et al. 2015, Wang et al. 2019). Additionally, they have been detected in the air (Shoeib et al. 2005, Barber et al. 2007), sediment (Yeung et al. 2013, Mussabek et al. 2019, Sammut et al. 2019), animal tissues (Smithwick et al. 2005, Dassuncao et al. 2019), and even human blood samples (Graber et al. 2019, Spratlen et al. 2019). Typically, C8-based compounds, namely, perfluorooctanoic acid (PFOA) and PFOS, have been the dominating compounds. The accumulation behaviour, environmental persistence, and negative health effects of

PFAS are related to the release of long-chain PFAS, which has increased the level of regulatory attention and led to the replacement of such chemicals with shorter-chain ones.

PFAS can be released to the environment during their whole life cycle, such as their production, use, and disposal of industrial and consumer products (Ahrens & Bundschuh 2014). Emission sources of PFAS can be direct and indirect. Direct emission sources include the product cycle of PFAS, and indirect sources are the transformation of PFAS precursors.

The grade of environmental impact of a PFAS source depends on various parameters, including the scale of PFAS release, the type, and concentrations of PFAS. Identifying PFAS sources in surface water is crucial for establishing effective strategies to control their release. For example, the most likely main source was the wastewater treatment plant (WWTP) effluent in Lake Michigan, U.S.A. (Simcik & Dorweiler 2005). Although industrial facilities and wastewater discharge seem to be the main sources of PFAS, atmospheric reactions of volatile fluorotelomer alcohols (FTOHs) may also produce PFAS (Ellis et al. 2004, Müller et al. 2011). For instance, some studies have reported that PFAS concentrations increase downstream of urban areas, indicating that urban activities are a source of PFAS (Kim & Kannan 2007, Sharma et al. 2016). Another study reported that surface runoff water mostly contributed to contamination by PFAS in urban lakes (Cai et al. 2012). However, the sources of PFAS in numerous rivers remain unknown due to the lack of studies.

The environmental fate of PFAS defines their transport, transformation, and partitioning processes after their release into the environment (see Fig. 1). PFAS can be discharged into the environment during their production and usage from point sources (i.e., manufacturing facilities, WWTPs, landfills, and application of aqueous firefighting foams-AFFFs) and diffuse sources, including surface runoff, atmospheric deposition, and application of biosolids.

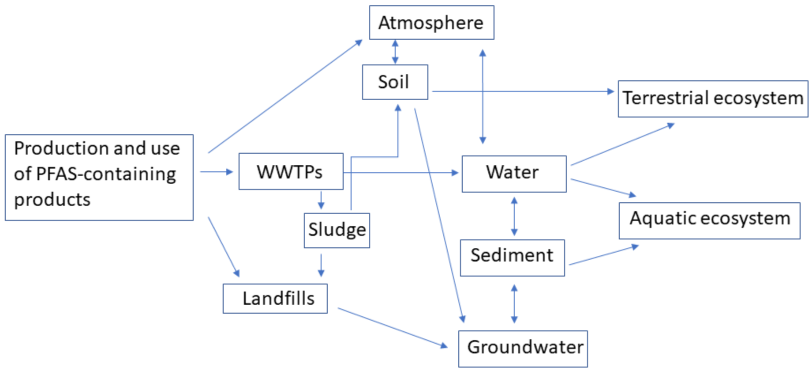

Figure 1. *Schematic of PFAS fate and transport in the environment.*

The precursors of PFAS are typically transported through the atmosphere due to their volatility and can then be degraded to PFCA and perfluorosulfonic acids (PFSA). Fig. 2 illustrates the schematic diagram of PFAS sources in remote regions resulting from atmospheric deposition. Transformation pathways of PFAS precursors in the atmosphere may vary depending on the environmental conditions (e.g., aerobic or anaerobic conditions). Furthermore, degradation intermediates (i.e., fluorotelomer carboxylic acids-FTCAs) can be formed during atmospheric transformation. These by-products have been shown to exhibit acute and chronic toxicity to aquatic organisms (Manojkumar et al. 2023). The transport processes of the final transformation intermediates occur primarily in water, but can also proceed via sea spray, gas-phase, and particle-bound transport in the atmosphere (Shoeib et al. 2005). It was stated that the long-range transport of PFCAs was 1-2 orders of magnitude higher in the water phase compared to transport in the atmosphere in remote regions such as the Arctic (Yamashita et al. 2008, Muir & de Wit 2010). However, it is still being debated whether the leading transport pathway for ionic PFAS is transport in the atmosphere or in the water phase. Atmospheric transport seems to be the dominant pathway of volatile PFAS in remote regions.

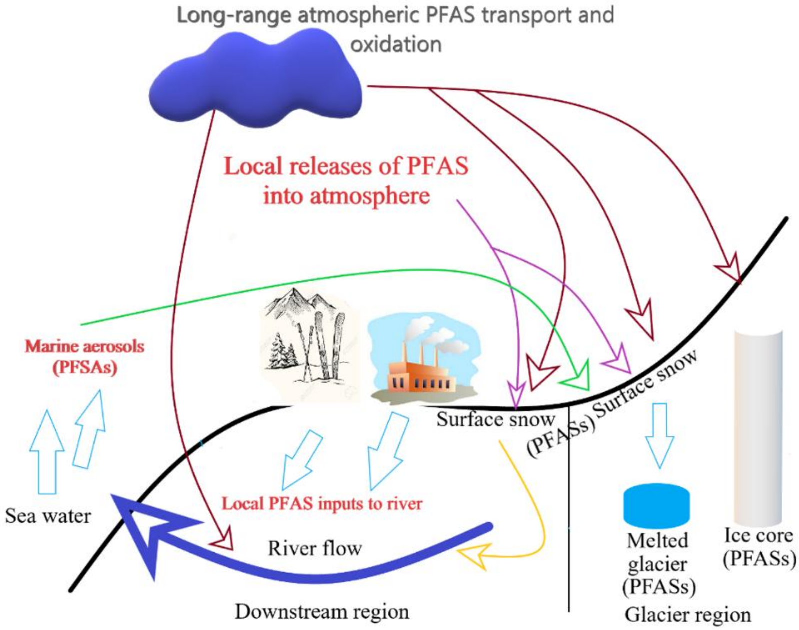

Figure 2. *Schematic of PFAS pollution sources and pathways in remote regions such as the Arctic (Adapted from (Kwok et al. 2013)).*

The environmental fate and transport of PFAS depend on various environmental conditions, including temperature, pH, concentration of atmospheric oxidants, organic carbon content, and the physicochemical properties of PFAS. The last one primarily depends on the functional groups and chain length of PFAS. For instance, while short-chain PFAS exhibit hydrophilic properties and are generally more mobile in aquatic ecosystems, long-chain PFAS are predominantly hydrophobic and tend to bind to particles, resulting in considerable bioaccumulation potential (Shi et al. 2018). Salinity may also affect the environmental fate of PFAS. It was noted that the composition of perfluoroalkyl acids (PFAAs) in two river estuaries in China differed due to independent sources and varying salinity gradients (Cai et al. 2018). This suggests that salinity may affect the fate of waterborne PFAAs, as well as the partitioning behaviour of specific compounds in certain estuarine environments. Finally, the largest global pools of PFAS appear to be in the oceans and sediments throughout the entire ecosystem.

2. TREATMENT TECHNOLOGY LANDSCAPE

2.1 Traditional Methods

Activated carbon adsorption and ion exchange resins are the primary technologies used for removing PFAS. Most full-scale treatment systems utilizing activated carbon primarily target the removal of PFAS from contaminated drinking water sources. There exists a paucity of information concerning the elimination of PFAS from industrial and municipal wastewater. The more complex matrix inherent to wastewater may impede the direct application of activated carbon for wastewater treatment; however, carbon-based adsorption may be effectively implemented following pretreatment methods and/or recovery of wastewater effluents. A correlation is typically observed between the chain length and functional groups of PFAS and the treatment efficiency (Rodowa et al. 2020). Specifically, PFAS with carboxylate groups generally exhibit lower removal efficiencies in comparison to those with sulfonate functional groups. Furthermore, the duration before column breakthrough diminishes with shorter chain lengths, suggesting that agglomeration and/or micelle formation for long-chain PFAS is less effective for PFCAs than for PFSAs (Wu et al. 2020). Current apprehensions regarding the adsorption of PFAS by carbon include the tendency of longer-chain PFAS to adsorb effectively, whereas shorter-chain PFAS may not. Additionally, the presence of competing ions adversely affects removal efficiencies (Du et al.

2014). Consequently, there is a pressing need to enhance the efficiency of activated carbon treatments while simultaneously reducing operational costs, potentially through the incorporation of pretreatment measures or the utilization of alternative sorbents.

Ion exchange resins, particularly anion exchange resins, exhibit considerable effectiveness in the removal of a wide range of PFAS from water. This efficacy can be attributed to their molecular structure, which facilitates simultaneous removal mechanisms through both anion exchange and adsorption processes. PFAS compounds consist of two distinct functional components: a hydrophobic fluorinated carbon chain (non-ionic tail) and a negatively charged functional group (anionic head). The anion exchange resin is composed of neutral co-polymers (primarily plastics) and exchange sites that carry a positive charge. The hydrophobic tail of PFAS interacts with the hydrophobic backbone of the resin, while the anionic head is attracted to the positively charged ion exchange sites (Zaggia et al. 2016, Woodard et al. 2017, Fang et al. 2023). The removal efficacy of PFAS by anion exchange resins is significantly influenced by the type and concentration of inorganic constituents in water, as well as the resin's affinity for PFAS. Certain resins demonstrate lower sensitivity to inorganic ions alongside a greater affinity for PFAS. The majority of PFAS are characterized by an anionic head; however, some molecules exhibit a cationic head, while others are zwitterionic, possessing both anionic and cationic features. Consequently, it is imperative to conduct bench-scale column tests to determine the most suitable resin for the effective removal of PFAS.

2.2 Emerging Solutions

A variety of innovative treatment technologies have been developed to effectively eliminate PFAS from various water matrices. These methodologies encompass electrochemical oxidation (EO), photocatalysis (PC) utilizing advanced semiconductors, supercritical water oxidation, plasma treatment, ultrasound applications, next-generation adsorbents, and hybrid techniques such as photoelectrocatalysis (PEC). This chapter provides a comprehensive overview of the EO, PC, and PEC technologies.

Electrochemical oxidation (EO) is an emerging method for destroying PFAS and has been employed as an effective approach for the oxidative destruction of pollutants by applying an electrical current to a solution. The notable electronegativity and electron affinity of fluorine facilitate the cleavage of the carbon-fluorine (C-F) bond, leading to the reduction of fluorine atoms when a high overpotential, exceeding 3 V, is applied (Barisci & Suri 2021). The predominant mechanism of destruction involves the sequential removal of CF_2 groups, resulting in the formation of shorter-chain PFAS until complete defluorination of the carbon chain occurs. Various electrode materials, such as boron-doped diamond (Carrillo-Abad et al. 2018, Barisci & Suri 2020, Nienhauser et al. 2022), titanium suboxides (Wang et al. 2020, Barisci & Suri 2021), and tin and lead oxides (Niu et al. 2016), have been utilized to enhance the degradation efficiency of PFAS in aqueous solutions. Furthermore, technology offers advantages since it can be operated at ambient temperature and pressure. However, EO processes are subject to diffusion limitations, resulting in remediation rates declining as PFAS concentrations decrease. Consequently, innovative designs for electrodes and reactors are critical for scaling up the treatment process. Additional challenges include mineral accumulation on the anode, the potential formation of perchlorate (Barisci & Suri 2022), and other inorganic by-products, as well as the generation of volatile by-products that require further treatment.

PFAS have presented significant environmental challenges; however, PC technologies have emerged as a promising solution for their degradation. The semiconductor most frequently employed in the photocatalytic process is titanium dioxide (TiO_2), which is valued for its abundance, cost-effectiveness, and efficiency. Nevertheless, titanium dioxide is constrained by a rapid rate of electron recombination and a large band gap energy, which necessitates the use of high-energy light sources, such as ultraviolet C (UVC) radiation, for effective operation. To overcome these challenges, the incorporation of nanomaterials, including carbon quantum dots (CQDs), has been developed to synthesize composites. The development of heterojunction composites has proven effective in enhancing charge separation and improving photocatalytic activity. While noble metals like Ag, Pb, and Pt exhibit excellent catalytic properties, their limited natural abundance, high cost, and scalability challenges can restrict their practical use in large-scale applications (Hong et al. 2023). In contrast, CQDs offer low toxicity, abundance, tunable electronic properties, and relatively low production costs, making them more favorable for scalable and sustainable photocatalytic systems (Su et al. 2023, Nejatpour et al. 2025). Constructing CQD/TiO_2 heterojunctions offers a viable strategy to overcome these limitations by facilitating efficient charge separation and extending light absorption, thereby enhancing overall photocatalytic performance (Mohery et al. 2025, Nejatpour et al. 2025). A recent study investigated the photooxidation of PFOA and short-chain PFCAs using TiO_2 and peanut shell biomass-derived carbon quantum dot (PCQD)-doped TiO_2 photocatalysts under UVC and visible light irradiation. The incorporation of PCQDs enhanced the optical properties of the composite materials, resulting in increased degradation efficiency. The PCQD/TiO_2 composite demonstrated PFOA degradation effectiveness of 78.6% under UVC irradiation and 55.0% under visible light, significantly surpassing the performance of pure TiO_2, which exhibited efficiencies of 41.0% and 24.0%, respectively. Additionally, there were substantial improvements in the degradation efficiencies for short-chain PFCAs (Ünsür et al. 2025).

PEC is an advanced hybrid methodology that integrates photocatalysis and electrocatalysis, with applications ranging from waste treatment and energy production to inactivation of microorganisms and oxidation processes. This approach encompasses various scientific disciplines, including material science, electrochemistry, solid-state physics, and optics. The principal setup for this technique involves a semiconductor that is both irradiated by light energy equal to or exceeding its band gap energy and subjected to a potential gradient. Furthermore, the semiconductor's performance can be optically enhanced through the application of photocatalyst coatings or films.

During the PEC application process, enhancing the optical, electrical, and stability properties of the photoanode is crucial. Various alternatives must be considered based on specific usage areas and conditions, including acidic environments, the necessity for low toxicity, and interactions with particular compounds and materials. Metal and half-metal oxide-based nanomaterials are utilized to enhance electrical capacities through improved charge separation, as well as to augment optical properties. Additionally, certain inert materials are favored in applications such as water treatment due to their stability under acidic and other challenging conditions. CQDs are employed to improve the band gap in photoactive applications, as they can effectively suppress electron-hole pair recombination in semiconductor and CQD nanocomposites, thereby facilitating the generation of electron-hole pairs. A study reported that PEC effectively degraded PFAS in contaminated groundwater from two wells in Italy's Veneto Region, achieving a total PFAS removal of 63–65%. Compared to photolysis and other advanced oxidation processes (AOPs), PEC demonstrated superior efficiency based on electrical energy per order metrics

(Tucci et al. 2025). The PEC process, utilizing a TiO_2 nanoporous material, demonstrates efficacy in degrading various PFAS in saline water (Thind et al. 2025). Additionally, it offers a more energy-efficient alternative compared to existing methods for PFAS elimination.

3. FISHERIES SPECIFIC CHALLENGES

3.1 Treatment Barriers

The presence of PFAS poses a significant threat to the global fisheries sector, a fundamental component of food security and coastal economies. These so-called "forever chemicals" infiltrate aquatic ecosystems through various pathways, resulting in their accumulation in fish species and jeopardizing both ecological integrity and human health and safety. Although advancements in PFAS treatment technologies have been substantial in municipal and industrial contexts, their implementation within the fisheries sector, especially in dynamic coastal and aquaculture environments, presents distinct and often underappreciated challenges. Two critical barriers dominate this struggle: high salinity may interfere in marine and brackish systems, and co-contaminant interference from microplastics (MPs) and heavy metals, which are ubiquitous in fisheries. Coastal salinity may disrupt the molecular interactions that are critical for the removal of PFAS (Jeon et al. 2011). Furthermore, MPs function as carriers, facilitating the transportation of adsorbed PFAS past conventional filtration systems (Salawu et al. 2024). The investigation into the adsorption of PFAS onto MPs has demonstrated that this process is thermodynamically spontaneous at a temperature of 25 °C, as indicated by Gibb's free energy values ($\Delta G = -16$ to -23 kJ/mol). This spontaneous adsorption is primarily attributed to an increase in entropy following the interaction. Equilibrium for the adsorption process was achieved within a timeframe of 7 to 9 hours. Consequently, PFAS are expected to partition onto the surfaces of secondary microplastics within a matter of hours in both freshwater and saline environments (Salawu et al. 2024). A recent study suggests that the adsorption of PFAS onto polymeric materials is influenced by several factors, including the type of polymer, the composition of functional groups, the polarity of the PFAS compounds, and environmental conditions such as pH. Remarkably, polyamide polymers showed much higher adsorption rates for numerous PFAS compounds (Freilinger et al. 2025). Additionally, heavy metals, which frequently coexist with PFAS in proximity to fishing hubs, compromise treatment efficacy due to competitive binding and chemical interference (Tshangana et al. 2025). Collectively, these factors may result in a reduction of PFAS removal rates by 30-60% in actual fisheries compared to controlled laboratory settings. However, recent research presents encouraging findings regarding the treatment of PFAS in seawater. The study indicates that employing a controlled gas flow of 1 to 4 liters per minute can achieve the removal of over 90% of perfluorooctanoic acid (PFOA) and perfluorooctane sulfonate (PFOS) through the foam fractionation method utilizing both air and ozone (O'Connor et al. 2020). Foam fractionation capitalizes on the surfactant characteristics of PFAS, thereby promoting their aggregation at the surface of bubbles introduced into the contaminated liquid. The process referred to as "ozofractionation," as examined in this research, reveals that the inclusion of ozone significantly enhances the overall efficacy of the method. It is imperative, however, to monitor ozone concentrations to ensure compliance with acceptable thresholds for aquaculture applications. A recent study evaluated the degradation of PFAS in seawater using the PEC process. The findings indicated a substantial enhancement in photocatalytic reactivity in both distilled water and seawater across various salinity levels. These results demonstrate that the PEC process is effective in destroying multiple PFAS compounds with notable energy efficiency. Furthermore, the defluorination of PFAS chains was successfully achieved (Thind et al. 2025).

3.2 Cost Analysis

The cost of treatment for the removal of PFAS represents a critical factor for large-scale applications. The majority of PFAS removal projects that have reported treatment costs primarily focus on long-chain PFAS, including PFOS and PFOA. These compounds are typically among the more manageable PFAS to eliminate from water due to their relative hydrophobic nature. In contrast, certain PFAS, such as fluorinated gases, present significant challenges due to the lack of established technologies for their effective removal and destruction from environmental media, resulting in the absence of reliable cost estimates for remediation efforts (Evich et al. 2022).

The expenses related to the removal and destruction of PFAS from environmental media are dependent on the specific media being addressed and the technologies utilized in the process. Nevertheless, current analyses are confined to environmental media where treatment applications have been sufficiently developed to yield accurate cost assessments and PFAS destruction rates at larger scales. According to the study, estimated costs per kilogram of PFAS removed and destroyed from environmental media range dramatically from \$0.9 to \$67 million USD (Ling 2024). However, this analysis does not address the costs associated with exposure to PFAS, which are extensive, long-term, and typically externalized onto the public, disproportionately impacting affected communities. For example, a recent evaluation of the health impacts of PFAS exposure in Europe recognized direct annual healthcare expenditures ranging from €52 billion to €84 billion (Cordner et al. 2021). Additionally, there are other externalized costs to consider. For instance, a public wastewater utility in Merrimack, New Hampshire, produces \$400,000 yearly from processing sludge into compost as fertilizer. Should the utility be unable to sell the contaminated sludge due to PFAS issues, it will incur an annual expense of $2.4 million in landfill fees. Therefore, it is essential to expand research efforts aimed at estimating the costs associated with the treatment of PFAS from contaminated media and to compare these costs with the externalized expenses. Preliminary assessments suggest that the costs of PFAS treatment will be significantly lower than the costs associated with health issues stemming from exposure, such as consuming contaminated fish. Furthermore, research into replacing PFAS with safer alternatives should be prioritized as a crucial area of study.

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GOVERNANCE AND INSTITUTIONAL FRAMEWORK OF THE FISHERIES SECTOR IN TÜRKIYE

DENIZ GÜNAY
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Introduction

The fisheries sector holds critical importance in terms of global food security, economic development, and ecosystem health. This sector encompasses multidimensional activities such as capture fisheries, aquaculture, processing, and marketing, thereby necessitating the sustainable management of natural resources (FAO, 2024). For countries like Türkiye, endowed with dynamic marine and inland water resources, the full realization of this sector's potential is directly associated with an effective governance system and institutional framework. Policies, legislation, and implementation processes in the field of fisheries are generally shaped through ministries within the central administration and the affiliated or related public institutions under their authority. This institutional and governance framework fulfils key functions vital to the sustainability of the sector, ranging from regulation and development to resource conservation and the promotion of innovation.

However, the complex and multidisciplinary nature of the fisheries sector occasionally challenges the effectiveness of governance structures. Fisheries management requires a balance between ecological sustainability and socio-economic equity, which in turn necessitates coordinated efforts among different ministries and public institutions (Şakıma & Çevrimli, 2021). In the specific case of Türkiye, the historical transfer of fisheries management responsibilities among different ministries, along with occasional disputes over authority, further underscores the need to examine the institutional framework. An effective governance system should support decision-making processes grounded in scientific evidence, ensure stakeholder participation, and provide mechanisms that prevent the misallocation of resources.

In this context, the institutional structure and organization of the fisheries sector should be examined comprehensively through the ministries and relevant public institutions in Türkiye. An analysis of the existing institutional arrangements and the distribution of responsibilities is crucial for understanding the challenges faced by the sector as well as identifying potential solutions. The current administrative structure is capable of taking into account dynamics such as sectoral growth and the process of harmonization with EU legislation (Öztürk & Yılmaz, 2020). This study aims to determine the current situation and to assess the strengths and weaknesses of the system from a scientific perspective. In this regard, it first examines the historical and legal framework of fisheries management, outlining the institutional evolution. The mandates and responsibilities of key public institutions—including the Republic of Türkiye Ministry of Agriculture and Forestry Ministry of Agriculture and Forestry (MAF), the General Dırectorate of State Hydraulıc Works State Hydraulic Works (DSI), the Republic of Türkiye

Ministry of İnterior Turkish Coast Guard Command, research institutes, and universities—are discussed in detail. Their roles in legislation drafting, monitoring, resource conservation, and development activities are analyzed. Based on relevant laws, regulations, and institutional strategy documents, the study also evaluates the differences between official frameworks and actual practices.

Ultimately, this book chapter focuses on the decisive role of institutional effectiveness in the sustainability and competitiveness of the fisheries sector. It seeks to discuss the requirements of an ideal institutional model for fisheries management and to propose policy recommendations regarding the existing structure in Türkiye. By offering a scientifically grounded perspective on improving institutional governance practices in fisheries, this study aims to make a valuable contribution to the literature for sector stakeholders, policymakers, and the academic community.

Theoretical Framework: Institutional Structure and Organization

Institutional structure refers to the systematic arrangement of duties, authorities, responsibilities, and hierarchical relations in order to achieve an organization’s fundamental goals and objectives (Çamur, 2020). This structure regulates the institution’s interaction with its internal and external environment, ensures the efficient use of resources, and guarantees transparency and accountability in decision-making processes. In public administration, institutional organization is primarily determined by laws, statutes, and regulations; this normative framework clearly defines the purpose for which the institution was established, to whom it is accountable, and which powers it may exercise. In a sector such as fisheries, which involves dynamic and biological resources, it is of great importance for the institutional structure to be flexible, evidence-based, and sustainability-oriented (Eger et al., 2021; Sønvisen & Vik, 2021).

In Türkiye, the institutional framework of the fisheries sector has largely been shaped by the Fisheries Law No. 1380 (Official Gazette, 1971) and the Fisheries Regulation issued under this Law (Official Gazette, 1995). These legal provisions define the boundaries of capture, aquaculture, processing, marketing, and monitoring activities, while designating central administration as the competent authority. Within the central administration, the MAF assumes the primary responsibility for fisheries, alongside agricultural and livestock policies and the protection and development of water resources. This legal foundation defines the roles of all other public institutions in the sector in line with the authority of the Ministry.

1. Ministry of Agriculture and Forestry: The Central Authority of Power

Republic of Türkiye Ministry of Agriculture and Forestry (MAF) represents the highest-level authority in policymaking and oversight within the fisheries field. It is organized hierarchically in order to achieve its institutional objectives, with a structure composed of central, provincial, and affiliated bodies (see Figure 1). Personnel within both the central and provincial units carry out direct inspections. Additionally, other public authorities—including the Coast Guard Command, the Gendarmerie, the Police, Customs, and Municipal Police—are also vested with inspection authority under the Fisheries Law No. 1380.

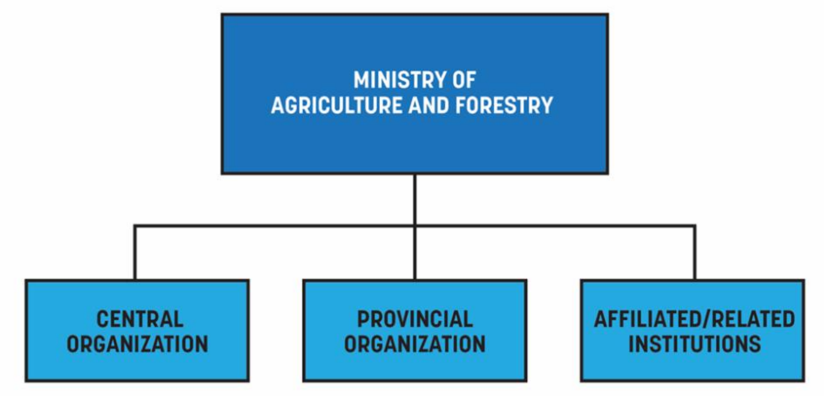

Figure 1. Organizational structure of the Republic of Türkiye Ministry of Agriculture and Forestry

Within the Ministry's central organization, the General Directorate of Fisheries and Aquaculture (GDFA) is directly responsible for the preparation of fisheries policies, the development of legislation, and the determination of implementation standards. The duties and powers of the GDFA are elaborated particularly in the relevant articles of the Fisheries Law, the Law No. 3046 on the Financial Rights of Deputy Ministers and Certain Regulations (Official Gazette, 1984), and Presidential Decree No. 1 on the Organization of the Presidency (Official Gazette, 2018). These powers include: developing policies for the conservation and sustainable exploitation of fisheries resources; conducting or commissioning stock assessments and research; preparing fishing regulations (such as bans, seasons, mesh size requirements, etc.); setting quotas and catch limits; issuing and monitoring fishing licenses; overseeing authorization processes for aquaculture (including site selection, capacity, and environmental impact); conducting studies in line with international agreements and the EU harmonization process; and coordinating inspection and control activities (with the Coast Guard Command, the Gendarmerie, etc.).

In exercising its authority, the GDFA generally takes into account international standards, such as the European Union Common Fisheries Policy (CFP), as well as scientific reports when issuing regulatory acts (Düzgüneş et al., 2015; Ak & Balık, 2020). The Communiqués issued by the Directorate (e.g., those regulating commercial and recreational fishing) and Guidelines constitute the legal basis for all sectoral activities. These communiques operationalize sustainable fisheries management by regulating technical details such as closed seasons, minimum catch sizes, and gear standards.

The provincial and district directorates of the MAF, which form the Ministry's local organization, are the key units that implement central policies in the field. These directorates carry out licensing, inspection, training, and extension activities through direct contact with producers and fishers. They derive their authority from regulations, communiqués, and guidelines issued by the Ministry and, in particular, conduct food safety inspections of fisheries processing facilities within the framework of the Law No. 5996 on Veterinary Services, Plant Health, Food, and Feed (Official Gazette, 2010). At the same time, these local units provide feedback to the central administration by reporting field-level information, thereby contributing to the policy-making process.

2. Affiliated and Related Institutions: Supportive and Regulatory Roles

In addition to the MAF, several affiliated and related institutions play significant roles in supporting and regulating Turkey's fisheries sector. The General Directorate of State Hydraulic Works (DSI) holds a critical position in the management and allocation of inland water resources, including dams, reservoirs, and rivers. Pursuant to Law No. 6200 (Official Gazette, 1953), DSI is responsible for controlling the water regime in inland waters and is required to consider its impacts on aquaculture and fish stocks. DSI's planning and infrastructure projects directly affect the fisheries sector, particularly regarding fish passages, water quality, and the protection of aquatic habitats.

The Scientific and Technological Research Council of Turkey (TUBİTAK) and universities serve as the principal institutions providing research and development (R&D) and scientific support for the sector. Their roles are primarily focused on knowledge generation and technology transfer rather than regulation. Through their Faculties of Fisheries, universities contribute to human resource development, while TUBİTAK funds scientific research projects on aquaculture technologies, stock assessment, and disease control. The scientific outputs generated by these institutions serve as key inputs for the GDFA in policymaking and management decisions.

Fisheries Research Institutes operate as specialized regional units conducting applied research on fisheries biology, stock assessment, aquaculture, and fish health. Directly affiliated with GDFA, these institutes develop region-specific management plans supported by scientific reports and provide the technical basis for establishing fishing quotas. Within the limits set by law and secondary regulations, they function as practical sources of knowledge for the sustainable management of regional aquatic resources.

Fisheries cooperatives and associations are essential institutions supporting fishers' production activities, promoting collective organization in marketing processes, and protecting their economic interests (Doğan, 2017). These organizations play a key role in promoting sustainable fishing, managing common-use areas, and facilitating access to state subsidies. Moreover, cooperatives act as an interface between fishers and public authorities, contributing to the enhancement of institutional capacity within the sector.

3. Local Institutions: Implementation and Environmental Contributions

Beyond central and affiliated institutions, local governments also play supportive and supervisory roles in the fisheries sector. Under the framework of the Municipal Law No. 5393 (Official Gazette, 2005) and related regulations, local administrations contribute indirectly through the management of fishing shelters, regulation of fish markets, and environmental inspections—particularly concerning water pollution control. Although their legal competences are generally limited to urban infrastructure, environmental protection, and public health, their actions significantly affect the daily commercial and operational activities of fishers. At the provincial level, directorates and municipalities ensure environmental compliance through field inspections and enforcement. At this stage, the Ministry of Environment, Urbanization and Climate Change provides an additional framework for the protection of aquatic ecosystems, prevention of pollution, and mitigation of climate change impacts on the sector. The institutional structure governing Turkey's fisheries sector represents a complex system woven around the centralized authority of the MAF, with multiple institutions operating under various legal mandates. Effective governance requires robust coordination and information exchange among GDFA's policymaking authority, DSI's water management functions, the scientific data produced by research institutes, and the field-level enforcement carried out by local governments (Mumlu, 2024; Aküzüm et al., 2010). Strengthening institutional effectiveness depends on the establishment of mechanisms that promote interagency coordination without exceeding the legal boundaries of each actor's mandate.

Institutional Relations in Fisheries Governance

Effective management and coordination in the fisheries sector require a clearly defined institutional hierarchy and well-structured horizontal linkages. The organizational framework, centered on the MAF—the main authority in the sector—illustrates the chain of command and functional division extending from decision-making to field implementation. This structure is based on the principles of accountability and delegation of authority (Şamdan, 2023).

Central Authority and Steering Function

At the top of the organizational hierarchy stands the MAF, who serves as the highest political authority and decision-maker within the Ministry. In accordance with Presidential Decree No. 1 on the Organization of the Presidency, the Minister holds ultimate responsibility for approving fisheries policies and providing strategic direction. The Minister defines the overall sectoral vision and ensures the legal and administrative legitimacy of subordinate units.

Directly beneath the Minister, GDFA operates as the primary technical and administrative executive body responsible for implementing fisheries legislation and policies. The Directorate coordinates with other general directorates within the Ministry—such as legal, foreign relations, and inspection units—as well as with external stakeholders. It functions as the central hub of communication and coordination within the fisheries governance framework.

Specialization and Departmental Structure

Given the complex and multidisciplinary nature of its mandate, the GDFA is organized into four specialized departments, each focusing on a distinct functional domain. This specialization enhances the effective and targeted use of institutional resources (Özkan, 2022). The departmental divisions within the Ministry foster sectoral expertise and establish a bridge between policy formulation and implementation. Organizational chart showing the hierarchical structure of the GDFA under the Ministry of Agriculture and Forestry of the Republic of Türkiye (Figure 2). The GDFA oversees various departments responsible for policy development, resource management, aquaculture and processing, inspection and control, and provincial agricultural directorates, which include Fisheries Branch Directorates.

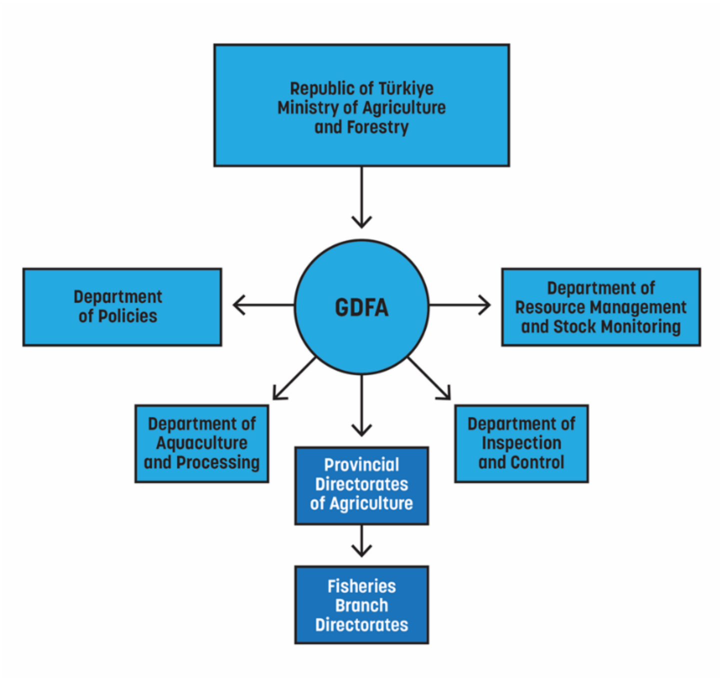

Figure 2. Organizational Structure of the General Directorate of Fisheries and Aquaculture

Department of Fisheries Policy

This department is responsible for formulating medium- and long-term strategies for the sector, coordinating national policies, and aligning them with the European Union's Common Fisheries Policy. Its primary functions include drafting legislation, ensuring compliance with international agreements, and preparing strategic planning documents.

Department of Aquaculture and Processing

This unit focuses on the development of aquaculture, including species selection, disease control, and the adoption of new production technologies. It also provides guidance on the post-harvest processes of processing, storage, and marketing. Although the enforcement of food safety standards primarily falls under the jurisdiction of the General Directorate of Food and Control, this department coordinates and facilitates aquaculture-related activities within the sector.

Department of Inspection and Control

This department manages licensing procedures, monitors fishing quotas, and coordinates fisheries inspections. It develops control mechanisms to combat illegal, unreported, and unregulated (IUU) fishing. Its authority is primarily derived from the Fisheries Law No. 1380, while administrative sanctions are applied in accordance with the Misdemeanors Law No. 5326.

Department of Resource Management and Stock Monitoring

This department is responsible for the scientific monitoring and assessment of fish stocks in marine and inland waters. It provides the scientific foundation for fishing bans, quotas, and other conservation measures. The department cooperates closely with

Fisheries Research Institutes and supports stock monitoring programs in line with FAO and EU standards.

Provincial Organization: Implementation and Field Communication

The Provincial Organization represents the most critical link between decision-making and field implementation. The central authority transmits its directives to the field through the Provincial Directorates, which exercise both the Ministry's and the General Directorate's powers at the provincial level. Their responsibilities include licensing, establishing local inspection teams, and conducting training programs. These duties are delegated further to District Directorates, which maintain the closest contact with producers, fishers, and other local stakeholders. The ultimate purpose of this hierarchical structure is to ensure a legally compliant and sustainable production–consumption chain, corresponding to the field-level interaction described as Producer–Consumer Communication in the organizational framework.

Inter-Agency Relations (Horizontal Coordination)

Although the organizational chart reflects a hierarchical chain of command, effective governance of the fisheries sector requires strong horizontal coordination among institutions. For instance, the General Directorate of State Hydraulic Works (DSI) maintains continuous collaboration with GDFA on the allocation of inland water resources. TÜBİTAK and universities provide scientific data and R&D support, particularly to the Departments of Resource Management and Aquaculture. The Coast Guard Command cooperates with the Department of Inspection and Control to conduct maritime surveillance and combat IUU fishing. These inter-agency relationships are formalized through protocols and annual coordination meetings, ensuring a holistic and integrated approach to fisheries governance (MAF, 2023).

The Ministry of Trade oversees export, import, and customs processes, facilitating the integration of Turkish fishery products into global markets. The Ministry of Transport and Infrastructure contributes to the safety and efficiency of the supply chain through logistics, port infrastructure, and distribution networks, thus creating a functional synergy between economic objectives and physical infrastructure.

Inter-institutional coordination in the sector operates through multi-layered mechanisms. The Turkish Statistical Institute (TSI) compiles production, catch, consumption, and trade data, thereby supporting evidence-based policy formulation. Collaborations with the Ministry of Environment, Urbanization and Climate Change strengthen the ecological dimension of governance, ensuring that fisheries management in Turkey addresses not only economic efficiency but also environmental sustainability.

Conclusion

The institutional and governance structure of Türkiye's fisheries sector represents a highly centralized yet functionally diversified system. MAF, through the General Directorate of Fisheries and Aquaculture (GDFA), plays a pivotal role in policy formulation, implementation, and coordination. This centralized authority has enabled consistency in regulatory standards and the alignment of national practices with international frameworks such as the FAO's Code of Conduct for Responsible Fisheries and the European Union's Common Fisheries Policy (FAO, 2024; Düzgüneş et al., 2015; Ak & Balık, 2020). However, the sector's complexity—encompassing capture fisheries, aquaculture, processing, and marketing—necessitates robust horizontal coordination among institutions with overlapping responsibilities, including DSI, TSI, the Coast Guard Command, and local administrations (Şakıma & Çevrimli, 2021).

Findings indicate that although Türkiye possesses an extensive legal foundation through the Fisheries Law No. 1380 and related regulations, gaps persist between institutional design and practical implementation. The interagency coordination mechanisms remain partially fragmented, particularly between resource management and enforcement domains. Strengthening data integration, ensuring the scientific use of monitoring outputs, and harmonizing inter-ministerial processes are vital steps toward achieving institutional coherence and sustainability (Öztürk & Yılmaz, 2020; Twelfth Development Plan, 2023).

From a governance perspective, the effective functioning of the fisheries sector depends not only on hierarchical authority but also on participatory and evidence-based decision-making. Incorporating scientific research outputs from universities and research institutes into policy cycles, expanding the role of cooperatives in community-based resource management, and improving feedback loops between provincial and central units are key for adaptive governance. These measures align with the FAO's "Blue Transformation" vision, which promotes productivity, sustainability, and resilience across the fisheries and aquaculture sectors (FAO, 2022).

In conclusion, Türkiye's fisheries governance framework demonstrates both structural capacity and areas for reform. Future policy efforts should focus on:

1. Enhancing institutional coordination through integrated data and management systems.

2. Establishing multi-stakeholder platforms for participatory decision-making.

3. Reinforcing the scientific basis of fisheries management through sustained collaboration between GDFA and research institutions.

4. Promoting decentralized, ecosystem-based management in line with international commitments.

By advancing institutional efficiency and interagency synergy, Türkiye can strengthen its transition toward a sustainable, competitive, and resilient fisheries sector that contributes to both national food security and the global blue economy.

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POSITIVE CONTRIBUTIONS OF BIVALVES TO CLIMATE CHANGE MITIGATION AND THE POTENTIAL OF ECOCULTURE

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1.INTRODUCTION

Over the past century, climate change has intensified as a result of human-driven factors such as industrial growth, fossil fuel consumption, urbanization, and land degradation. These pressures now pose serious risks, particularly to marine and coastal

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ecosystems. The most visible consequences include rising global temperatures, melting glaciers, sea-level rise, irregular rainfall, ocean acidification, and the increasing frequency of extreme weather events. Such changes not only reshape terrestrial environments but also alter the biological, chemical, and physical balance of marine systems, influencing species distribution, reproduction, metabolism, and survival (IPCC, 2023).

Between 1982 and 2023, the Mediterranean Sea experienced a steady increase in sea surface temperature anomalies, with warming rates surpassing the global mean. Long-term observations from the Copernicus Marine Service show that the region's annual average temperature has risen by about 0.041 ± 0.001 °C (Figure 1). This warming trend has particularly affected organisms sensitive to thermal stress, causing biodiversity declines and reducing the efficiency of production systems (Pastor et al., 2020).

At the same time, atmospheric CO_2 levels have climbed to roughly 420 ppm, altering ocean chemistry and intensifying acidification. This shift is especially harmful to calcifying organisms, as it weakens shell and skeletal formation (Gattuso et al., 2015). Changes in salinity, reductions in dissolved oxygen, and shifts in phytoplankton communities have further disrupted marine food webs.

Within this framework, bivalves—both from natural populations and aquaculture—stand out as a key element of nature-based strategies to buffer climate impacts. Through their filter-feeding activity, these organisms remove excess phytoplankton and suspended particles, create habitats that support biodiversity, store carbon through shell formation, and contribute to biogeochemical cycles (Van der Schatte Olivier et al., 2018). Their low dependence on external feed and naturally small carbon footprint also make them an environmentally responsible protein source.

Overall, bivalves deliver diverse ecosystem services that align with the objectives of the blue economy, such as sustainable coastal management, integrated production models, and carbon mitigation. In semi-enclosed basins highly exposed to climate change—like the Mediterranean—promoting bivalve ecoculture can therefore serve as a strategic pathway toward food security and ecosystem resilience (Gentry et al., 2017).

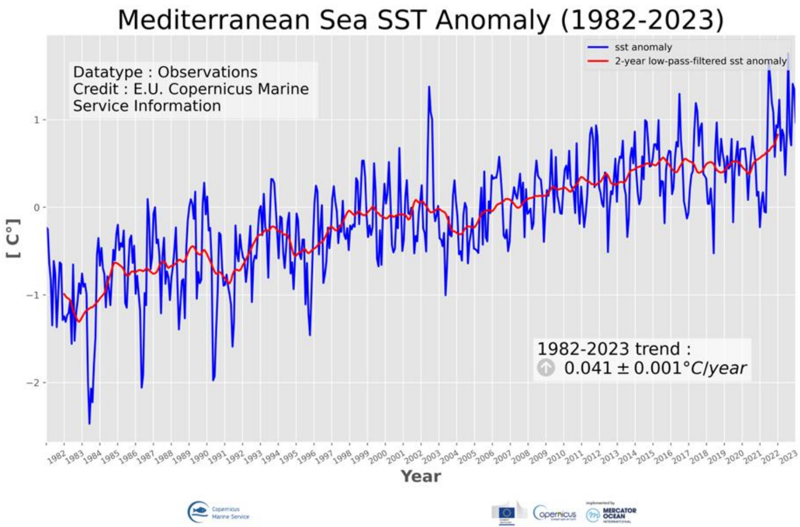

Figure 1. Sea Surface Temperature Anomalies in the Mediterranean (1982–2023). Data obtained from the E.U. Copernicus Marine Service. The graph illustrates the pronounced warming trend in the region (0.041 ± 0.001 °C/year).

2.ECOSYSTEM SERVICES OF BIVALVES

2.1.NUTRIENT REMEDIATION (NITROGEN AND PHOSPHORUS REMOVAL)

Through their remarkable filtration capacity, bivalves remove excess nutrients—particularly nitrogen and phosphorus—from the water column, thereby reducing the risk of eutrophication. For instance, in *Crassostrea virginica*, individual removal rates have been measured at approximately 2.1 g nitrogen/year and 0.35 g phosphorus/year (Newell, 2004). **Table 1** provides a comparative overview of nutrient removal capacities among various bivalve species.

Table 1. Nutrient Removal Capacities of Selected Bivalve Species

Species	Nitrogen Removal (g/ind./year)	Phosphorus Removal (g/ind./year)	Filtration Rate (L/hour)	Source
Crassostrea virginica	2.1	0.35	1.8-2.5	Newell (2004)
Mytilus sp.	1.7	0.28	1.2-1.8	Petersen et al. (2018)
Ruditapes philippinarum	0.8	0.19	0.5-1.5	Nizzoli et al. (2011)

2.2.CARBON SEQUESTRATION AND SHELL ACCUMULATION

Bivalves play a dual role in the marine carbon cycle. Through their filter-feeding activity, they help reduce the amount of organic carbon suspended in the water column, while their shells—composed of biogenic calcium carbonate ($CaCO_3$)—act as a long-term carbon sink. These combined functions make bivalves valuable contributors, offering both biochemical and structural pathways to address climate change.

The process of carbon sequestration through shell formation is especially significant in aquaculture systems (Feng et al., 2022; Song et al., 2024; Liang et al., 2024). For instance, large-scale mussel and oyster farms along the Chinese coast are estimated to store around 50,000 tons of carbon equivalent per year in their shells

(Zhang et al., 2017). Roughly 60% of this carbon is locked in the shell material itself, while the remainder is linked to tissues and surrounding environmental interactions. Studies further indicate that the creation of one ton of shell corresponds to approximately 0.44 tons of stable carbon storage (Filgueira et al., 2015). When managed responsibly, these biogenic carbon stocks can persist within sediments for thousands of years. In doing so, they not only sequester carbon but also enhance habitat heterogeneity, supporting higher levels of biodiversity in coastal ecosystems (Olivier et al., 2018).

Tamburini et al. (2022) reported that during the growth of clams and mussels, shell formation captures about 254 g and 146 g of CO_2 per kilogram of harvested product, respectively, whereas farming operations emit only 22 g and 55 g CO_2 equivalents. On a larger scale, shellfish aquaculture in Norway contributes to the sequestration of nearly 6.3×10^5 tons of CO_2 per year (Filgueira et al., 2019). Similarly, mariculture systems in China are estimated to reduce atmospheric CO_2 by approximately 0.0125% (Li et al., 2014).

Beyond chemical sequestration, bivalves also stabilize sediments through shell accumulation. The natural reefs they form can dissipate wave energy, reducing coastal erosion and creating microhabitats for a variety of marine species. In this way, carbon sequestration functions both as a biochemical process and as a form of physical ecosystem engineering.

The potential of bivalve aquaculture has also drawn attention from the carbon credit sector. It is estimated that a one-hectare oyster farm can capture around 5 tons of CO_2-equivalent carbon annually (Filgueira et al., 2015). Nevertheless, challenges remain in accurately quantifying and verifying the long-term stability of these carbon pools (Macreadie et al., 2019). Recent pilot studies by the FAO (2022b) have made progress toward establishing standard methodologies in this field.

Overall, these findings underline the emerging recognition of bivalve aquaculture as a nature-based solution for carbon management. Beyond its role in food production, it offers meaningful contributions to climate adaptation, habitat restoration, and carbon footprint reduction.

3.CLIMATE RESILIENCE AND PHYSIOLOGICAL RESPONSES

Bivalves demonstrate remarkable tolerance to a variety of environmental stressors and can adjust their metabolism and behavior to cope with changes in salinity, temperature, pH, and oxygen availability. These flexible responses contribute to their persistence and ecological importance in coastal ecosystems that are increasingly affected by climate change.

Studies on species such as Ruditapes decussatus have shown that temperature and salinity strongly influence metabolic activity and growth. Rato et al. (2022) found that this species maintained physiological stability over a wide range of conditions (5–35°C and 0–40‰), with optimal performance between 20–35‰. Such findings indicate that, under suitable environmental thresholds, bivalve aquaculture can remain productive even as climatic variability increases.

At the molecular level, recent research highlights the ability of bivalves to reorganize their microbial communities when exposed to stress. Shifts in the microbiome, often triggered by heat or low-oxygen conditions, have been linked to altered immune functions and improved resistance to environmental fluctuations (Masanja et al., 2023; Lokmer & Wegner, 2014). Morphological changes, such as variations in shell thickness or microstructure, have also been documented in response to environmental stressors, reflecting an additional level of phenotypic plasticity.

Overall, these physiological and microbial adjustments underline the adaptive potential of bivalves. Their resilience mechanisms—ranging from behavioral responses to microbiome restructuring—play a crucial role in sustaining both natural populations and aquaculture systems under ongoing ocean warming and acidification.

4.FIELD APPLICATIONS AND MANAGEMENT STRATEGIES

4.1.DESIGN FOR BIOREMEDIATION

Bivalve aquaculture systems are used not only for production but also for ecosystem restoration. Species such as mussels, oysters, and scallops are strategically deployed in coastal areas to improve water quality, effectively controlling particulate matter, phytoplankton, and dissolved organic substances.

For instance, in the United States, the “Oyster Restoration” projects in Chesapeake Bay have demonstrated significant improvements in water quality through the reestablishment of natural oyster populations, integrated with blue carbon strategies. It has been reported that the introduction of 10 billion oysters in the bay resulted in a 20% reduction in nitrogen levels.

4.2.INTEGRATED MULTI-TROPHIC AQUACULTURE (IMTA)

In IMTA systems, bivalves utilize waste generated by higher trophic-level fish species (e.g., gilthead seabream and European seabass) as a nutrient source, creating a circular production system. These systems are highly effective in reducing organic loads, preserving biodiversity, and minimizing the environmental impacts of aquaculture operations.

In Canada, IMTA projects integrating *Mytilus edulis* and *Crassostrea virginica* with salmon cages showed both increased biomass productivity and a substantial reduction (30–40%) in nitrogen and phosphorus levels in the water (Chopin et al., 2013). Similarly, in the Mediterranean, integrating bivalve cultivation with seabream and seabass cage farms is expected to reduce organic loads and carbon emissions, while simultaneously generating economic benefits through increased biomass production.

5.REGIONAL AND GLOBAL SIGNIFICANCE

5.1.SUSTAINABLE FOOD SOURCE

Bivalves offer high-efficiency sources of animal protein with low environmental costs. The resources required to produce 1 kg of mussel meat are substantially lower than those needed for beef production. Moreover, their growth without feed inputs makes bivalves one of the protein sources with the lowest carbon footprint. Producing 1 kg of mussels generates 20 times less CO_2 emissions compared to 1 kg of beef (FAO, 2022a).

According to FAO (2022a), global bivalve production has exceeded 17 million tons, with approximately 90% derived from aquaculture. This underscores the strategic importance of bivalves in ensuring food security and the sustainability of the human food chain.

5.2.COASTAL PROTECTION

Bivalve reefs—particularly oyster and mussel reefs—act as ecological engineering structures that absorb 60–80% of wave energy along coastlines, preventing coastal erosion (Scyphers et al., 2011). These natural barriers protect shoreline habitats while mitigating the destructive impacts of extreme weather events such as tsunamis, cyclones, and storm surges associated with climate change.

Unlike traditional concrete structures (e.g., seawalls, breakwaters), bivalve reefs provide ecosystem services and are self-sustaining living structures, making them essential components of sustainable coastal management. Bangladesh, one of the countries most vulnerable to climate change, has implemented pilot projects employing ecosystem-based bivalve barriers instead of conventional hardened structures. In the Gulf of Mexico, oyster reefs constructed along the Louisiana coast have prevented shoreline retreat by up to 3 meters per year and increased local fisheries income by approximately 20% (La Peyre et al., 2014).

In the Netherlands, strategies such as "Room for the River" and "Building with Nature" have integrated living coastal systems, establishing soft barrier systems reinforced with mussel banks along the Zeeland coast. These initiatives provide multifunctional benefits, including physical protection, habitat enhancement, carbon sequestration, and recreational opportunities.

Bivalve reefs also enhance local marine biodiversity by providing habitat for resident species, increasing ecosystem resilience. Studies show that areas with reefs exhibit 30–50% higher diversity of fish and invertebrate species (Grabowski & Peterson, 2007). Collectively, these findings demonstrate that bivalve reefs are not merely structures that reduce wave energy, but also nature-based solutions and critical components of ecological infrastructure. Thus, integrating bivalves into coastal management plans is of strategic importance for climate adaptation.

5.3.ECONOMIC CONTRIBUTIONS AND CARBON CREDIT POTENTIAL

Bivalve aquaculture is gaining increasing economic significance beyond being a traditional livelihood for coastal communities. In developing countries, small-scale aquaculture provides vital employment and income opportunities for local populations.

Recently, the carbon sequestration potential of bivalve farming has received growing attention. Studies have shown that significant amounts of carbon can be stored in bivalve shells and tissues. For example, a 1-hectare oyster farm can sequester approximately 5 tons of CO_2-equivalent carbon annually (Filgueira et al., 2015). This potential makes bivalve aquaculture an attractive option for carbon credit systems.

However, there are considerable technical and methodological challenges in implementing bivalve-based carbon credit schemes. The main challenge lies in verifying and monitoring the long-term storage of carbon within bivalve shells. Existing carbon certification programs primarily focus on other blue carbon ecosystems such as mangroves and salt marshes (Macreadie et al., 2019). Standardized methodologies need to be developed to include bivalve systems in these programs.

Promising progress is underway. The FAO initiated a pilot program in 2022 to support the development of bivalve-based carbon methodologies (FAO, 2022b). Similarly, in Galicia, Spain, certification schemes have been launched to offset the carbon footprint of mussel farms. These developments indicate that, in the coming years, bivalve aquaculture could provide an additional income stream through carbon credits.

6.CONCLUSION

Bivalves are increasingly recognized not only as organisms resilient to climate change but also as nature-based solutions that contribute to the carbon cycle, regulate nutrient excess, and protect coastal habitats. Their ecosystem services encompass a wide range of functions, including carbon sequestration, nitrogen and phosphorus removal, bioremediation, habitat formation, coastal protection, and sustainable food production.

In this context, the expansion of bivalve aquaculture represents a multifunctional strategy offering cost-effective, integrated solutions for climate change mitigation. Sustainable production models, such as Integrated Multi-Trophic Aquaculture (IMTA), enhance economic returns while minimizing environmental footprints. Moreover, the potential integration into carbon credit systems positions bivalve production not only as a food industry but also as a provider of ecosystem services and a participant in carbon markets.

Future advancements in this field should be supported through multifaceted scientific and management actions, including:

- Detailed determination of the environmental tolerance ranges of bivalve species,
- Clarification of the contributions of microbial interactions to ecosystem health,
- Strengthening collaborations among local authorities, producers, and the scientific community,
- Development of bivalve-based carbon certification systems.

When bivalve aquaculture is approached as an integrated solution targeting climate resilience, ecosystem restoration, and coastal development, it can play a fundamental role not only in seafood production but also in the construction of a sustainable blue economy.

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THE IMPORTANCE OF ANIMAL ORIGIN INGREDIENTS IN DIETS FOR RAINBOW TROUT (*ONCORHYNCHUS MYKISS*) FRY

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İLKER AYDIN

Introduction

Rainbow trout is one of the most widely cultured cold-water salmonids, and the success of trout hatcheries depends critically on early life-stage nutrition. Fry (from first feeding through the early juvenile phase) are characterised by rapid somatic growth, relatively undeveloped digestive capacity, high metabolic rates and strong requirements for specific nutrients that support organogenesis, neural development and membrane biogenesis. These physiological features make diet composition during the fry period particularly influential for survival, growth trajectory and later performance (Altan, 2019; Engin and Altan, 2022).

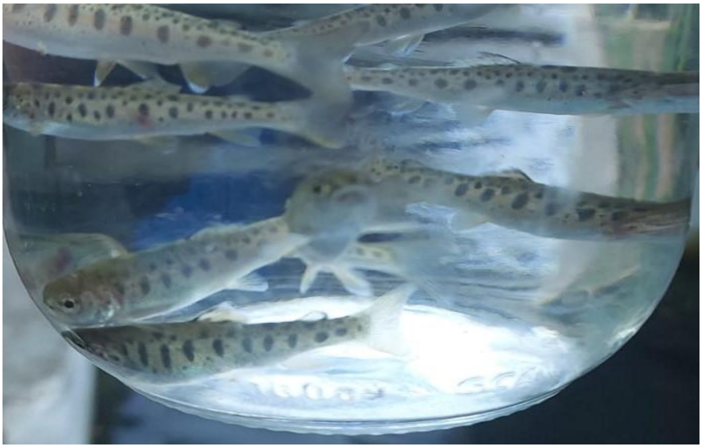

Photo 1. Rainbow trout fry in a glass beaker (original photo courtesy by Ozgur ALTAN)

Over the past few decades, there has been strong pressure to reduce reliance on traditional marine animal ingredients, particularly fishmeal and fish oil due to cost, supply constraints, and sustainability concerns. This has driven research into plant proteins, single-cell proteins, rendered terrestrial animal by-products, insect meals and functional additives. However, replacement is not very successful in fry diets, because numerous studies and reviews report that complete replacement of high-quality marine animal ingredients often reduces growth, survival, feed intake or alters tissue composition in early life stages. In contrast, partial replacement with careful balancing or inclusion of attractants and supplements can be successful in some contexts. The classic advantages of animal-origin ingredients — balanced indispensable amino acid profiles, high digestibility, presence of LC-PUFAs (EPA/DHA), nucleotides and bioactive pigments — largely explain this persistent role (Cho and Cowey, 1991; Hardy, 2002)

2. Nutritional requirements of rainbow trout fry

2.1 Protein and indispensable amino acids

Rainbow trout fry display very high mass-specific protein deposition and relatively immature digestive and metabolic systems. During this period, an inadequate supply of one or more indispensable amino acids (IAAs; commonly called essential amino acids, EAAs) rapidly constrains growth: the first-limiting amino acid is catabolised rather than incorporated into tissue protein, lowering feed conversion and increasing nitrogen waste. Therefore, hatchery feeds must be formulated to meet **digestible** IAA targets rather than crude protein alone (Li et al., 2021). Fry have very high protein requirements on a per-unit-body-weight basis. Beyond total protein, the profile and bioavailability of indispensable amino acids (lysine, methionine, threonine, arginine, etc.) determine growth and feed conversion (Abboudi et al, 2006; Andersen et al, 2013; Rolland et al., 2015). Animal-origin proteins, and especially marine sources such as fishmeal and krill, generally supply a favourable amino acid profile with high digestibility — essential when the digestive system is immature and enzymatic hydrolysis capacity is lower than in older fish. When plant proteins are used, lysine and methionine frequently become limiting and require supplementation; even with supplementation, plant matrices can contain antinutritional factors (trypsin inhibitors, phytates, lectins) that impair nutrient uptake in fry (Tacon and Metian, 2008).

Photo 2. Rainbow trout fry eagerly attack a well-formulated diet (original photo courtesy by Ozgur ALTAN).

Fry have limited enzymatic and physiological capacity to compensate for imbalanced diets. Amino acids serve both as the building blocks for structural protein and as substrates for metabolic pathways (methyl donors, antioxidant precursors, neurotransmitter synthesis). When dietary IAAs are deficient, growth rate suffers, and physiological functions (immune response, oxidative balance) may be impaired — effects that are proportionally greater in fry than in older life stages because of their higher relative growth rates and developmental demands. These general functions are reviewed comprehensively in recent amino-acid-focused reviews (Tan et al., 2016).

2.1.2. Key indispensable amino acids for rainbow trout fry

Lysine is frequently the first-limiting amino acid when fishmeal is partially or largely replaced by plant proteins. Classical and contemporary trials indicate lysine must be supplied at sufficient levels to support maximum growth and protein retention. Experimental work in trout fry has reported lysine requirements expressed either as g/kg diet or as percentage of dietary protein; values vary with experimental design, but a recurring practical target is to meet lysine levels recommended by authoritative nutrient guides and species-specific trials (Abboudi et al., 2006; Thu et al., 2007; Plakas et al., 1988).

Methionine (often considered together with cystine) is essential for protein synthesis and as a methyl-group donor (S-adenosylmethionine) and is linked to antioxidant status through glutathione synthesis. Empirical trials in trout indicate methionine requirements are modest in absolute terms (commonly reported in the range of ~0.5–0.8% of the diet depending on cystine levels), but deficiencies reduce growth and can alter hepatic metabolic enzyme activities

Arginine and threonine can become limiting depending on ingredient mix; arginine is important for nitrogen metabolism and immune-related nitric oxide production, while threonine affects mucosal integrity and gut function. The actual limiting amino acid depends on the combination of ingredients used in the feed matrix (Li et al., 2021).

For rainbow trout fry, protein **quality** (digestible indispensable amino acid balance) is more consequential than crude protein level alone. Meeting digestible lysine and methionine targets, ensuring peptide-rich and palatable starter diets, and validating formulations empirically are practical strategies to maximise early survival and growth — investments that pay off across the production cycle.

2.2 Lipids — The Essential Role of Long Chain Fatty Acids

Lipids represent the second major macronutrient class in fish feeds after protein, contributing both energy (9 kcal g^{-1}) and essential fatty acids (EFAs). For rainbow trout fry, adequate lipid nutrition is vital for growth and metabolic development because energy from lipid oxidation spares dietary protein for tissue synthesis (Sargent et al., 2002; Tocher, 2010). The most critical lipids for early stages are long-chain polyunsaturated fatty acids (LC-PUFAs) of the $n-3$ and $n-6$ series, particularly eicosapentaenoic acid (EPA) and decosahexaenoic acid (DHA), which are primarily derived from marine oils such as fish oil and krill oil.

Unlike marine species, rainbow trout possess a partial but limited capacity to biosynthesize LC-PUFAs from shorter-chain precursors. However, at early developmental stages (first feeding to 1 g body weight), the activity of n-5 and n-6 desaturases is insufficient to meet physiological demands. Therefore, dietary inclusion of EPA and DHA is indispensable for optimal fry performance (Bell & Sargent, 2003).

Long-chain omega-3 fatty acids, EPA and DHA, play critical structural and functional roles in neural tissues, retina, gill and gut membranes and are particularly important for larval and fry development. Deficiencies in DHA and EPA impair growth, survival, visual function and stress resistance in many marine and freshwater species; for rainbow trout fry, dietary supply of LC-PUFAs is associated with improved somatic growth and condition. Marine animal ingredients are the most reliable dietary sources of EPA/DHA, whereas plant oils provide limited or no preformed LC-PUFAs and require metabolic elongation/desaturation pathways that may be immature in fry.

Lipids play a crucial role in fish nutrition, serving as a dense source of energy, essential fatty acids (EFAs), and structural components of cellular membranes. In rainbow trout fry, long-chain polyunsaturated fatty acids (LC-PUFAs), particularly eicosapentaenoic acid (EPA, 20:5n−3) and docosahexaenoic acid (DHA, 22:6n−3), are indispensable for optimal growth, neural development, stress resistance, and survival. During early ontogeny, trout fry have limited enzymatic capacity to elongate and desaturate shorter-chain precursors (such as α-linolenic acid, 18:3n−3) into LC-PUFAs, making direct dietary provision essential. This paper reviews the biochemical and physiological importance of LC-PUFAs in rainbow trout fry, with emphasis on their roles in membrane fluidity, immunity, and development, and discusses recent findings on lipid requirements in starter feeds.

2.2.1 Biochemical and physiological importance of LC-PUFAs

EPA and DHA are integral to the phospholipid bilayer of cellular and mitochondrial membranes, where they determine membrane fluidity, permeability, and the activity of membrane-bound enzymes and receptors (Tocher, 2003). DHA, in particular, is highly enriched in neural and retinal tissues, facilitating efficient synaptic transmission and visual acuity — critical functions for prey capture and survival in newly feeding fry. Deficiency of DHA has been associated with impaired vision and abnormal behavior in fish larvae and fry (Izquierdo et al., 2001).

LC-PUFAs serve as both structural components and metabolic modulators. EPA and DHA influence gene expression via peroxisome proliferator-activated receptors (PPARs), which regulate lipid oxidation and energy balance (Glencross, 2009). Adequate dietary inclusion of LC-PUFAs promotes efficient energy utilization, higher specific growth rate (SGR), and improved feed conversion ratio (FCR) in trout fry (Turchini et al., 2009; Li et al., 2021).

LC-PUFAs also modulate immune and inflammatory processes through the production of eicosanoids. EPA-derived eicosanoids tend to be less inflammatory than those from arachidonic acid (ARA, 20:4n−6), thus promoting controlled immune responses. Fish fed diets deficient in EPA and DHA often show elevated stress indicators and reduced resistance to bacterial or viral pathogens (Montero & Izquierdo, 2010).

2.2.2. Essential fatty acid requirements in rainbow trout fry

Empirical studies have established that rainbow trout fry require *n−3* LC-PUFAs for optimal performance. Early work by Watanabe (1982) demonstrated that *n−3* deficiency results in poor growth, fin erosion, and high mortality. Bell et al. (1991) later confirmed that the minimal requirement for *n−3* HUFA (highly unsaturated fatty acids; mainly EPA + DHA) is approximately **0.5–1.0% of diet dry matter,** corresponding to **1.5–2% of total lipids** for fry under typical hatchery conditions. Recent refinements suggest that DHA should comprise at least **0.3–0.5% of the diet,** with an EPA: DHA ratio between **1:1 and 2:1** for balanced membrane composition and eicosanoid synthesis (Tocher, 2010; Torstensen et al., 2011). Furthermore, the ratio of *n-3 and n-6* fatty acids should exceed **2:1,** since excessive *n−6* fatty acids (from vegetable oils) can competitively inhibit LC-PUFA metabolism and incorporation into tissues (Turchini et al., 2009).

Lipids, and particularly LC-PUFAs such as EPA and DHA, are indispensable nutrients in the diets of rainbow trout fry. These fatty acids underpin key physiological processes — from membrane integrity to immune modulation and visual function. Because fry fish have limited ability to biosynthesize LC-PUFAs from shorter precursors, direct dietary inclusion of EPA and DHA is essential. Future feed development should focus on sustainable LC-PUFA sources, ensuring optimal growth and health without reliance on finite marine resources. Balancing lipid sources to maintain adequate EPA:DHA ratios will remain a cornerstone of successful trout fry nutrition.

Photo 3. Highly digested starter feeds give a clear appearance in the concrete tanks (original photo courtesy by Ozgur ALTAN).

2.3 Micronutrients, minerals and bioactive compounds

Animal-origin ingredients often supply highly bioavailable forms of phosphorus, heme-iron, B-vitamins and trace minerals (zinc, selenium) that are more readily assimilated than many plant-bound forms. Further, components such as nucleotides (from fishmeal, krill), peptides and certain marine carotenoids (e.g., astaxanthin from krill or shrimp by-products) have documented roles in immune maturation, antioxidant protection and pigmentation — traits that matter for fry robustness and later market quality (Hernandez de Dios et al. 2022).

3. Mechanisms by which animal ingredients support fry performance

3.1 Digestibility and pancreatic/enzyme stimulation

High digestibility minimizes the energetic cost of digestion and maximizes nutrient availability for growth. Fishmeal and many processed animal proteins contain peptides and free amino acids that stimulate feed acceptance and digestive enzyme secretion (proteases, lipases), which is particularly important during first-feeding when endogenous enzyme production is ramping up. Hydrolysed animal proteins can be used to improve digestibility and early intake (Haghbayan and Mehrgan, 2015).

3.2 Palatability — attractants and feed intake

Marine animal proteins contain a suite of small soluble compounds (free amino acids, betaines, nucleotides, trimethylamine oxide derivatives) that act as powerful feed attractants. High and consistent feed intake in the first days after yolk absorption is essential; reduced palatability in plant-heavy diets is a common cause of slower growth or higher mortality in fry trials.

3.3 Essential fatty acids and membrane function

Preformed DHA and EPA are integrated into the phospholipids of neural and retinal membranes; during early development, rapid neurogenesis and retinal differentiation demand a substantial supply of LC-PUFAs. Inadequate dietary EPA/DHA in fry can produce subtle but important deficits in sensory function and behaviour that translate into poorer feeding performance and survival.

3.4 Immunomodulatory and trophic factors

Nucleotides, certain peptides and small molecules in animal by-products can modulate innate immunity, enhance gut maturation and support the development of mucosal barriers in fry. Krill meal and other marine ingredients are often credited with increasing resistance to pathogens and improving early survival in several studies (Hernández de Dios et al., 2015).

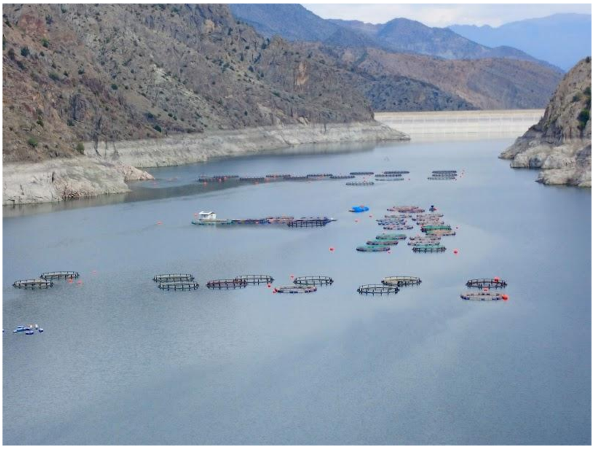

Photo 4. A good aquaculture environment supports the feed efficiency in rainbow trout fry production (original photo courtesy by Ozgur ALTAN)

4. Commercial animal origin ingredients in fry diets

4.1 Fishmeal as the historical benchmark

Fishmeal has long been the gold standard for aquafeeds due to its balanced amino acid composition, high digestibility and presence of LC-PUFAs and micronutrients. Numerous trials have demonstrated superior growth and feed efficiency in trout fry and juveniles fed diets with appreciable fishmeal inclusion compared to unmodified plant-based diets, particularly when replacement is high and without compensatory formulation strategies. Meta-analyses and long-term trials indicate that while older juveniles can adapt more effectively to plant-based diets, early life stages are more sensitive to the removal of fishmeal. While excellent amino acid profile, high digestibility, natural supply of LC-PUFAs, attractants, minerals and nucleotides can be counted as the advantages of the ingredient, supply volatility, cost, and sustainability concerns (pressure on wild fisheries) can be counted as the disadvantages. For first-feeding diets, fishmeal remains a robust baseline ingredient.

4.2 Krill and squid meals

Krill meal is rich in high-quality protein, phospholipid-bound EPA/DHA, astaxanthin and soluble attractants; multiple studies have shown that partial inclusion of krill meal in plant-heavy diets can restore feed intake, improve FCR and sometimes fully recover growth performance to fishmeal-based controls (Barrows et al. 2023)..

Squid meal provides highly digestible protein and attractive peptides and has been used successfully in early diets in combination with marine oils or other attractants. Recent peer-reviewed trials in salmonids and other species report improved growth and feed intake with krill/squid inclusion (Cho et al., 2022).

4.3 Insect meals (Hermetia illucens, Tenebrio molitor)

Insect meals (black soldier fly — BSF; mealworm) are gaining traction as sustainable animal-origin protein sources. Studies in trout show potential for partial replacement of fishmeal without negative effects on survival and growth when inclusion levels are moderate and diets are balanced; however, results vary by insect species, processing (full-fat vs defatted), batch variability and fatty acid profile (insects are typically low in EPA/DHA). Digestibility and chitin content may affect nutrient utilisation in fry and must be considered. Overall, insect meals are promising as a complement to marine ingredients but are rarely complete substitutes in fry diets without additional supplementation (e.g., LC-PUFAs, synthetic amino acids) (Renna et al., 2017; Sandor et al., 2022).

4.4 Rendered terrestrial animal proteins and single-cell proteins

Rendered proteins (poultry by-product meal, blood meal, hydrolysed fish protein) and single-cell proteins (yeast, bacterial biomass) can supply concentrated amino acids and energy.

Hydrolysed or enzymatically treated animal proteins often improve feed intake and digestibility in fry. Still, their mineral and fatty acid profiles differ from marine sources, and palatability or specific growth responses can vary; these ingredients are often best used in combination with marine lipids or krill to supply EPA/DHA.

4.5 Replacement limits and practical outcomes

Experimental trials show that partial replacement (often 30–60% depending on ingredient and life stage) of fishmeal is often achievable without marked performance loss if diets are reformulated for amino acid balance, supplemented with limiting amino acids and LC-PUFAs, and include attractants or hydrolysed proteins. Complete replacement from first feeding remains difficult in many hatchery contexts and can lead to lower growth, altered fatty acid composition, and lower survival unless intensive supplementation and processing strategies are applied (Lazzarotto et al., 2018).

5. Specific considerations in formulation for fry

Balancing indispensable amino acids: When replacing animal proteins, formulators must identify first-limiting amino acids (often lysine and methionine in plant-heavy diets) and supply them either through crystalline amino acid supplementation or targeted animal proteins that are naturally rich in those amino acids. Carefully balanced amino acid profiles reduce catabolism of amino acids for energy and support efficient growth.

LC-PUFA supply (EPA/DHA): Due to fry have limited capacity for elongation/desaturation of short-chain omega-3s, provision of preformed EPA and DHA is recommended during early feeding. Sources include fish oil, phospholipid-rich krill meal and certain marine by-products. Even when insect meals or rendered terrestrial proteins replace fishmeal as protein sources, the diet must still supply sufficient LC-PUFAs to support neural and visual development.

Use of hydrolysed proteins and attractants to stimulate intake: Hydrolysed fish proteins and certain processed animal by-products containing free amino acids and small peptides can enhance early feeding response, increase palatability and support gut development. Inclusion of such products at low to moderate levels can improve early growth and reduce wasted feed (Haghbayan 2015).

Phosphorus bioavailability and mineral balance: Marine ingredients typically provide more bioavailable phosphorus than plant sources; insufficient available phosphorus in fry diets can impair skeletal development. When plant ingredients are used, phytase treatment and careful inclusion of highly bioavailable mineral sources are recommended.

Microbiota and gut development: Early diet composition shapes the gut microbiome; animal-origin ingredients, peptides and nucleotides can favour beneficial microbial assemblages and mucosal development. This area is active research and may underpin some of the observed improvements in disease resistance and nutrient use in fry fed animal-inclusive diets (Aragao et al., 2023).

Photo 5. Well-balanced diets provide a rapid growth rate with a high survival rate (Original photo courtesy by Ozgur ALTAN)

6. Conclusions

Animal-origin ingredients continue to play a central role in diets for rainbow trout fry because they provide a package of highly bioavailable indispensable amino acids, preformed LC-PUFAs, minerals, pigments and soluble attractants that together support rapid growth, digestive maturation, immune competence and survival during the vulnerable early life stages. While advances in ingredient processing, supplementation and alternative proteins (insects, single-cell proteins, rendered products) offer promising pathways to reduce fishmeal dependence, practical hatchery nutrition strategies should prioritize the biological needs of fry. Strategic partial replacement, rigorous balance of nutrients (particularly LC-PUFAs and limiting amino acids), and use of hydrolysed/attractant-rich animal fractions where necessary represent the pragmatic middle ground: reducing ecological footprint without compromising the survival and performance that underpin efficient aquaculture production.

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RAISING AWARENESS IN FISHERIES

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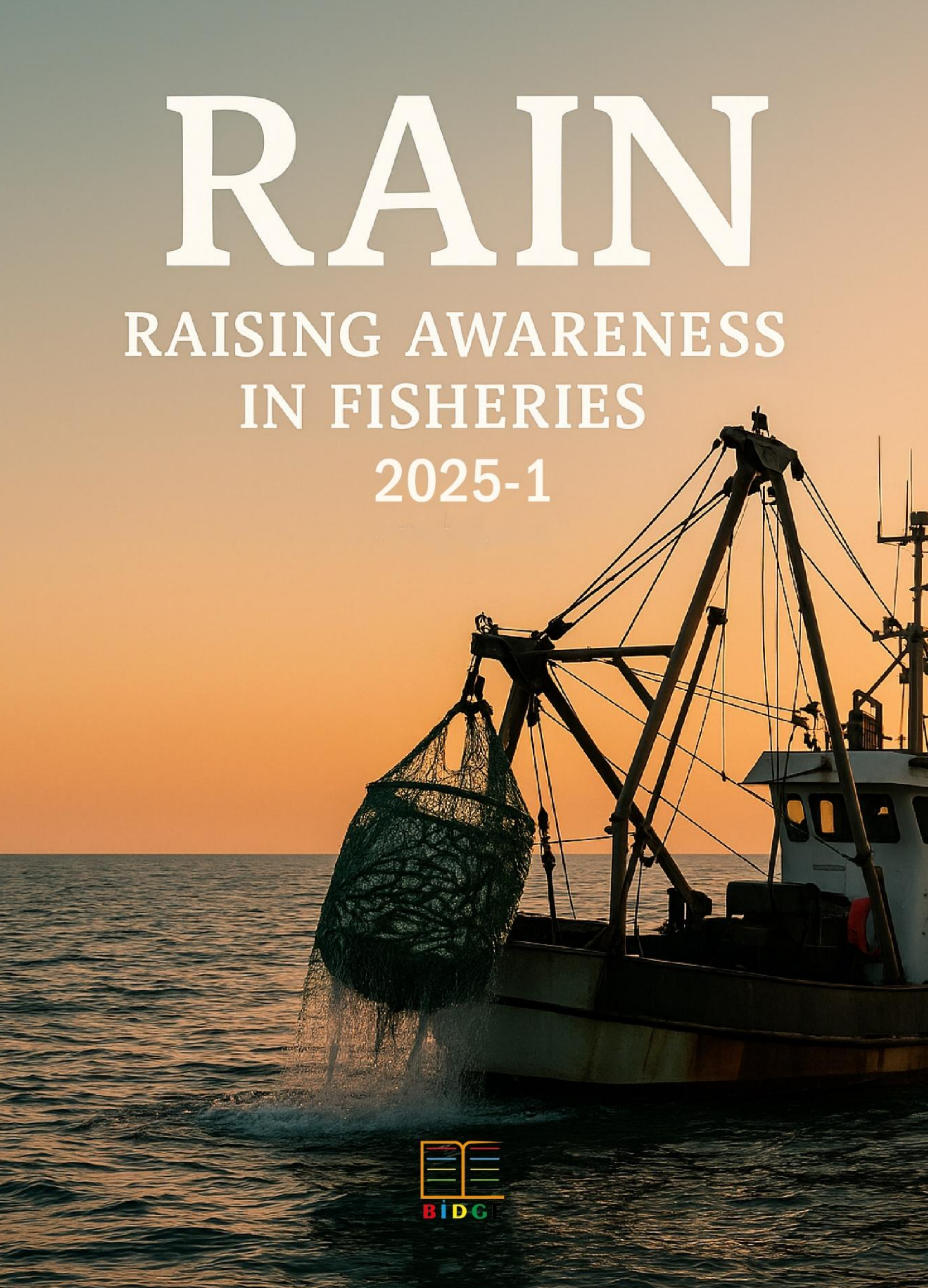

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