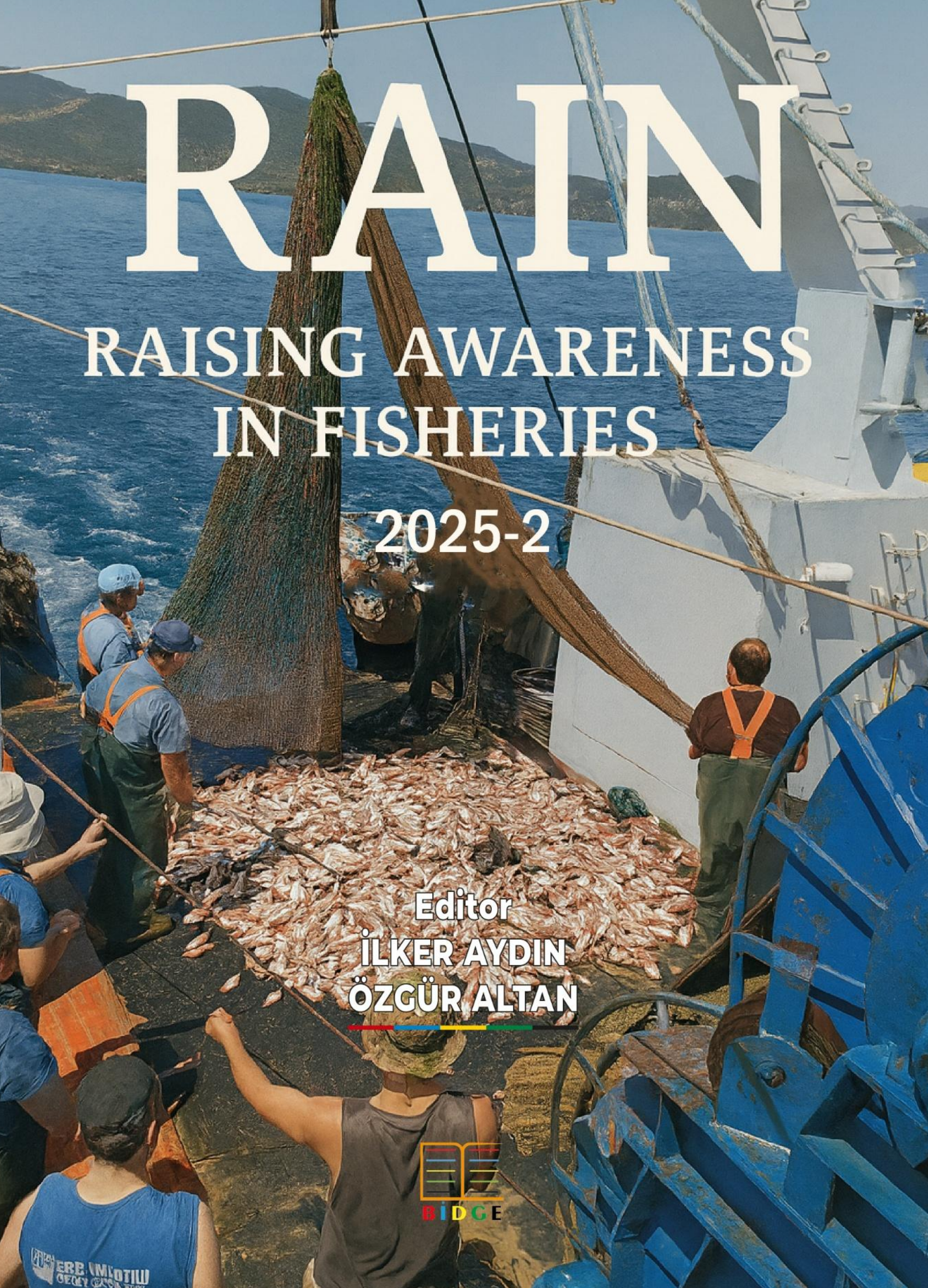

RAIN

RAISING AWARENESS IN FISHERIES

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1. Lessepsian Species as a New Asset

1.1. The Lessepsian Migration Phenomenon

The Mediterranean Sea, a semi-enclosed basin with a rich and complex geological history, has experienced a profound biogeographic transformation since the mid-19th century. This transformation is primarily attributed to the human-mediated

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creation of a maritime connection with the Red Sea: the Suez Canal. Opened in 1869, the Canal effectively removed the last land barrier between the Indian Ocean and the Mediterranean, acting as a novel corridor for marine life and initiating one of the most significant and well-documented bio-invasions in the world, the Lessepsian migration (Por, 1978).

The term "Lessepsian migration," coined by ichthyologist Georg Haas and later popularized by Fernando Por, derives from the name of the French diplomat Ferdinand de Lesseps, who oversaw the Suez Canal's construction (Golani, 2010). It refers specifically to the ongoing migration of marine organisms from the Red Sea to the Mediterranean Sea. This migration is overwhelmingly unidirectional; while a handful of Mediterranean species have been recorded in the Red Sea (a process sometimes termed "anti-Lessepsian migration"), the number is negligible compared to the influx into the Mediterranean (Zenetos et al., 2012). This asymmetry is largely driven by the prevailing northward currents in the Suez Canal and the pronounced environmental gradient, which has historically favored species pre-adapted to the more saline and warmer conditions of the eastern Mediterranean Basin (Por, 1978; Galil, 2009).

The initial phase of the migration was relatively slow, limited by the Canal's narrow, shallow, and brackish-water conditions. However, a series of successive enlargements and deepening projects, most notably the Canal's expansion in 2015, have dramatically altered its hydrography. These modifications have reduced the physiological barriers for crossing organisms, effectively turning the Canal from a filter into a increasingly efficient conveyor belt for marine species (Galil et al., 2017). Consequently, the rate of new introductions has accelerated sharply in recent decades, a trend exacerbated by the concurrent effects of climate change and sea surface warming, which makes the Mediterranean, particularly its eastern basin, more hospitable for thermophilic Red Sea species (Raitsos et al., 2010).

The scale of this bio-invasion is staggering. To date, over 400 non-indigenous species of fish, mollusks, crustaceans, polychaetes, and other marine taxa of Red Sea origin have established stable populations in the Mediterranean Sea (Zenetos et al., 2022). The eastern Mediterranean, especially the Levantine Basin, has been the primary recipient, now hosting a marine community where Lessepsian migrants often dominate biomass and alter local food webs (Edelist et al., 2013). The ecological impacts are multifaceted, including competition with native species for food and habitat, predation on native fauna, and subsequent changes in ecosystem structure and function (Golani, 2010). It is within this context of a rapidly changing and "tropicalized" sea that the traditional narrative of Lessepsian migrants solely as a threat is being re-evaluated, giving way to discussions on their potential as a novel and adaptive fisheries resource.

1.2. Ecological Threat and Biodiversity Loss

The initial and long-prevailing narrative surrounding Lessepsian migrants has been overwhelmingly one of ecological crisis and biodiversity loss. From this perspective, these non-indigenous species are framed as disruptive "invaders" or "aliens," whose establishment and proliferation pose a fundamental threat to the native structure and function of the Mediterranean ecosystem (Golani, 2010). This view is supported by a growing body of evidence documenting negative impacts across multiple trophic levels, leading to significant community restructuring, particularly in the eastern Mediterranean Basin (Edelist et al., 2013).

A primary concern is trophic disruption through competition and predation. Many Lessepsian migrants are generalist and opportunistic feeders with high reproductive rates, allowing them to outcompete native species for limited resources such as food and habitat. A canonical example is the brushtooth lizardfish (*Saurida undosquamis*), a voracious piscivore that directly competes with and preys upon native commercial species like hake (*Merluccius merluccius*) and mullets (Mugilidae), potentially suppressing their populations (Golani, 1998). Similarly, the goldband goatfish (*Upeneus moluccensis*) has become one of the most abundant demersal fish in the Levant Sea, competing directly with the native red mullet (*Mullus barbatus*) for benthic invertebrates (EastMed, 2010). This intense competition can lead to the displacement of native species from their preferred ecological niches, altering the composition of entire benthic communities.

Beyond competition, direct predation by Lessepsian migrants has had devastating effects on specific native populations. The most cited case is that of the marbled spinefoot rabbitfish (*Siganus rivulatus*), whose herbivorous feeding has been linked to the overgrazing and decline of native macroalgal forests, critical nursery habitats for many native fish and invertebrate species (Sala et al., 2011). The silver-cheeked toadfish (*Lagocephalus sceleratus*) represents another potent symbol of this narrative. As a large, toxic predator, it consumes a wide variety of commercially valuable fish, cephalopods, and crustaceans, causing direct damage to fishing gear and catches (Kalogirou, 2013). Its presence in catches has created a significant nuisance and economic burden for fishers, reinforcing the perception of Lessepsian migrants as pests.

The cumulative impact of these biological interactions is a phenomenon often described as the "tropicalization" of the Mediterranean Sea. This process involves a shift in the marine community from one historically dominated by temperate Atlantic species to a new state increasingly characterized by thermophilic Indo-Pacific species (Raitsos et al., 2010; Vergés et al., 2014). This restructuring is not merely a change in species identity but can lead to a simplification of food webs, reduced native biodiversity, and potentially a loss of ecosystem resilience to further perturbations (Galil, 2007). The narrative of threat is further compounded by economic impacts, where fishers report damaged nets, reduced catches of valuable native species, and safety concerns, particularly when handling toxic species like *L. sceleratus* (Streftaris & Zenetos, 2006).

1.3. The "Silver Lining"

While the narrative of Lessepsian migrants as ecological threats is well-founded and supported by significant evidence, a pragmatic counter-narrative is steadily gaining traction among scientists, fisheries economists, and forward-thinking policymakers (Figure 1). This perspective does not seek to dismiss the documented ecological impacts but rather proposes a strategic shift in management philosophy. It argues that for many established Lessepsian species, their proliferation is an irreversible ecological fait accompli, a new baseline for the Mediterranean ecosystem (Golani, 2010). Instead of focusing solely on the intractable problem of eradication, this counter-narrative asks a different question: given their established and often abundant presence, can these species be transformed from perceived pests into a sustainable socio-economic asset? (FAO, 2023; Zemah-Shamir et al., 2023).

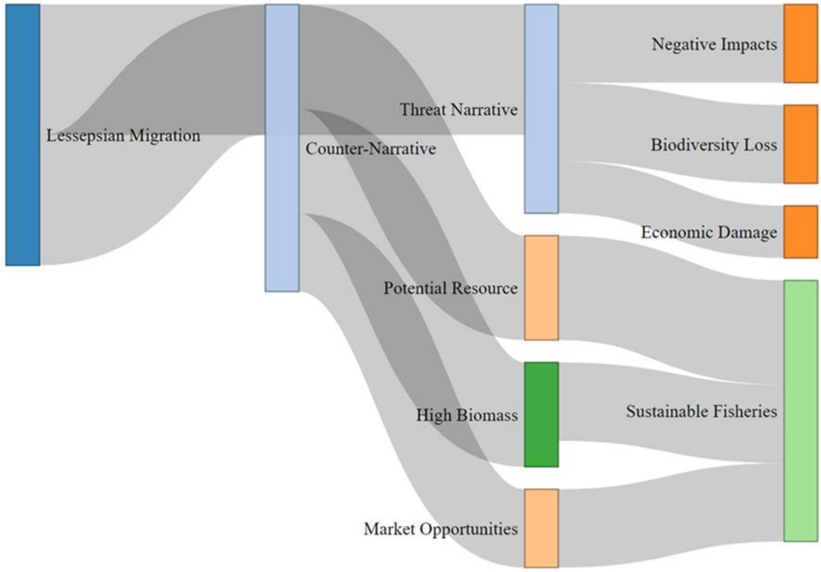

Figure 1. *Competing narratives surrounding Lessepsian migration in the Mediterranean Sea. The traditional "Threat Narrative" (orange/red flows) has long dominated scientific and management discourse, emphasizing biodiversity loss and economic damage. A pragmatic "Counter-Narrative" (green flows) is now gaining ground, viewing established Lessepsian species as a high-biomass resource that can support sustainable fisheries and new market opportunities in an irreversibly changed ecosystem.*

The foundation of this argument is the sheer biomass represented by these populations. In the heavily fished waters of the Mediterranean, where many native stocks are overexploited, the abundant and often underutilized biomass of Lessepsian migrants represents a substantial, self-sustaining, and largely untapped resource (Edelist et al., 2013). For instance, in the shallow waters of the Levantine Basin, Lessepsian fish like the marbled spinefoot (*S. rivulatus*) and the goldband goatfish (*U. moluccensis*) can constitute over 80% of the total catch in certain areas (EastMed, 2010). To discard or cull this biomass at sea, as still sometimes occurs, is an economic loss and a wasted opportunity. The counter-narrative posits that harnessing this biomass through targeted fisheries could alleviate fishing pressure on overexploited native stocks, contribute to local food security, and provide a new source of income for coastal communities (Rousseau et al., 2022).

This approach is fundamentally an exercise in adaptation and resilience. The Mediterranean is changing due to a confluence of factors, including climate change, pollution, and bio-invasions. A management strategy fixated solely on restoring a historical, pre-Lessepsian ecosystem is increasingly viewed as unrealistic (Katsanevakis et al., 2025). A more resilient and adaptive strategy involves learning to live with and even benefit from the new ecological reality. This involves a paradigm shift from "invasion biology" towards "invasion ecology and economics," where the focus expands from purely ecological impacts to include the potential for ecosystem goods and services (Shackleton et al., 2019).

Crucially, this is not a theoretical proposition. Practical examples of successful exploitation are emerging across the region. In Lebanon and Egypt, the rabbitfish (*S. rivulatus* and *S. luridus*) has transitioned from a discarded bycatch to a valuable target species, now commonly found in local markets (Ulman et al., 2021). Similarly, the blue swimmer crab (*Portunus segnis*) has spurred the development of new, profitable small-scale fisheries in Greece, Tunisia, and Italy, with products even reaching export markets (Mancinelli et al., 2017; Kleitou et al., 2021). These case studies serve as powerful proof-of-concept, demonstrating that with the right approach, involving market development, gear adaptation, and regulatory support, a successful fishery on a Lessepsian species is not only possible but can be economically viable. This perspective is further bolstered by the global example of the lionfish (*Pterois volitans/miles*) fisheries in the Western Atlantic and is now supported by quantitative scientific evidence from the Eastern Mediterranean demonstrating that local populations are underexploited and can sustain a targeted fishery (Kondylatos et al., 2024).

Therefore, the "silver lining" narrative reframes the Lessepsian migration from an unmitigated disaster into a complex challenge with a potential socio-economic upside. It acknowledges ecological disruptions while simultaneously advocating for a pragmatic, solution-oriented approach that views these established populations as a novel marine resource.

1.4. Chapter Objectives and Scope

Lessepsian migration represents both a significant ecological disruption and an emerging resource, prompting new thinking about how non-indigenous species can be integrated into sustainable fisheries development. A growing body of scientific knowledge, socio-economic analysis, and practical experience now points toward realistic pathways for harnessing the expanding biomass of these species in the Mediterranean.

A central focus is identifying the Lessepsian species with the greatest fisheries potential. Current evidence highlights species already demonstrating commercial promise, such as the rabbitfishes *S. rivulatus* and *S. luridus*, the blue swimmer crab *P. segnis*, and the goldband goatfish *U. moluccensis*, alongside high-biomass but problematic newcomers like the silver-cheeked toadfish *L. sceleratus*. Their distribution, abundance, life-history traits, and population trends reveal why they are becoming increasingly important components of regional catches. Across the Levant, the Aegean Sea, and North Africa, these species have transitioned from incidental bycatch to valuable targets. Shifts in catch rates, adaptations in fishing techniques, and evolving perceptions among fishers demonstrate their growing integration into local fisheries (Ulman et al., 2021; Kleitou et al., 2021).

Developing viable markets is equally crucial. Opportunities lie in product diversification, marketing and branding strategies that reduce consumer hesitation, and more efficient supply chains that connect landing sites with local and international markets (Rousseau et al., 2022). Yet several challenges must be addressed, including biological uncertainties stemming from limited stock assessments, socio-economic barriers such as gear limitations or fisher resistance, regulatory restrictions that impede commercialization of non-native species (Galil et al., 2017), and food-safety concerns surrounding toxic species. To move forward, a modern and adaptive policy framework is needed, one that embeds the exploitation of well-established Lessepsian migrants within ecosystem-based fisheries governance. Such an approach can help policymakers, researchers, and industry stakeholders transform a long-standing ecological challenge into a genuine socio-economic opportunity (Golani, 2010). With its clear geographical focus on the eastern Mediterranean and taxonomic emphasis on fish and crustaceans, this perspective offers a coherent and actionable roadmap for sustainable use of Lessepsian biomass in a rapidly changing marine environment.

2. Proliferation of Lessepsian Species in the Mediterranean

2.1. Key Species with Fisheries Potential

The successful development of a fishery for any species, native or non-indigenous, hinges on a combination of factors: high abundance, desirable taste and flesh quality, marketable size, and the existence of feasible capture methods. For Lessepsian migrants, their rapid population growth and establishment in the Eastern Mediterranean have created a new, abundant biomass that meets many of these criteria (Table 1).

Table 1. *Promising Lessepsian Species for Fisheries in the Mediterranean.*

Species Name	Common Name	Key Characteristics	Current Exploitation Status	Primary Challenges
S. rivulatus *S. luridus*	Marbled Dusky Spinefoot Rabbitfish	Herbivorous, schooling, high abundance, excellent taste, bony structure.	Actively targeted and highly valued.	Bony flesh requires skilled processing or specific cooking methods.
P. segnis	Blue Swimmer Crab	Large size, high meat yield, aggressive, forms aggregations.	Targeted in Tunisia, Greece, and Turkey; export potential.	Requires specific traps/pots; can damage nets; market development needed in some regions.
U.moluccensis	Goldband Goatfish	Demersal, high abundance, outcompetes native red mullet, good taste.	Common in trawl and gillnet catches, sold alongside native mullets	Smaller average size than native mullet; perceived as lower value.
S. undosquamis	Brushtooth Lizardfish	Voracious piscivore, very abundant, firm flesh.	Often discarded but increasingly landed for fishmeal or low-price markets.	Negative perception as a pest; predatory impact on other commercial species.
P. miles	Devil Firefish (Lionfish)	Venomous spines, voracious predator, premium taste, underexploited population.	Targeted in local removals; high-value niche market potential.	Safe handling required; specialized training; overcoming negative public perception.
L. sceleratus	Silver-cheeked Toadfish	Very large size, extremely high abundance, toxic tissues.	No direct consumption; trials for fishmeal, leather, or controlled biotoxin extraction.	TTX prohibits human consumption; damages gear and catches.

2.1.1. Established Commercial Targets

The most successful examples of Lessepsian fisheries are the rabbitfishes of the genus *Siganus*. The marbled spinefoot (*S. rivulatus*) and the dusky spinefoot (*S. luridus*) are now foundational to small-scale fisheries in the Levantine Basin. Their success is attributed to their high population density, schooling behavior, and excellent taste, which is often compared favorably to native sparids (Ulman et al., 2021). Despite their bony structure, which requires specific culinary preparation, they have been fully integrated into local markets and cuisine, demonstrating that consumer acceptance can be rapidly achieved for a high-quality product.

Similarly, the blue swimmer crab has transitioned from a curious bycatch to a valuable commodity. Its large size, high meat yield, and the existence of established global markets for similar crab species have facilitated its commercial exploitation. In Tunisia and Greece, fishers have adapted their methods, using specialized traps to target the crab, with catches often destined for export, proving that a high-value Lessepsian fishery is economically viable (Mancinelli et al., 2017; Kleitou et al., 2021).

2.1.2. Abundant Species

The Goldband goatfish represents a case of a species that has effectively filled the ecological and market niche of its native relative, the red mullet (*M. barbatus*). It is now one of the most abundant demersal fish in trawl and gillnet catches in the Eastern Mediterranean (EastMed, 2010). While sometimes sold at a lower price, its consistent availability and acceptable taste have ensured its place in the market. Its exploitation demonstrates how a Lessepsian migrant can become a staple of local fisheries, providing a reliable catch even as native stocks fluctuate.

2.1.3. Challenging Species

The brushtooth lizardfish presents a more complex case. As a voracious predator, it is often viewed negatively by fishers. However, its sheer abundance and firm flesh suggest significant potential, if market barriers can be overcome. Current uses are often low-value (fishmeal, bait), but there is potential for product development (surimi, fish burgers) to create a market for this prolific species (Golani, 1998).

The silver-cheeked toadfish (*L. sceleratus*) is the most notorious and challenging Lessepsian migrant. Its tissues contain potent tetrodotoxin, making it unsafe for direct human consumption (Kalogirou, 2013). However, its large size and extremely high biomass cannot be ignored. Research is exploring alternative uses, including the production of fishmeal, the utilization of its skin for leather, and even the controlled extraction of tetrodotoxin for pharmaceutical and biomedical applications. While a direct food fishery is not feasible, a "biorefinery" approach could potentially transform this significant problem into a source of valuable industrial and medical products.

2.1.4. The Devil Firefish

The devil firefish (*Pterois miles*) stands out as a high-profile Lessepsian invader, notorious for its venomous spines, voracious appetite, and significant negative impacts on native fish communities (Kleitou et al., 2021). Recognized as one of the 100 worst invasive alien species in the Mediterranean Sea, its rapid spread and lack of native predators pose a major ecological threat. However, its high abundance, consistent growth, and high-quality flesh have positioned it as a compelling potential commercial fishery, especially in regions like Rhodes, where populations are thriving

Scientific data from Rhodes indicates the population is underexploited, with the current exploitation rate (E=0.48) suggesting substantial potential for a further increase in fishing mortality to support commercial exploitation (Kondylatos et al., 2024). Management strategies, therefore, include targeted removals, establishing a commercial market for this species, and promoting lionfish gastronomy to reduce its population and mitigate its ecological impact.

2.2. Main Areas of Establishment

The establishment and proliferation of Lessepsian migrants in the Mediterranean Sea are not uniform. Their distribution is heavily influenced by a combination of oceanographic currents, temperature gradients, and the availability of suitable habitat, resulting in distinct biogeographic hotspots. The pattern of establishment reveals a clear and accelerating front of colonization, originating from the Suez Canal and progressively expanding northward and westward.

2.2.1. The Levantine Basin

The Levantine Basin remains the undisputed epicenter and primary hotspot for Lessepsian migrants. The coastal waters of Israel, Lebanon, and Syria represent the first point of entry and establishment. Here, the environmental conditions are most favorable, with high salinity and warm temperatures year-round that closely mimic the Red Sea habitat of the invaders (Por, 1978). The impact is so profound that Lessepsian species often dominate nearshore fish communities, constituting up to 80% of the total catch biomass in some trawl surveys (Edelist et al., 2013). The Levant is not just an area of high diversity but also of high density, serving as a source population for subsequent northward and westward expansion. It is in this region that the ecological shift from a temperate Atlantic to a subtropical Indo-Pacific community is most advanced, a phenomenon often described as the "tropicalization" of the Levantine Sea (Raitsos et al., 2010).

2.2.2. The Aegean Sea

The Aegean Sea, particularly its southern and eastern sectors, has emerged as a major secondary hotspot. Acting as a transitional zone, the Aegean receives a steady influx of species from the Levantine Basin via the prevailing currents that flow northward along the Anatolian coast and through the Cyclades (Zenetos et al., 2012). The islands of Rhodes and Crete are critical steppingstones, with their warm, isolated embayments often serving as the first sites of establishment in the Aegean. The south-eastern Aegean, influenced by Levantine Surface Water, now hosts a significant subset of the Lessepsian community, including commercially important species (Zenetos et al., 2020). The continued warming of the Aegean Sea is progressively reducing the physiological barriers for these thermophilic species, allowing them to establish and proliferate further north, including commercially important species, which has established thriving, structured populations in the Rhodian coastal waters (Kondylatos et al., 2024).

2.2.3. The Ionian Sea and Central Mediterranean

A clear and concerning trend for the wider Mediterranean is the ongoing westward expansion of Lessepsian migrants. Species are now being routinely recorded, and in some cases establishing populations, in the Ionian Sea (off the coasts of Greece and Italy), the Strait of Sicily, and even along the southern shores of the Italian peninsula (Zenetos et al., 2022). This expansion is facilitated by a combination of factors: the sheer population pressure from the eastern source regions, the transport of larvae and juveniles by currents, and the overarching effect of climate change, which is warming the entire Mediterranean basin and making western regions more hospitable (Galil et al., 2017). The sighting of species like *L.*

sceleratus and *P. segnis* in the waters around Malta, Sicily, and Puglia signals that the Lessepsian invasion is no longer an "eastern Mediterranean problem" but a basin-wide phenomenon.

2.2.4. Future Trajectory and Latitudinal Spread

The established pattern demonstrates a clear trajectory from the Suez Canal, through the Levantine Basin, into the Aegean Sea, and onward to the Central Mediterranean. Future hotspots are predicted to develop along the North African coast and continue into the Tyrrhenian Sea (Galil, 2009). Furthermore, there is evidence of successful colonization in new, previously cooler habitats, indicating a potential for future latitudinal spread into the northern Adriatic and the Gulf of Lion as sea temperatures continue to rise. This geographic expansion underscores the urgency of developing management strategies, such as the fisheries proposed in this chapter, that are adaptive and applicable across the entire Mediterranean region.

2.3. Ecological Niche and Trophic Impact

The successful establishment of Lessepsian migrants is not merely a matter of geographic arrival but a profound process of integration into the existing Mediterranean food web. This integration often involves occupying vacant ecological niches or, more disruptively, displacing native species from their established roles. The trophic impact of these invaders is multifaceted, creating a complex web of competition, predation, and novel predator-prey relationships that fundamentally restructure the ecosystem (Edelist et al., 2013).

2.3.1. Competition and Niche Displacement

A primary mechanism of impact is resource competition. Many Lessepsian migrants are generalist species with high reproductive rates and opportunistic feeding strategies, allowing them to outcompete ecologically similar native species for limited food and habitat. A quintessential example is the competition between the Goldband goatfish (*U. moluccensis*) and the native red mullet (*M. barbatus*). Both species are benthic feeders, consuming similar invertebrate prey. The high abundance and rapid population growth of *U. moluccensis* have been linked to a decline in the native mullet populations in the Levantine Basin, as they directly compete for the same benthic resources (EastMed, 2010).

Similarly, the herbivorous rabbitfishes have occupied a previously underutilized herbivory niche in the eastern Mediterranean. Their intensive grazing on macroalgae has led to the overgrazing and decline of native algal forests, which serve as critical nursery and feeding grounds for a variety of native fish and invertebrate species (Sala et al., 2011; Vergés et al., 2014). This represents a form of interference competition where the invader's feeding activity directly degrades the habitat quality for a wide range of native species, causing a cascading effect through the ecosystem.

2.3.2. Novel Predation Pressure

The introduction of new predators adds a top-down pressure that the native fauna is evolutionarily unprepared to handle. The brushtooth lizardfish (*S. undosquamis*) is a voracious piscivore that preys upon a wide range of native fish, including commercially important species, potentially stunting their recovery (Golani, 1998). Even more impactful is the silver-cheeked toadfish, an apex predator that consumes a variety of commercially valuable fish, cephalopods, and crustaceans. Its predation pressure can directly reduce the standing stock of native fishery resources, creating a direct economic conflict with fishers (Kalogirou, 2013).

2.3.3. Integration as Prey

However, the narrative is not solely one of negative impact. As the biomass of Lessepsian migrants increases, they themselves become a significant food source, integrating into the diet of native predators. This represents a potential stabilizing force and a "silver lining" in the trophic web. Larger native piscivores, such as groupers (*Epinephelus* spp.) and the common dolphinfish (*C. hippurus*), have been documented preying upon smaller Lessepsian fish (Kalogirou, 2013). Over time, this can lead to the development of new, stable predator-prey dynamics.

This integration as prey is a critical ecological argument for their exploitation by humans. By fishing these species, we are essentially acting as a top-down control, mimicking and amplifying the role of a native apex predator. A directed fishery on abundant species like *S. undosquamis* or *U. moluccensis* could help regulate their populations, potentially alleviating some of their competitive and predatory pressure on native species (FAO, 2023). Therefore, human fishery can be viewed as a novel and deliberate trophic interaction, one that has the potential to mitigate the very disruption it aims to harness.

3. The Current State of Exploitation

The journey of a Lessepsian species from an unwanted invader to a valuable commodity is not instantaneous. It is a socio-ecological transition that begins with its unavoidable appearance in fishing gear as bycatch. This initial phase is characterized by a complex interplay of economic loss, adaptive behavior, and deeply rooted perceptions that shape the foundation upon which future fisheries must be built.

3.1. Incidental Catches and Fishermen's Perceptions

The first and most widespread interaction between fishers and Lessepsian migrants is an incidental one. For decades, the presence of these species in nets and on hooks has been a source of frustration and economic strain. The initial and often persistent perception among fishers is that these "alien" species are a nuisance, directly damaging their livelihoods (Kleitou et al., 2021).

3.1.1. The Burden of Bycatch

The immediate impact is on fishing operations. Large, powerful species like the silver-cheeked toadfish are notorious for damaging nets and longlines, leading to costly repairs and lost fishing time. Their tendency to prey on captured fish further reduces the value of the catch (Kalogirou, 2013). For many fishers, the reaction to catching such species, particularly in the early stages of invasion, is discarded at sea. This practice represents a direct economic loss in terms of wasted effort and gear damage, while doing nothing to reduce the population of the invader.

Even for non-destructive species, their initial appearance is often met with skepticism. When a species like the brushtooth lizardfish or the goldband goatfish first became abundant, they were frequently perceived as "trash fish" that clogged nets and displaced valuable native species like hake and red mullet (Golani, 1998). In many ports, especially where markets were undeveloped, these catches were either discarded or sold for a pittance, often for use as animal feed or fertilizer (EastMed, 2010).

3.1.2. The Evolution of Perception and Nascent Markets

However, perception is not static. As the abundance of native species has declined and the biomass of Lessepsian migrants has become impossible to ignore, a pragmatic adaptation has occurred.

Fishers, driven by economic necessity, have begun to land these incidental catches wherever a market exists, however nascent.

The goldband goatfish exemplifies this transition. Initially dismissed, its consistent abundance and similarity to the prized red mullet have led to its widespread landing. It is now commonly sold in markets across the Levant and Aegean, often at a lower price than its native counterpart, but providing a reliable source of income (Zenetos et al., 2020). This represents a shift from pure discard to low-value utilization.

Fishermen's perceptions are thus a critical barrier, or potential catalyst, for the development of targeted fisheries. A study by Kleitou et al. (2021) found that fishers' willingness to fish for non-indigenous species is highly correlated with their perception of its market value and the existence of a ready buyer. Negative perceptions are strong for species that cause direct damage (*L. sceleratus*) or have no market, while they soften for species that can be easily sold, even at a low price.

3.2. Emerging Targeted Fisheries

Moving beyond incidental catch, the most compelling evidence for the fisheries potential of Lessepsian migrants comes from the successful development of targeted fisheries in various parts of the Mediterranean. These case studies demonstrate a conscious shift in strategy, where fishers, entrepreneurs, and sometimes government initiatives have actively worked to transform these biological resources into economic opportunities. They serve as vital blueprints for other regions grappling with the same ecological reality.

3.2.1. The Rabbitfish Fishery in the Levant: A Model of Market Integration

The most successful and established example is the targeted fishery for rabbitfish, specifically the marbled spinefoot and the dusky spinefoot, in the Levantine countries of Lebanon and Egypt. Within a few decades of their establishment, these herbivorous fish have become a cornerstone of the local small-scale artisanal fishery (Ulman et al., 2021).

The success of this fishery is attributed to several key factors:

- **High Abundance and Schooling Behavior:** Their predictable presence in large schools makes them an efficient and reliable target for fishers using gillnets and beach seines.
- **Consumer Acceptance:** Despite their bony structure, the fish possess firm, white flesh with a good flavor, which has been successfully integrated into local cuisine. They are often grilled or fried whole; a preparation method suited to their morphology.
- **Economic Necessity:** As catches of traditional native species declined, the consistent and abundant rabbitfish provided a vital alternative source of income and protein for coastal communities.

In these regions, rabbitfish are no longer "alternative" catch; they are a mainstream commodity, commonly found in local markets and restaurants, demonstrating a near-complete transition from invasive species to a fully integrated fisheries resource (EastMed, 2010).

3.2.2. The Blue Swimmer Crab

The blue swimmer crab provides a powerful case study of fishery driven by market demand and technological adaptation. Initially considered a pest that damaged nets, this species is now the target of a lucrative, emerging fishery, particularly in Tunisia, Turkey, and Greece.

The development of this fishery required a fundamental shift in approach:

- **Gear Adaptation:** Fishers moved from passive, damaging encounters in gillnets to active, targeted fishing using specially designed traps or pots. This not only increased catch efficiency but also improved the quality of the landed crabs, as they are brought aboard alive and undamaged (Mancinelli et al., 2017).
- **Existing Markets:** Unlike rabbitfish, which required local market development, *P. segnis* benefited from the pre-existing high global demand for swimming crabs. This allowed fishers and processors to tap into a ready-made export market. In Turkey and Tunisia, catches are often processed and frozen for export to European and Asian markets, commanding a significantly higher price than in local sales (Kleitou et al., 2021).

3.2.3. The Goldband Goatfish

While not always commanding the highest price, the Goldband goatfish has become a fundamental component of bottom trawl fisheries in the Eastern Mediterranean. Its ecological success in outcompeting the native red mullet has been mirrored by its commercial adoption (EastMed, 2010). Trawl vessels now routinely land large quantities of this species. It is sold fresh in markets across the region, often at a lower price point than the native mullet, but its sheer volume ensures its economic importance. This fishery demonstrates a passive but effective form of adaptation, where the fishing sector has incorporated a new, dominant species into its landings out of sheer necessity and abundance.

3.2.4 The Devil Firefish

The management of *P. miles* in the Mediterranean is a perfect example of transforming an ecological control measure into a potential economic opportunity. Initially, removal efforts were purely conservation-driven, focused on mitigating its predatory impact on native species. However, studies have confirmed that the Rhodes population of *P. miles* is underexploited, meaning that the current fishing mortality rate is lower than the calculated optimum and limit for fishing, indicating a significant potential for commercial harvest (Kondylatos et al., 2024). The population is characterized by positive allometric growth (it gets stouter as it ages) and a longevity of about 14.4 years. Reproduction is highest during summer and autumn, which suggests that targeted removals during these periods could have the greatest impact on population control. The species is already being sold in Rhodes for approximately EUR 10 per kilo, but the slow rate of commercial adoption is attributed to public fear of its venomous spines. Promoting *P. miles* as a "green alternative" seafood source, through gastronomy events and public education, is essential for normalizing its consumption and creating the market demand necessary to drive the targeted removals for population control.

3.3. Economic Viability at a Small Scale

While case studies demonstrate that targeted fisheries are possible, their ultimate sustainability hinges on economic viability. Preliminary data from emerging small-scale fisheries for Lessepsian migrants, though often fragmented, provide compelling evidence that harvesting these species can be not just feasible but also profitable for coastal communities. This viability is driven by high catch rates, relatively low effort due to the species' abundance, and the development of local market value.

3.3.1. High Catch Per Unit Effort (CPUE)

A fundamental economic advantage of fishing for established Lessepsian species is their high population density, which translates into a high CPUE. For small-scale fishers, this means less time and fuel spent searching for fish and more time with nets or traps in the water yielding catch. In the Levant, *Siganus* spp. are known for their dense schooling behavior. Studies have shown that they can constitute most of the catch in gillnet and beach seine operations in shallow waters, sometimes representing over 50% of the total catch weight in a single haul, making them an incredibly efficient target for artisanal fishers (Ulman et al., 2021; EastMed, 2010). Trials using specialized traps in Greece and Turkey have demonstrated high catch rates in *P. segnis*. A study in Crete showed that traps baited for *P. segnis* could yield several kilograms of high-value crab per trap per day, making targeted potting a highly efficient alternative to trawling (Kleitou et al., 2021). This high CPUE directly offsets the initial investment in specialized gear.

3.3.2. Local Market Value and Income Generation

The development of the local market, even at a modest price point, is critical for transforming a high CPUE into tangible income. The market value for these species varies significantly based on location, consumer familiarity, and the species itself.

Across the eastern Mediterranean, Lessepsian species illustrate different economic models through which non-native biomass can contribute to fisheries revenue. Rabbitfish, for example, have established a stable market value in Lebanon and Egypt, where they are now a recognized and consistently traded commodity. Although their price typically falls below that of higher-value native species such as sea bream, their constant availability and high daily landings provide fishers with a dependable source of income and supply local markets with an affordable protein source (Ulman et al., 2021). Other species demonstrate how value can increase through processing and international trade. The blue swimmer crab offers a clear case, while it already sells for a good price when marketed whole in local markets, its economic potential rises dramatically when processed and exported. Fishers and cooperatives supplying processing plants can obtain significantly higher prices per kilogram, greatly enhancing the overall profitability of the fishery (Mancinelli et al., 2017).

A different model emerges with high-biomass, low-unit-value species such as the goldband goatfish. In Turkish and Greek trawl fisheries, it is landed in substantial quantities. Despite its relatively low price, the volume of the catch makes it an economically important component of trawler revenues, increasingly substituting for declining native species within the catch portfolio (EastMed, 2010).

3.3.3. Cost-Benefit Considerations

The preliminary economic data suggest a favorable cost-benefit ratio for small-scale operations targeting these species. The primary costs involve gear adaptation (purchasing crab traps) and potential initial market development. However, these are often balanced by:

- Reduced search time and fuel costs due to high abundance.

- Reduced gear loss and damage when moving from passive gillnetting to active, targeted potting.
- The creation of a new revenue stream from a resource that was previously a cost (discarded bycatch) or a nuisance (gear damage).

4. Value Chains and Market Development

4.1. Product Development and Processing

A critical step in transforming Lessepsian migrants from low-value bycatch or niche products into mainstream commodities is innovation in product development and processing. The biological characteristics of these species, ranging from bony structures to unfamiliar morphologies, often present challenges that can be overcome through strategic processing, thereby enhancing their marketability, shelf life, and economic value. Moving beyond selling whole fish opens new market segments and can significantly increase the overall value derived from this new biomass.

4.1.1. Whole Fish and Minimal Processing for Familiar Species

For species with a familiar morphology and high consumer acceptance, the primary product form is whole, fresh fish on ice. This is the dominant model for rabbitfish and goldband goatfish in local Levantine and Aegean markets (Ulman et al., 2021; Zenetos et al., 2020). The processing is minimal, involving mainly gutting and scaling, which aligns with traditional practices and keeps costs low for small-scale fishers. This approach capitalizes on the existing culinary traditions and is the most straightforward path to market.

4.1.2. Value-Added Products

For many Lessepsian species, creating value-added products is essential for overcoming consumer hesitancy or biological limitations. Filleting and de-boning offer one of the most effective pathways. Species with a bony structure or unfamiliar appearance can become far more marketable when processed into clean fillets. Skilled filleting not only reduces the challenge posed by their bones but also opens opportunities to supply restaurants and consumers who prefer boneless fish. The brushtooth lizardfish, often regarded negatively despite its firm flesh, can similarly be transformed into a neutral, versatile product through filleting, helping to shed its reputation as a "pest" species and enabling its use in a wide range of culinary applications (Golani, 1994). The devil firefish represents another strong candidate: once its venomous spines are removed and the fish is converted into safe, boneless fillets, it has clear potential as a premium seafood item, turning a hazardous predator into a high-value product.

Surimi production offers an additional strategy for adding value, particularly for abundant species with low market appeal. Surimi allows processors to convert firm-fleshed species such as *Saurida* spp. and other underutilized Lessepsian migrants into a versatile intermediate product. This paste can then be used to manufacture widely accepted items including fish balls, crab sticks (kamaboko), and seafood sausages (Rousseau et al., 2019).

4.1.3. Non-Food Applications for Problematic Species

The most innovative processing pathways are required for high-biomass, problematic species like the silver-cheeked toadfish. Since its tissues contain tetrodotoxin, rendering it unsafe for direct human consumption, research has focused on non-food applications that still extract economic value:

- **Fishmeal and Fish Oil:** The most straightforward application is the rendering of the whole fish into fishmeal and fish oil for use in aquaculture feeds, agricultural fertilizers, or industrial uses. This provides a direct, if low-value, outlet for removing this pest from the ecosystem (Kalogirou, 2013).

- **Leather Production:** The skin of *L. sceleratus* is thick, durable, and has a distinctive pattern. Trials have shown it can be successfully tanned into high-quality, exotic leather for the fashion and accessories industry, potentially creating a high-value product from a toxic waste problem (Kleitou et al., 2021).
- ***Biotoxin Extraction:*** The most high-tech and speculative avenue is the controlled extraction of tetrodotoxin (TTX) itself. TTX is a potent neurotoxin with valuable applications in neurological research and as a pharmaceutical agent (as a pain reliever for cancer patients). If a safe and economically viable extraction process can be developed, it could transform *L. sceleratus* from a costly nuisance into a prized biomedical resource (Kalogirou, 2013).

4.2. The Market

The successful commercialization of a product relies as much on perception as on its inherent qualities. For Lessepsian migrants, overcoming the negative stigma of being "alien invaders" is a paramount marketing challenge. A deliberate and strategic branding campaign is essential to reframe these species in public consciousness, shifting the narrative from ecological threat to desirable, sustainable seafood. This involves emphasizing their positive attributes, learning from successful rebranding case studies, and leveraging key influences in the food industry.

4.2.1. Marketing Focus

An effective marketing strategy for Lessepsian seafood should center on three core messages. First, the focus should be on taste and culinary quality. Many of these species have excellent organoleptic properties that can be highlighted to reshape consumer perceptions. Rabbitfish, for example, offer firm, white flesh with a flavor often compared favorably to sea bream (Ulman et al., 2021), while the blue swimmer crab provides sweet, delicate meat similar to that of other prized swimming crabs. Endorsements from chefs and satisfied consumers can reinforce these qualities.

Second, nutritional value should be clearly communicated. These species are generally lean, high in protein, and rich in omega-3 fatty acids, vitamins, and minerals, allowing them to be positioned as healthy choices for nutrition-oriented consumers.

The third and most distinctive marketing message is sustainability. Framing these fisheries as a form of “conservation through consumption” offers a powerful narrative: eating invasive species actively supports the protection of Mediterranean ecosystems (Kleitou et al., 2021). This perspective transforms consumers into contributors to environmental stewardship and can attract a growing eco-conscious market segment. Within this framework, the devil firefish stands out as a compelling premium product. Its excellent flavor, combined with the strong ecological rationale for harvesting an underexploited invasive population, supports branding it as a “sustainable delicacy” that directly contributes to ecosystem management (Kondylatos et al., 2024).

4.2.2. "Silverfin"

A pivotal strategy in overcoming negative perceptions is rebranding through renaming. The most successful example of this comes from the United States, where the invasive "Asian carp" was rebranded as "Silverfin." The term "carp" carried connotations of a muddy-tasting, bottom-feeding fish, while "Silverfin" sounded appealing, clean, and premium. This rebranding, coupled with taste tests that highlighted its mild flavor and flaky texture, was instrumental in changing public perception and creating a new market (Richardson, 2011). This case study provides a direct template for Lessepsian species. For example, the brushtooth lizardfish could be rebranded as "Mediterranean lizardfish" or given a more appealing market name to dissociate it from its invasive past.

4.2.3. The Role of Culinary Influencers: Chefs, Restaurants, and Food Festivals

Top-down marketing alone cannot drive widespread acceptance. Chefs, restaurants, and food festivals serve as influential catalysts, helping transform unfamiliar species into desirable culinary options. Chefs often act as innovators, developing creative dishes that highlight the best qualities of these species. By featuring a “Lessepsian special” on their menus, they lend immediate credibility and inspire consumers with preparation ideas that can be replicated at home. Restaurants, especially those emphasizing local or sustainable cuisine, provide ideal platforms for introducing these species to broader audiences. They offer a low-risk setting where diners can try new seafood without committing to buying or cooking it themselves. Food festivals further improve this momentum. Events such as “Invasive Species Feasts” or “Eat the Invader” celebrations can generate strong public engagement and media visibility. By pairing tasting experiences with education, they help normalize the consumption of invasive species and transform an ecological challenge into a shared culinary experience (Rousseau et al., 2019).

4.3. Supply Chain and Logistics

The transformation of Lessepsian migrants from a local novelty to a stable commodity, particularly for export markets, is critically dependent on the development of robust and efficient supply chains. A reliable product flow from the sea to the consumer requires significant investment in infrastructure, logistics, and coordination among various stakeholders. Overcoming these logistical hurdles is the final, essential step in unlocking the full economic potential of these fisheries.

4.3.1. Establishing a Reliable Cold Chain

Seafood's highly perishable nature makes an unbroken cold chain essential, yet this remains a major gap for many emerging fisheries targeting Lessepsian species. Maintaining optimal temperatures from harvest to final sale is crucial for product quality, safety, and marketability. The process starts onboard. Fishers need access to insulated boxes, reliable ice supplies at landing ports, and proper handling training to preserve freshness. For high-value species like the blue swimmer crab, using holding tanks or specialized containers to keep crabs alive until landing can significantly boost market value (Mancinelli et al., 2017).

Infrastructure at landing sites is often another bottleneck. Many areas still lack adequate cold storage, blast freezers, or refrigerated rooms. Upgrading these facilities allows catches to be stabilized, aggregated, and prepared for processing. This is especially critical for export-oriented products, which must be deep-frozen to –18°C or below to meet international standards (Rousseau et al., 2019). A seamless refrigerated transport network is the final link. Reliable chilled trucks are necessary to move products between landing sites, processors, and distributors. In small-scale or remote communities, establishing centralized collection hubs equipped with cold storage can aggregate catches from multiple fishers, making it feasible for larger refrigerated transporters to service these areas.

4.3.2. Developing Distribution Networks

Efficient distribution networks are essential for matching the growing supply of Lessepsian species with appropriate markets, yet current distribution is often localized and informal. Strengthening and formalizing these systems can significantly enhance the economic potential of these fisheries. At the local level, establishing cooperatives or fisher associations can help standardize quality, consolidate volumes, and improve negotiating power with wholesalers and retailers. Such structures also facilitate more reliable supply and better coordination across the value chain.

Reaching regional and international markets requires broader partnerships. Collaborations with established seafood importers and distributors provide access to expertise in logistics, customs procedures, and market dynamics that small-scale fishers typically lack. Successful examples illustrate how cross-border trade linkages can elevate the value of Lessepsian products and expand their market reach (Kleitou et al., 2021).

4.3.3. Export Possibilities

Successful entry into export markets can significantly boost profitability while validating these products on an international stage. However, accessing such markets requires meeting stringent standards and tailoring products to specific consumer preferences. Compliance with international food safety and traceability requirements demands investment in HACCP-certified processing facilities, proper labeling, and robust documentation systems. Although these requirements pose challenges, they also help elevate the overall quality and reliability of the supply chain. Export opportunities expand further when product forms match market expectations. Frozen IQF blue crab clusters or rabbitfish fillets may be attractive to Asian buyers, while surimi made from lizardfish can target established markets in Japan and Korea (Golani, 1998; Rousseau et al., 2022). Certification and strategic storytelling can add additional value. Sustainability labels and compelling narratives can differentiate these species in competitive international markets and command a premium from environmentally conscious consumers.

5. Sustainable Exploitation

5.1. Biological and Ecological Considerations

The proposition of exploiting Lessepsian migrants, while economically appealing, must be grounded in a rigorous understanding of marine ecology to avoid unintended negative consequences. Simply because a species is non-native and abundant does not automatically mean it can be fished without limit or without triggering complex ecological feedback. Moving from opportunistic harvesting to a managed, sustainable fishery requires confronting key biological uncertainties and acknowledging the potential for unforeseen ecosystem-level reactions.

5.1.1. Data Deficit

A major challenge for developing sustainable fisheries for Lessepsian species is the lack of basic scientific knowledge. Unlike native commercial stocks, which benefit from decades of research, the population dynamics of these invaders remain largely unknown. Addressing the question, "Can we fish them sustainably?" requires urgent data collection in several areas. Understanding stock structure and biomass is critical. It is unclear whether Mediterranean populations of a given species represent a single, well-mixed stock or multiple sub-populations. Accurate estimates of total biomass and spatial distribution are essential for setting meaningful catch limits and reference points (Golani, 2010).

Knowledge of life-history parameters is equally important. Many Lessepsian species are r-selected, growing quickly and reproducing prolifically, which could confer resilience to fishing pressure. However, species-specific studies are needed to confirm these traits (Edelist et al., 2013). Fishery-independent surveys are also vital. Reliance solely on commercial catch data can produce a biased picture, whereas standardized, independent monitoring allows accurate tracking of population trends and helps distinguish fishing impacts from natural fluctuations. Without this scientific foundation, fisheries risk shifting from sustainable exploitation to overfishing, potentially depleting resources before their dynamics are fully understood.

5.1.2. The "Hydra Effect" and Trophic Cascades

A subtle but potentially significant ecological risk is the "Hydra Effect," named after the mythical creature that grew two heads for each one cut off. In ecology, it describes a counter-intuitive situation where increased mortality, such as fishing, can lead to a rise in adult population size. This occurs in density-dependent populations when reducing adult numbers lowers juvenile mortality from competition or cannibalism, resulting in higher juvenile survival and overall population growth (Jørgensen et al., 2008).

Among Lessepsian migrants, this effect warrants careful consideration. Heavy fishing on generalist predators like the brushtooth lizardfish could reduce adult density, easing cannibalism and competition among juveniles and ultimately boosting population size, making the species more problematic. Trophic cascades may also be triggered. Removing a dominant herbivore such as the rabbitfish could release macroalgal forests from grazing, potentially benefiting the ecosystem, or it could enable the spread of less palatable invasive algae. Similarly, extracting mid-trophic predators may free their prey, which may include other invasive species, leading to unintended ecological consequences (Vergés et al., 2014).

5.2. Socio-Economic and Regulatory Hurdles

Beyond the biological uncertainties, the development of fisheries for Lessepsian migrants faces a complex array of human-centered challenges. These socio-economic and regulatory hurdles are often the most immediate barriers to implementation, stemming from deep-seated traditions, economic risks, and legal frameworks that have not yet adapted to the new ecological reality of the Mediterranean.

5.2.1. Fishermen View

A key barrier to developing Lessepsian fisheries is the conservatism and tradition embedded within fishing communities. Generations of experience with native species shape knowledge of their behavior, habitats, and market value, making non-native species a perceived disruption. Many fishers view species such as *L. sceleratus*, which can damage gear, or other so-called "trash fish" as threats rather than opportunities, creating a psychological barrier to targeting these invaders (Kleitou et al., 2021). Consumer habits also reinforce this challenge: introducing unfamiliar species requires overcoming long-standing culinary traditions. Fishers may be hesitant to invest in catching species with unproven or low market value, fearing economic loss (Kleitou et al., 2021).

5.2.2. Lack of Tailored Fishing Gear

Effective fishing requires gear and techniques specifically adapted to the target species' behavior and habitat. For many Lessepsian migrants, this specialized knowledge is in its infancy. While fishers using gillnets and trawls encounter these species as bycatch, targeted fishing often requires different methods. For example, the successful exploitation of the blue crab in the Mediterranean relied on the adoption of specialized pots or traps, which was a new and initially risky investment for many fishers (Mancinelli et al., 2017). A lack of accessible information on effective gear and methods stifles the development of efficient, targeted fisheries.

5.2.3. Outdated and Restrictive Regulations

A major institutional barrier is the persistence of outdated regulations. Many legal frameworks, originally designed to protect native biodiversity, explicitly restrict the landing, sale, or transport of non-native species. In some regions, policies prohibit landing certain invasive species, reflecting a conservation-focused approach aimed at eradication. This creates a direct disincentive for fishers, who may be forced to discard valuable catches at sea, preventing the development of any market (Kleitou et al., 2021).

Even where landing is allowed, formal management frameworks, such as quotas, size limits, or closed seasons, are typically absent. This regulatory gap generates uncertainty for fishers and processors, who are hesitant to invest in fisheries lacking clear rules and long-term stability.

5.3. Lagocephalus sceleratus

Any discussion on the fisheries potential of Lessepsian migrants must confront the most problematic and high-profile invader: the silver-cheeked toadfish. This species embodies the extreme challenges of the Lessepsian phenomenon, being both extraordinarily prolific and dangerously toxic. Its management represents a unique and urgent problem that tests the limits of the "fisheries as a solution" paradigm. This section is dedicated to dissecting the specific challenges it poses and evaluating the potential, however limited, for its utilization. *L. sceleratus* is not merely present in the Mediterranean; it has become a dominant apex predator in the Levantine Basin and is rapidly expanding westward. Its success is attributed to its rapid growth, high fecundity, and a lack of natural predators. This has resulted in immense biomass, making it impossible to ignore (Kalogirou, 2013).

The primary challenge, however, is its toxicity. The fish's tissues, particularly the liver, gonads, and skin, contain very high concentrations of TTX, a potent neurotoxin that is up to 1,200 times more poisonous than cyanide. There is no known antidote. This makes the fish absolutely unfit for direct human consumption, and its accidental consumption has led to numerous severe poisonings and fatalities across the Mediterranean (Ulman et al., 2021). For fishers, it is a triple threat: it damages nets and catches, it is a hazard to handle, and it represents a complete economic loss as it must be discarded.

5.3.1. Eradication vs. Control

The toxicity of *L. sceleratus* makes traditional fishery-based control via human consumption impossible, leaving managers with few, often unappealing, options. Culling and bounty programs have been attempted in some regions, offering fishers payment for each specimen caught. However, these programs are logistically complex, economically unsustainable over time, and may create perverse incentives to maintain the population. There is also a risk of misidentifying non-toxic species as targets (Kleitou et al., 2021). A more practical approach is mandatory landing combined with safe disposal. Requiring all caught specimens to be brought to port prevents discarding at sea, while designated containment or rendering facilities treat the toxic carcasses as hazardous waste (Kalogirou, 2013). Nevertheless, this approach imposes substantial financial and logistical burdens on port authorities.

5.3.2. Non-Food Applications

Since a food fishery is not viable, research has explored non-food applications to convert the prolific biomass of *L. sceleratus* into value. One option is processing the fish into fishmeal and fish oil for uses such as organic fertilizer, biofuel, or livestock feed, which would require secure, specialized facilities to handle the toxic material. The skin of *L. sceleratus* is thick, durable, and patterned, making it suitable for tanning into high-quality exotic leather for the fashion industry, offering a potential high-value product that could partially offset disposal costs (Kleitou et al., 2021). A more speculative but potentially high-value avenue is the controlled extraction of TTX. This potent neurotoxin has applications in neurological research and could serve as a non-opioid pain reliever for cancer patients (Kalogirou, 2013). While technologically complex and distant from widespread implementation, successful extraction could transform *L. sceleratus* from a costly nuisance into a valuable biomedical resource.

6. A Framework for the Future

6.1. Recommended Policy Actions

For the potential of Lessepsian fisheries to be fully realized, proactive and enabling policy frameworks must be established. Current regulations are often reactive, designed for a pre-invasion ecosystem, and now act as barriers to sustainable exploitation. A paradigm shift in policy is required, from a focus solely on prevention and eradication to one that also enables adaptive management and sustainable use of established species.

6.1.1. Legalize and Regulate the Landing of Lessepsian Species

A key policy priority is removing legal barriers that currently prohibit the landing, sale, and transport of established Lessepsian species. Many existing regulations, originally intended to prevent the spread of invasives, inadvertently criminalize the use of a persistent and abundant resource. Amending outdated legislation is the first step. National and regional authorities should revise fisheries and environmental laws to explicitly allow the landing of well-established Lessepsian migrants. This formal recognition enables market development and signals that these species are now a permanent part of the ecosystem and a potential economic asset (Kleitou et al., 2021). Legalization alone is not enough; it should be paired with species-specific management plans to prevent overexploitation and ecological harm. These plans could include permit systems to monitor fishing effort and catch, as well as gear regulations promoting selective, low-impact methods, such as traps for crabs or nets with specific mesh sizes, to minimize bycatch of native species and reduce habitat damage.

6.1.2. Invest in Scientific Research for Stock Monitoring and Sustainable Yield

Managing a fishery without solid data is a recipe for failure, making public investment in scientific research an urgent priority for Lessepsian species. Funding fishery-independent stock assessment surveys is essential. Also, regular, standardized research voyages should measure biomass, distribution, and population structure of key species, providing unbiased data that cannot be obtained from commercial catches alone (Golani, 2010). Life history and ecological impact studies should also be supported. Research on growth rates, reproduction, age at maturity, diet, and ecological interactions, including risks such as trophic cascades or the Hydra Effect, is critical for predicting how fishing pressure may influence populations (Edelist et al., 2013). In parallel, precautionary reference points and harvest control rules must be developed. Conservative catch limits or effort controls can guide exploitation in the absence of long-term data and be adjusted as knowledge improves, avoiding "boom and bust" cycles (Pikitch et al., 2004).

6.2. Key Research Priorities

To transition from opportunistic harvesting to scientifically informed and sustainable management, targeted research is a non-negotiable prerequisite. The current knowledge gaps span biological, technological, and economic domains. A strategic research agenda must be implemented to provide the evidence base necessary for effective policy and profitable, sustainable fisheries.

6.2.1. Life History Studies

The greatest scientific gap for most Lessepsian species is the lack of fundamental life-history data, which is essential for modeling population dynamics and establishing effective management rules. Research must urgently focus on key biological parameters for the most commercially and ecologically significant species. Understanding age and growth through methods such as otolith analysis can reveal growth rates and longevity, while studies of reproductive biology, including spawning seasons, size at maturity, fecundity, and spawning grounds, are crucial for protecting critical life stages (Golani, 2010). Estimating natural mortality rates helps assess population turnover and resilience. Additionally, genetic analyses and oceanographic larval dispersal models are needed to determine whether populations across the Mediterranean represent a single panmictic stock or distinct sub-populations, which is vital for defining the appropriate spatial scale for management (Edelist et al., 2013). Establishing this biological foundation allows for the development of stock assessment models that provide science-based estimates of sustainable harvest rates and reference points, moving management beyond guesswork.

6.2.2. Development of Species-Specific, Selective Fishing Gear

The efficiency and sustainability of any fishery depend heavily on the fishing methods employed. At present, many Lessepsian species are caught incidentally as bycatch in gear designed for native species, highlighting the need for targeted innovation. Research and development should prioritize the design and testing of gear that selectively captures specific Lessepsian migrants while minimizing bycatch of vulnerable native species and reducing habitat impacts. This includes refining traps for species like the blue swimmer crab, developing new traps for other crustaceans or demersal fish, and testing gillnets and trawls with different mesh sizes, shapes, and materials to improve selectivity. Additionally, behavioral attractants such as specialized baits, lures, or acoustic signals could be tailored to the sensory ecology of invasive species, increasing catch efficiency (Kleitou et al., 2021). A central goal is bycatch reduction: promoting gear modifications that allow non-target species, including protected or overfished natives, to escape ensures that the emerging fishery contributes to sustainable exploitation without exacerbating existing conservation challenges.

6.2.3. Economic Analysis of Supply Chains and Market Potential

For a fishery to be viable, it must be economically sustainable, requiring research that examines and optimizes the entire value chain from the sea to the consumer. Economic analyses should evaluate the costs and benefits of targeting different Lessepsian species, considering investments in new gear, fuel, labor, and expected market prices, to identify fisheries with the greatest potential for success and investment. Supply chain research is also essential, mapping existing and potential logistics, identifying cold-chain bottlenecks, and assessing the economic viability of various product forms, whole, filleted, surimi, or frozen, for local, regional, and export markets (Rousseau et al., 2019). Equally important are socio-economic studies on consumer acceptance, willingness to pay, and effective marketing strategies, including rebranding, to support the uptake of products from “sustainable invasive” fisheries. By systematically addressing these research priorities, stakeholders can establish the knowledge base needed to manage Lessepsian migrants not as a crisis, but as a complex yet manageable new reality in the Mediterranean Sea.

7. Conclusion

The Lessepsian migration is one of the most rapid and profound biogeographic events in the modern Mediterranean, fundamentally reshaping its ecosystems (Figure 2).

Figure 2. *Turning a biological invasion into a socio-ecological opportunity.*

While much attention has rightly focused on the threats these species pose to native biodiversity and traditional fisheries, the sole emphasis on negative impacts is no longer sufficient. Many Lessepsian species are now a permanent feature of the Mediterranean, with substantial and growing biomass that presents both challenges and opportunities.

This reality calls for a shift in perspective: these organisms should be recognized not only as invaders but also as a novel, abundant, and underutilized marine resource. Emerging fisheries for rabbitfish in the Levant and blue swimmer crab in the Aegean demonstrate that commercial exploitation of Lessepsian migrants is feasible and can provide income, food security, and socio-ecological resilience for coastal communities.

Realizing this potential sustainably requires coordinated efforts to address biological uncertainties, modernize policies, adapt selective fishing methods, foster market demand, and develop robust value chains, including cold storage, processing innovations, and non-food applications for problematic species such as the toxic *L. sceleratus*. Framed within an Ecosystem Approach to Fisheries Management, these strategies enable fisheries to contribute to ecosystem stewardship, controlling invasive populations while supporting human well-being and integrating economic, ecological, and social objectives for the Mediterranean.

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AQUACULTURE İN LİTHUANİA: CURRENT STATE, CHALLENGES AND OPPORTUNİTİES

MIDONA DAPKIENĖ[1]

1. Introduction

The European fisheries and aquaculture sector operates in a constantly changing and increasingly complex environment. The European Union (EU) aquaculture strategies aim to ensure its long-term economic, environmental, and social sustainability (Luna et al., 2024).

Currently, Lithuania is implementing a Multi-annual National Strategic Plans for the development of sustainable Aquaculture for the period 2021-2030, which sets out ambitious goals. The plan aims to promote a sustainable, innovative, resilient, and diverse aquaculture sector that ensures a stable supply of fish products while contributing to environmental and climate objectives (Lithuanian aquaculture…, 2023).

The production volume is expected to nearly double, from 4,400 tonnes in 2022 to 8,500 tonnes in 2030, while its value is

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projected to rise from almost EUR 13 million to EUR 27 million. Achieving these objectives requires stronger emphasis on the protection and restoration of natural ecosystems, the sustainable use of resources, and the promotion of human health (Multi-annual National…, 2022).

It is important to analyze the current state of Lithuania’s aquaculture sector - including its strengths, weaknesses, opportunities, and threats - in order to inform appropriate decision-making.

2. Lithuanian climate, water resources and hydrography

Lithuania is a semi-humid country. The climate is transitional between maritime and continental. In the 12-15 km-wide coastal zone it is maritime, and in the east of the country it is continental.

The average annual precipitation is 748 mm ranging from less than 550 mm in the north to a maximum of more than 846 mm. The precipitation is 1.6 times higher the evaporation.

Lithuania possesses abundant freshwater resources, particularly in its groundwater reserves. Country's renewable surface water resources are significant, estimated at 15.36 km^3/year. Natural resources of fresh groundwater in Lithuania are estimated at 13 million m^3 per day, and operational resources are 3.72 million m^3 per day.

Lithuania’s inland waters hold significant untapped potential, covering a total area of 2,621 km^2, which is about 4% of the country’s territory. The country has approximately 29,900 rivers and streams longer than 0.25 km, with a combined length of 64,000 km, resulting in an average river network density of 1 km/km^2. The Nemunas River, the longest in Lithuania, drains a basin that accounts for around 74% of the country’s total area. Annual river runoff, including transit flow, amounts to 26.2 km^3. Lithuania is home to

2,830 natural lakes larger than 0.5 hectares, 25 of which exceed 10 km^2, collectively representing 1.5% of the country's total area. In addition, there are roughly 340 artificial ponds larger than 5 hectares. (Climate atlas of Lithuania, 2013; Dapkiene & Kustiene, 2008).

Water from approximately 75% of Lithuania's territory enters the Curonian Lagoon. There are large concentrations of nutrients and main eutrophication elements. The Nemunas River flows into Baltic Sea via the Curonian Lagoon and Klaipėda Straits with an approximate total annual inflow to the Baltic Sea up to 23 km^3. Both the Curonian Lagoon and the Baltic Sea are the primary sources of Lithuania's fish resources, the status of which is directly affected by pollution.

Lithuania has a relatively short coastline of only 90 km, and its territorial waters and exclusive economic zone in the Baltic Sea amount to 7000 km^2. The Port of Klaipėda is the only multipurpose, deep-water port in Lithuania. Fishing vessels also use small ports like Nida and Šventoji.

The country's fishing catch mainly consists of round sardinella, horse mackerel, sardine, and Atlantic cod.

The Lithuanian fleet is divided into 3 segments: small-scale operating in the Baltic Sea coastal area; large-scale vessels operating in the Baltic Sea; long-distance fleet that is the largest in terms of capacity and economic size (Overview of Lithuania's..., 2023).

3. Lithuanian aquaculture sector

The Lithuanian aquaculture sector produced around 4,393 tonnes of fish for human consumption in 2022. The most common production method is ponds, accounting for around 70% of total production for consumption (Fig.1). The area of aquaculture ponds is about 10,100 hectares, of which 4,300 hectares are cultivated with organic production. The volume of recirculation aquaculture systems is almost 15,300 m^3. The structure of the Lithuanian aquaculture sector is shown in Fig.2.

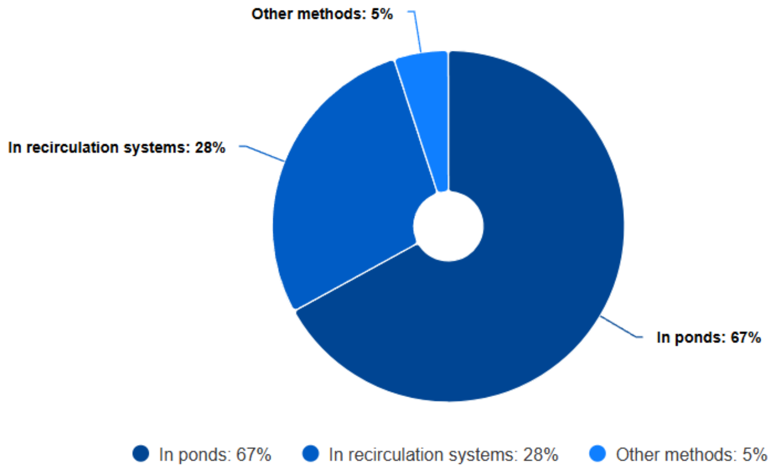
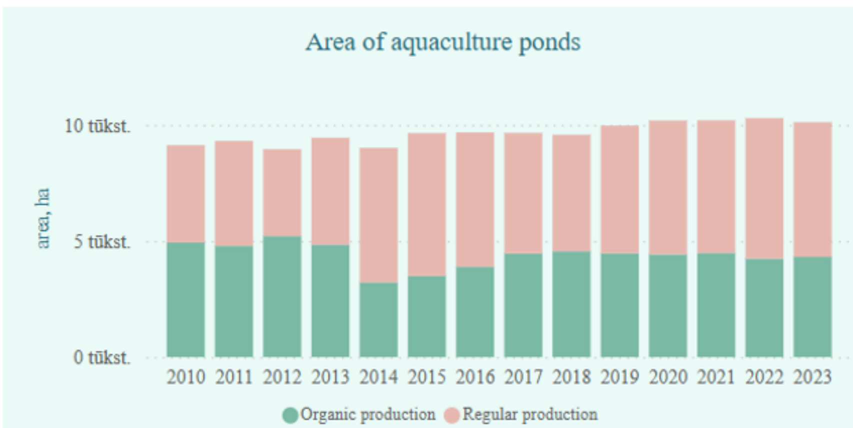


Figure 1. Methods of aquaculture in Lithuania (EUMOFA, 2025)



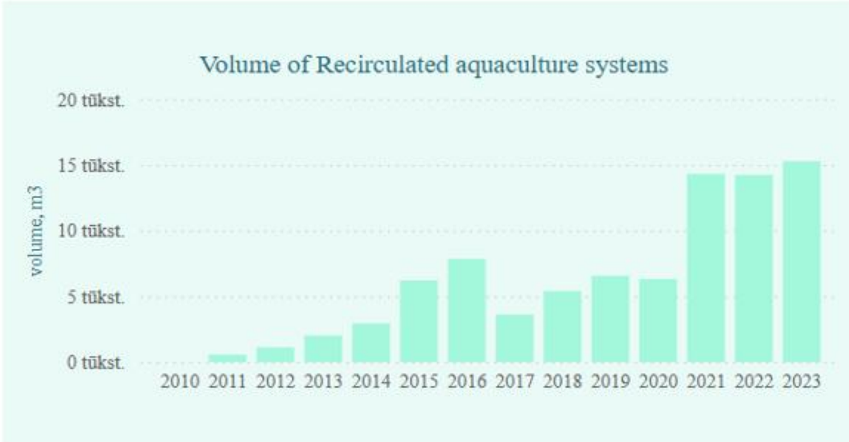


Figure 2. The structure of the Lithuanian aquaculture sector (Lithuanian national…, 2023)

Lithuania is a relatively small producer of aquaculture products within the European Union (Table 1). In terms of overall fisheries production, the country ranks around the middle among the 27 EU member states.

Table 1. Lithuania in the field of fisheries: global and EU context, 2022 (EUMOFA, 2025)

1000 tonnes	**World**	**EU-27**	**Lithuania**	**% World**	**% EU-27**
Catches	92,050	3,466	75	0.081	2.2
Aquaculture	130,885	1,089	4	0.003	0.4
Total	**222,936**	**4,554**	**79**	**0.035**	**1.7**

The aim is that by 2030, the annual aquaculture production in Lithuania would amount to at least 8,500 tonnes, the share of the area of stocked organic aquaculture ponds would increase by 16%, and organic aquaculture production would increase by 39%. The main export market for Lithuanian aquaculture production was

Poland and Latvia, corresponding to the 70% and 23% of total exports respectively (Lithuanian aquaculture…, 2023).

4. Challenges in the aquaculture sector

The main challenge for the Lithuanian fisheries sector is to develop environmentally sustainable and profitable fishing by reducing the impact of fishing on the marine environment. The challenges in the aquaculture sector are as follows to increase energy efficiency and the use of renewable energy in pond aquaculture; to promote the use of recirculation aquaculture systems; to cultivate fish species that can open new markets and ensure higher prices, while preserving traditional extensive aquaculture and organic production (EU aquaculture…, 2024).

In Lithuania, most production comes from traditional carp pond farms, but modern recirculating aquaculture systems are gaining popularity. These systems are used to raise African catfish, sturgeon species, eels, rainbow trout, and other salmonid fish. Fish consumption is primarily driven by habits. Consumers need to become accustomed to new fish species and their products.

Lithuania is a small country with a relatively limited domestic consumer market. Demand and consumption are primarily driven by three factors: quality, variety, and price. However, fish remains relatively expensive compared to livestock and poultry products. Advances in technology and targeted support for the sector could help lower production costs, ensure high product quality, and expand the diversity of aquaculture products (Lithuania: A challenging…, 2021).

5. The impact of pond aquaculture on biodiversity and climate

Global warming, ocean acidification, rising sea levels, and changes in precipitation patterns are progressively affecting aquaculture production worldwide (Lithuanian aquaculture…, 2023). The sector's contribution to climate change is associated with the farming, processing, transportation, and storage of fish and other aquatic organisms.

Most greenhouse gas (GHG) emissions from aquaculture come in the form of carbon dioxide (CO_2), generated primarily through energy production and consumption. However, an assessment by the Food and Agriculture Organization (FAO) of the United Nations indicates that the climate impact of aquaculture is relatively low, accounting for only 0.45% of total human-induced GHG emissions.

Pond aquaculture farms in Lithuania were originally developed to generate economic benefits, which also promoted intensive fish production. However, recent plans, such as the Multi-annual National Strategic Plan for the Development of Sustainable Aquaculture for 2021-2030, highlight the increasing ecological importance of these ponds. Increasing attention is being paid to protecting the environment and biodiversity, as well as preserving traditional landscapes and the unique features of aquaculture areas (Multi-annual National…, 2022).

Shallow ponds are especially attractive to birds. They provide excellent feeding opportunities and safe habitats for breeding. According to Lithuanian ornithologists in their 2021 study "Analysis and Evaluation of the Environmental Importance of Lithuanian Pond Fishery (Aquaculture) Farms", ponds often have the highest conservation value when located along bird migration routes, near important wetlands, or on former marshlands. During spring and autumn migrations, these ponds become gathering spots for waterfowl and marsh birds. Predatory birds also frequently visit to hunt.

Many pond farms serve as crucial breeding sites for rare bird species. In total, 29 bird species listed in the Lithuanian Red Data

Book and 20 species protected under the EU Birds Directive (Council Directive 79/409/EEC) are known to breed in these ponds.

Some ponds also host species of European conservation concern, including the European fire-bellied toad (*Bombina bombina*), smooth newt (*Lissotriton vulgaris*), and ten other protected amphibians, as well as otters (*Lutra lutra*), which were listed in the Lithuanian Red Data Book between 1989 and 2019. The fire-bellied toad, smooth newt, and otter are also included in the EU Habitats Directive, which requires active protection of these species.

Moreover, pond aquaculture helps to compensate for the loss of shallow wetlands that were drained or destroyed during agricultural development, thus maintaining ecological functions that would otherwise be lost. Importantly, these farms do not appear to negatively affect natural fish populations and have no significant adverse impact on the climate. Overall, pond aquaculture can be seen as a sustainable land use practice that balances economic activity with environmental benefits.

Objective of climate change adaptation and mitigation in Lithuania are as follows:

- to support the implementation of measures to reduce environmental pollution and technological innovation.
- to support the implementation of energy efficiency measures and to promote the use of energy from renewable energy sources.
- to support the implementation of adaptation measures.
- energy consumption and carbon emissions from production, transport and processing must be reduced as much as possible.

Aquaculture also has significant mitigation potential. As already mentioned, well-managed aquaculture can help preserve ecosystems such as wetlands. These ecosystems protect against climate change impacts such as sea-level rise and floods. This type of aquaculture should be promoted, as well as aquaculture providing circular economy, energy efficiency and ecosystem services (Multi-annual National…, 2022; Lithuanian aquaculture…, 2023).

6. Organic pond aquaculture

The responsible use of energy and resources aligns with EU strategies, and the European Commission is therefore encouraging Member States to increase organic production. In the European Green Deal strategy "Farm to Fork", it is emphasized that environmentally friendly practices should be widely promoted, with the goal of achieving significant growth in organic aquaculture production. The Action Plan for the Development of the Organic Food Sector also outlines initiatives aimed at supporting the expansion of organic aquaculture.

In organic fish farming, greater attention is given to sustainable production, fish stocking density, fish health and welfare, and water quality.

The main principles of organic fish farming are:

- production of high-quality products without the use of artificial additives.
- ensuring minimal environmental impact and protecting products from external pollution.
- proper fish health care, suitable living conditions, and minimal stress, which reduce disease occurrence while ensuring compliance with veterinary and sanitary requirements.

- prioritizing phytotherapeutic or homeopathic treatments for disease management, with allopathic veterinary medicines used only when alternative remedies prove ineffective.
- complete avoidance of synthetic fertilizers and pesticides.

Lithuania is among the main producers of organic carp in the EU, but the volumes are relatively small. In 2022, twelve pond aquaculture farms in Lithuania were engaged in organic production. The certified organic farming areas in individual farms ranged from 17 to 860 hectares. Stocked ponds used for organic aquaculture accounted for 43.9% of the total pond area. Organic products made up 23% of all aquaculture production from these ponds.

The volume of organic aquaculture production in 2023 is shown in Fig. 3. According to Lithuania's strategic plan, organic aquaculture production is expected to reach 1,200 tonnes by 2030. (Lithuanian aquaculture…, 2023).

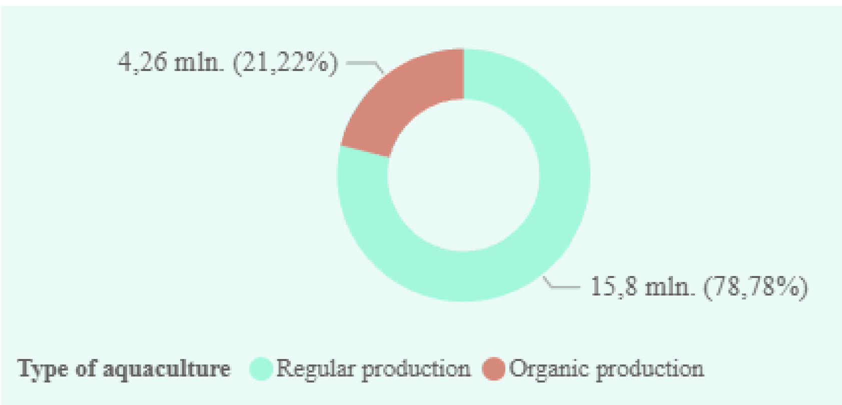


Figure 3. The amount of organic production in the Lithuanian aquaculture (Lithuanian national…, 2023)

7. SWOT of the Lithuanian aquaculture

Analysis of the strengths, weaknesses, opportunities and threats (SWOT) is very important for making appropriate decisions in the country's aquaculture (Table 2).

Table 2. SWOT of aquaculture in Lithuania (Multi-annual National…, 2022)

Strengths	Weaknesses
Large areas of aquaculture ponds. A sufficiently developed network of aquaculture enterprises capable of supplying consumers with fresh aquaculture products year-round. Long-standing traditions and experience in breeding and raising various fish species and strains in ponds, along with a developed network of aquaculture enterprises capable of supplying stocking material. Relatively strong skills among pond farm specialists in adopting new and promising fish breeding and farming technologies, with a system for training aquaculture specialists being developed. Development of organic aquaculture production methods. High interest in recirculation aquaculture systems (RAS). Environmental impact reduction through RAS development. High potential for ecosystem services. Experience in implementing biodiversity conservation measures.	Limited diversification of products manufactured by aquaculture enterprises and underdeveloped production of innovative, higher value-added products. Relatively low domestic supply of valuable fish species (such as sturgeon, pikeperch, trout) and their juveniles. Underdeveloped value-added chains in aquaculture enterprises, with insufficient infrastructure for product processing, storage, and organizing short supply chains. Insufficient financial capacity of aquaculture enterprises to modernize farms, adopt new technologies, and implement innovations. Inadequate implementation of environmental protection measures - pollution control and water resource protection are not ensured. Insufficient investment by aquaculture enterprises in energy efficiency measures; high dependency on energy resources.

Recognized organizations representing the interests of the aquaculture sector are active, with ongoing international and local cooperation. A modern fish processing sector capable of processing local aquaculture products. Application of new technologies to improve resource use and farm management efficiency. Increased availability of consulting and training services to raise the knowledge level of aquaculture specialists.	Shortage of specialists with higher or vocational education in aquaculture development. Underdeveloped research and application of new technologies in the sector. Weak management in some companies and poor marketing skills for operating in the EU market. Sector vulnerability to climate change impacts. Seasonality of income in pond aquaculture activities. Due to its climate zone, Lithuania lies on the edge of the carp farming area, meaning marketable production is achieved in three years instead of two.
Opportunities	**Threats**
A domestic market receptive to fresh fish and fish products. Growing demand for organic or higher-than-standard quality food products, including aquaculture, due to changing consumer dietary habits. Comparatively abundant national water resources. Favorable natural conditions (including clean groundwater) and engineering infrastructure for developing RAS. Shortening of supply chains. Increasing attention to aquaculture sector development in both EU and Lithuanian fisheries policy strategies. Scientific and technological progress enabling the	Instability in domestic and export markets, increasing competition. Rising energy prices and corresponding increases in aquaculture operational costs. Changes in the legal framework (environmental and production requirements) that may restrict aquaculture activities. Tightening lending policies by financial institutions and a lack of funding for new investments in the aquaculture sector. Intensifying climate change and adverse climatic factors negatively affecting aquaculture activities. Labor shortages, especially of qualified workers, due to worsening demographic trends in the country.

improvement of existing and development of new bioproducts in aquaculture. Adoption of international experience in aquaculture innovation. Creation of cooperation networks among producers, consultants, scientists, and consumers. Growing demand and consumer willingness to pay for ecosystem services, such as attractive landscapes, rich biodiversity, and healthy habitats. Increasing demand for local tourism and recreation services, with aquaculture pond environments offering attractive leisure opportunities. Untapped potential to improve energy efficiency and expand the use of renewable energy sources. Opportunities to breed new fish species in the context of climate change.	Declining appeal of aquaculture technologies and business among young people. Damage to fish resources in aquaculture farms caused by fish-eating birds. Emergence and spread of new infectious and invasive fish diseases (including those transmitted by birds).

8. The progress indicators and direction of activity to implement the plan for the development of the aquaculture sector

The progress indicators for the development of Lithuania's aquaculture sector by 2030 are presented in Table 3.

Table 3. Progress indicators for the development of Lithuania's aquaculture sector by 2030 (Multi-annual National…, 2022)

No.	Indicators	Unit of Measurement	Target Value
1.	Quantity of aquaculture production	tonnes	8,500
2.	Value of aquaculture production	mln. EUR	26.500
3.	Share of aquaculture production in flow-through aquaculture systems and RAS	%	47
4.	Number of companies engaged in aquaculture production and submitting official statistics	units	75
5.	Quantity of organic aquaculture production	tonnes	1,200
6.	Value of organic aquaculture production	mln. EUR	3.040
7.	Share of pond aquaculture production that is organic, in total pond aquaculture production	%	27
8.	Share of pond farming area producing higher quality (certified) aquaculture products	%	5
9.	Share of pond area used for organic aquaculture farming	%	50
10.	Number of aquaculture companies implementing environmental protection projects	units	30
11.	Share of aquaculture farms/companies using renewable energy resources	%	25
12.	Number of aquaculture farms/companies diversifying activities	units	25

The following main areas of activity are planned in the implementation of the Multi-annual National Strategic Plans for the development of sustainable Aquaculture for 2021-2030:

- to increase the resilience and competitiveness of the aquaculture sector, to orient it towards the market,
- to ensure that the aquaculture sector better meets societal needs related to food safety, animal health and welfare; to help mitigate and adapt to climate change;
- to promote effective management of natural resources and the preservation of habitats and landscapes;
- to modernize the aquaculture sector by accumulating and sharing knowledge, implementing innovations, encouraging cooperation, and attracting young professionals.

9. Conclusion

Lithuania is implementing a Multi-annual National Strategic Plans for the development of sustainable Aquaculture for the period 2021-2030, aimed at promoting a sustainable, innovative, resilient, and diverse aquaculture sector, while also pursuing environmental and climate-related objectives.

Since most production in Lithuania originates from traditional pond farms, a key challenge is improving energy efficiency and promoting the use of renewable energy in pond aquaculture. Another important priority is encouraging the adoption of recirculation aquaculture systems, cultivating fish species that can open new markets, and expanding ecological production.

Pond aquaculture generally has a positive impact on the environment and biodiversity. It provides suitable habitats and breeding grounds for birds, amphibians, and endangered mammals. Additionally, ponds create opportunities for recreational activities, allowing people to engage with nature within agricultural landscapes. When properly managed, aquaculture can help preserve wetlands, which in turn protect against climate change impacts such as sea-level rise and flooding.

Lithuania has substantial opportunities to develop and expand its aquaculture sector. Key advantages include abundant water resources and favorable natural conditions, as well as existing engineering infrastructure suitable for recirculation aquaculture systems. Advances in science and technology support the improvement of existing products and the creation of new aquaculture species. Additionally, growing consumer demand and willingness to pay for ecosystem services, untapped potential for renewable energy use, and opportunities to breed new fish species in response to climate change all contribute to the sector's development prospects.

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COATED FISH AND SHELLFISH PRODUCTS: MAPPING TECHNOLOGICAL TRENDS AND EMERGING REFORMULATION STRATEGIES

BURCU ÖZTURK-KERİMOĞLU[1]

1. INTRODUCTION

1.1 Global Overview of the Seafood Sector

Seafood represents one of the most dynamic and economically significant sectors of the global food industry, offering a diverse, accessible, and high-quality source of animal protein to consumers worldwide. According to the Organisation for Economic Co-operation and Development - Food and Agriculture Organization (OECD-FAO) Agricultural Outlook 2025-2034, which provides a comprehensive assessment of the ten-year prospects for agricultural commodity and fish markets at national, regional, and global levels, global fisheries and aquaculture production reached approximately 193 million tonnes (Mt) in 2024, reflecting continued growth in both aquaculture and capture fisheries. Aquaculture maintained its steady upward trajectory, while capture fisheries showed recovery after a slight decline in 2023. The report further indicates that global

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demand for fish and other aquatic foods intended for human consumption is projected to increase by 13% over the next decade, primarily driven by population growth. As a result, total apparent consumption is expected to reach 192 Mt (live weight equivalent) by 2034, an increase of 22 Mt compared with the 2022-2024 base period average (OECD-FAO 2025).

The global market for processed seafood products is experiencing significant growth, driven by factors such as consumer demand, technological advancements, and sustainability concerns. The rise in global demand for seafood has been spurred by changing lifestyles and a growing awareness of the health benefits associated with seafood consumption (Sandaruwan & Banerjee 2020). Technological advancements play a pivotal role in shaping the seafood processing industry, particularly through the adoption of Industry 4.0 technologies that enhance operational efficiency and accelerate the transition toward more sustainable and demand-oriented production practices. The implementation of advanced technologies not only aids in meeting consumer expectations for quality and sustainability but also enhances the competitiveness of seafood processing firms in global markets (Zhou 2025).

The Blue Transformation initiative, launched by FAO (2022), represents a global strategic framework designed to unlock the full potential of aquatic food systems. Its overarching goal is to enhance food and nutrition security, eradicate poverty, and advance the 2030 Agenda for Sustainable Development by promoting responsible and sustainable growth within fisheries and aquaculture. Aligned with the FAO's strategic narrative and key aspirations, the Blue Transformation Roadmap 2022-2030 defines three core pillars:

1. Sustainable expansion of aquaculture, ensuring growth that minimizes environmental impact while maximizing social and economic benefits.

2. Effective management of capture fisheries, emphasizing science-based governance, resource conservation, and equitable benefit distribution.
3. Improved value chains and market access, focusing on reducing post-harvest losses, enhancing processing efficiency, and promoting fair and inclusive trade.

The roadmap also sets quantifiable targets, supported by priority actions to guide national and international efforts. These include promoting digitalization and innovation in seafood processing, improving traceability and transparency, strengthening food safety systems, and fostering partnerships among governments, industries, and communities to achieve sustainable blue economies. In this context, technological progress and innovative processing approaches are regarded as key drivers for realizing the Blue Transformation vision, contributing to the sustainable growth, diversification, and resilience of aquatic food systems worldwide (FAO 2022, FAO 2024).

1.2 Processed Aquatic Food Products

Animal-based sources contribute substantially to the global average daily protein intake, providing 42% of total dietary protein. Within animal proteins, dairy products represent the largest share (10%), followed by poultry (8%), aquatic foods (6%), pork (6%), bovine (4%), and eggs (4%). Minor shares are derived from ovine and caprine products (1%) and other animal sources (2%) (FAO 2025). Aquatic foods, which include fish, shellfish, and other seafood, thus play a notable role in the global protein intake and form an essential component of animal-derived nutrition.

Owing to their rich content of marine-derived long-chain omega-3 polyunsaturated fatty acids (n-3 LC-PUFA; $C \geq 20$), fish and shellfish are widely recognized as foods of superior nutritional quality, playing an essential role in supporting human health and balanced dietary patterns (Xavier et al. 2018). Given their exceptionally high nutritional value, it is crucial to promote the development of diverse seafood products and to increase product variety through processing and innovation.

According to FAO (2024), global harvests of aquatic animals reached 185.4 million tonnes (live weight equivalent) in 2022, of which approximately 89% (164.6 million tonnes) was destined for direct human consumption. The remaining 11% (20.8 million tonnes) was allocated to non-food purposes, with about 83% (17 million tonnes) processed into fishmeal and fish oil. The rest, around 4 million tonnes, was mainly utilized for ornamental fish, aquaculture inputs (such as fry, fingerlings, or small adults for on-growing), bait, pharmaceutical applications, pet food, and as feed material in aquaculture, livestock, and fur animals. With some fluctuations over time, the share of aquatic animal production directed to human consumption has risen markedly over the past decades, from 62% in 1970 to 89% in 2022. In general, high-income countries exhibit a higher level of processing compared with lower-income regions, reflecting a growing preference for high-value, convenience-oriented products such as ready-to-eat meals. Figure 1 illustrates the global utilization of aquatic animal production by main use and product form over a six-decade period (1962-2022). During this time, production of both fresh and processed aquatic food products has increased substantially, reflecting overall growth in global fisheries and aquaculture output. The live, fresh, or chilled category has consistently remained the dominant form, underscoring consumers' preference for freshness and the expansion of cold-chain logistics. At the same time, the frozen and prepared or preserved categories have shown notable growth, driven by advances in processing technology and longer shelf-life requirements. In 2022, among aquatic animal products destined for human consumption in high-income countries, approximately 55% were marketed in frozen form, 26% as prepared or preserved products, and 13% as cured products, underscoring both technological capacity and consumer demand for processed seafood formats (FAO 2024). This trend illustrates the ongoing global shift toward processed and value-added seafood products, highlighting the importance of technological innovation in meeting evolving consumer preferences and market demands.

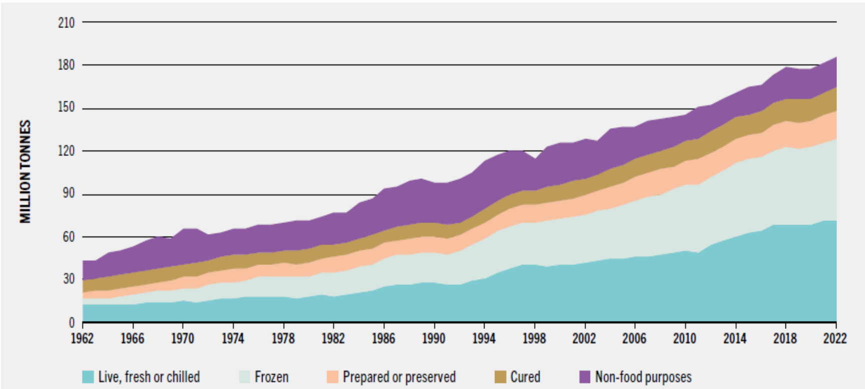

Figure 1. *Six decades of change in the utilization of global aquatic animal production (FAO 2024).*

**Aquatic animals excluding aquatic mammals, crocodiles, alligators, caimans, sponges, corals, pearls, and algae.*

2. COATED FISH AND SHELLFISH PRODUCTS

2.1 Definition and Classification

As also highlighted above, in recent years, there has been a notable shift from fresh seafood products toward value-added forms, driven by evolving consumer lifestyles, urbanization, and the growing demand for convenience. Ready-to-eat and ready-to-cook seafood segments are expanding rapidly, reflecting broader trends in the food industry toward products that combine nutrition, safety, and ease of preparation. This transition not only enhances the economic value and market reach of aquatic resources but also contributes to reducing post-harvest losses and promoting sustainable utilization through diversified product development and improved processing technologies.

Among the further processed marine-sourced products, coated aquatic foods represent a major segment of the value-added seafood market. These products are particularly popular in both retail and food service sectors due to their convenience, sensory appeal, and versatility, meeting the expectations of modern consumers for quick, palatable, and nutritionally balanced meals. They exhibit desirable sensory attributes, characterized by a crisp and tender outer layer coupled with a moist and juicy interior (Alizadeh and Rezaei 2025).

Coating is a broad term that encompasses both liquid mixtures—composed of water, eggs, flour, starch, and spices—into which food products (meat, fish, poultry, cheese, and certain vegetables) are dipped, as well as the textured dry mixtures—prepared with flour, starch, breadcrumbs, and spices—that are typically applied after the liquid mixtures (Kaymak-Ertekin, 2005; Serdaroğlu and Öztürk Kerimoğlu 2023). Coatings help preserve and improve food quality by minimizing moisture loss during frying and enhancing the development of desirable flavors (Carvalho and Ruiz-Carrascal 2018). According to Turkish legislations, coated meat products are defined as "prepared meat mixtures made from one or more portions of carcass meat of domestic ungulates or poultry, with the possible addition of fats from the same and/or different animal species, flavoring agents, and one or more other food ingredients, which are subsequently dipped into liquid mixtures composed of water, eggs, flour, starch, and flavorings, then coated with dry mixtures prepared from flour, starch, bread crumbs, and flavorings, resulting in either an unheated prepared meat mixture or a heat-treated meat product" (Turkish Food Codex 2019). Although this definition does not explicitly cover fish and shellfish, it generally corresponds to the description of coated products produced from fish and shellfish in terms of formulation and processing characteristics.

The term *coating*, as also discussed in subsequent sections, may encompass a broader range of applications, including products surrounded by edible films or similar materials. For products that are processed in multiple steps, such as battered and breaded items, the term *enrobing* is often used interchangeably (Xavier et al. 2018). In addition, these products could also be named after *batter-breaded* products (Chen et al. 2020, Zhai et al. 2024). However, in this chapter, the broader and more inclusive term *coating* has been preferred, and the bibliometric overview presented in the following section is organized accordingly.

2.2 Production Process and Coating Materials

A standard flow chart illustrating the main processing steps applied in the production of coated meat products is presented in Figure 2. Accordingly, the primary processes involved in the manufacture of such products include size reduction, batter preparation (mixing), forming (shaping), cold structuring, pre-dusting, battering, breading, thermal processing, cooling/freezing, and packaging. In production, the minced meat is first mixed in kneading or cutter equipment with the addition of salt, phosphates, water, and other ingredients, if present. The nugget mix, prepared at an appropriate formulation and temperature, is then formed using molds of suitable size and shape. In other products that are not prepared as a homogenized meat batter, the raw material is cut into suitable portions, such as strips. In addition, pieces that will be coated whole can be processed directly (Fiszman and Sanz 2010, Serdaroğlu and Öztürk Kerimoğlu 2023).

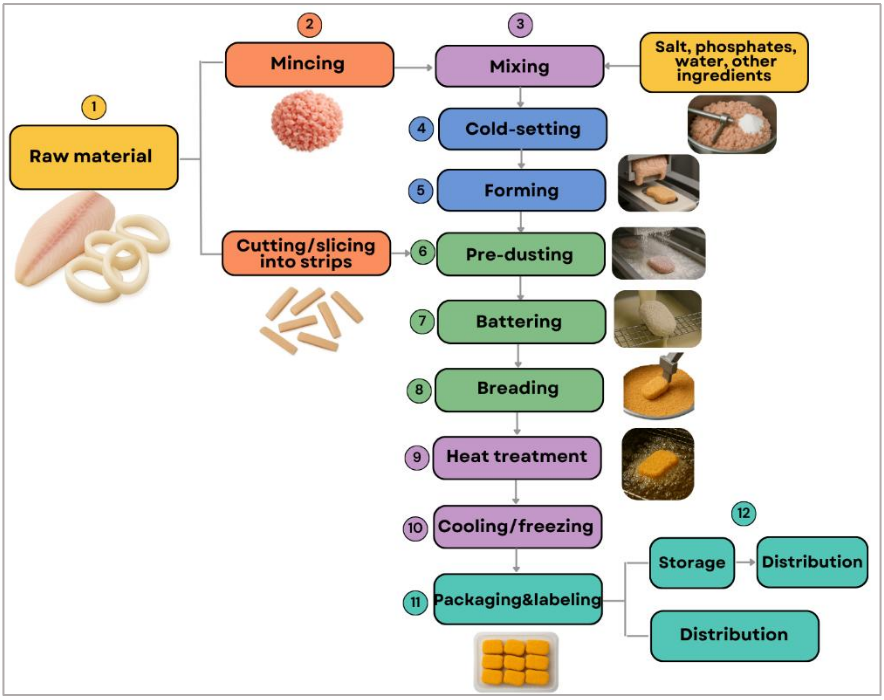

Figure 2. *General production flowchart of coated meat products.*

In a standard coated meat product production line, the coating process is carried out in three main stages:

1. Pre-dusting,
2. Battering (liquid coating),
3. Breading (dry coating).

On the other side, various alternative combinations can also be applied. For example, while one coated product may sequentially undergo pre-dusting, battering, and breading, another product may only receive battering and breading. In fact, some coated meat products are produced using only a single coating step, such as an outer dry coating or a tempura-type liquid coating (Serdaroğlu and Öztürk Kerimoğlu 2023).

The surface of the portioned meat mixture is first treated with a dry flour-based material for pre-dusting. It is then dipped into a semi-liquid coating batter composed of various ingredients such as different flours, starches, oils, eggs, water, and spices. Subsequently, an outer coating is applied using flour, an oil/flour blend, and/or breadcrumbs. In the final step of the process, the coated products are briefly deep-fried to stabilize the coating material on the meat surface. Following this pre-cooking operation, the desired color and texture are developed, preparing the product for consumption. In this way, coated meat products become ready-to-eat with a short cooking or reheating time (Serdaroğlu and Öztürk Kerimoğlu 2023).

In coated muscle foods, the primary quality criteria include the rheological properties and viscosity of the batter, coating pick-up and adhesion, cooking yield, oil absorption, moisture retention, color, texture, crispness, and microstructural characteristics (Chen et al. 2008, Fiszman 2009, Serdaroğlu and Öztürk Kerimoğlu 2023). The factor that most directly influences the visual quality of the final product is the outermost layer of the coating. This final integrated outer layer of the coated and pre-cooked products is known as the "crust". The crusts of fried products contribute to a crispy texture and golden-yellow color while serving as a barrier that prevents moisture loss and preserves the food's natural juices, resulting in a tender and juicy interior beneath the crisp exterior (Chen et al. 2008, Chen et al. 2020, Serdaroğlu and Öztürk-Kerimoğlu 2023). The quality of the crust is highly affected by several factors, such as the formulation of the batter, the heat treatment method, frying oil, frying temperature, frying time, and product shape (Chen et al. 2009).

Frying is the characteristic process shaping the final sensory and textural quality of the product. Moisture evaporation is one of the key physical processes during frying, causing dehydration of the product and the formation of a porous crust that primarily contributes to the crispy texture (Zhai et al. 2024). The mechanism of oil uptake is primarily governed by heat transfer and the migration of oil into the voids formed after water evaporation. During frying, moisture initially escapes from the outer crust, followed by the migration of water from the product's core toward the surface. This process leads to the formation of a porous and weakened crust structure, which subsequently allows fat from the frying medium to penetrate and fill the empty pores (Hauzoukim et al. 2019). He et al. (2026) extensively investigated the mechanism of deep-fat frying in batter-breaded fish nuggets. Their study showed that increasing both the degree of oil unsaturation and frying time intensified oil oxidation, which enhanced porosity and facilitated oil penetration. The observed decrease in interfacial tension and contact angle, along with increased viscosity and total polar compounds, further demonstrated that oil oxidation accelerated oil absorption during frying through the surfactant effect mechanism (He et al. 2026). These findings provide valuable insight into how the physicochemical changes in frying oils directly influence the microstructure and oil uptake behaviour of coated fish products. Furthermore, Zhai et al. (2024) investigated how frying temperature and time affect moisture state, wheat gluten structure, and oil penetration in batter-breaded fish nuggets. As a result, they found out that higher temperatures and longer frying times altered water mobility and gluten structure, leading to changes in crust porosity and oil uptake. These findings provide useful insights for optimizing frying conditions to produce lower-fat fried fish nuggets.

Wheat flour is the primary material used for pre-dusting, although corn and rice flours may also be incorporated. These flours can be blended with starches, gums, proteins, and, when necessary, spices or seasonings. Liquid coating (batter) formulations typically contain flours, starches, gums, and additional components such as proteins, dextrin, and dietary fibers. Wheat flour constitutes the major portion of the dry ingredients (about 90%), and batter properties—viscosity, adhesion, extensibility, frying color, and oil absorption—are strongly influenced by the flour type (Fiszman 2009, Serdaroğlu and Öztürk Kerimoğlu 2023). It is known that the use of alternative flours instead of wheat flour in batter formulations affects the physicochemical, sensory, and technological quality characteristics. Bechtel et al. (2018) investigated the effect of different batters (rice, corn, and wheat) and the effect of par-frying on the quality of baked catfish strips, and reported that par-fried baked products, including corn and wheat, exhibited significantly higher oil content than non-par-fried counterparts, and corn flour batters produced moister fillet strips.

Starches from different sources such as corn, rice, or wheat, further modify the viscosity and gelatinization behaviour of the batter. Furthermore, gums, which hydrate in cold water and form viscous solutions, are primarily used for viscosity control and may also reduce oil absorption while improving coating adhesion (Fiszman 2009, Serdaroğlu and Öztürk Kerimoğlu 2023).

Dry outer coatings typically consist of various types of breadcrumbs that differ in particle size, texture, color, and sensory attributes. American-style crumbs contain both crumb and crust fragments, whereas Japanese panko has elongated, flaky particles with a more uniform color. Cracker meal, produced by cooking, drying, and milling a simple flour–water dough, has fine and compact particles and can also be used as a pre-dust material (Serdaroğlu and Öztürk Kerimoğlu 2023).

In the production of coated meat products, plant- and animal-derived proteins, commonly incorporated into batter formulations, offer significant advantages due to their potential to enhance both functional and nutritional properties. Different types of proteins, owing to their varying water-holding capacities, gelling behaviours, and film-forming abilities, influence the final quality attributes of coated meat products in distinct ways. In a study performed by Cui et al. (2022); soy protein (SP), egg white protein (EP), and whey protein (WP) were added individually (6% w/w) to a wheat starch-gluten batter. SP markedly increased batter viscosity, elasticity, and pick-up, while EP and WP had the opposite effect. All proteins elevated gelatinization and denaturation temperatures, enhanced crust thermal stability, and reduced enthalpy and oil absorption, indicating their role in reinforcing the batter matrix and limiting fat uptake during frying. Chen et al. (2020) demonstrated that adjusting the wheat starch-to-wheat protein (WS/WP) ratio in the batter markedly affected the frying quality of battered and breaded fish nuggets. The optimal WS/WP ratio of 11:1 (w/w) yielded the best overall quality, producing nuggets with higher moisture retention, lower fat content and shrinkage, minimal acrylamide formation, and an appealing golden-yellow crust. These findings highlight the crucial role of wheat protein in enhancing the structural integrity and frying performance of coated fish products. In another study by Gaurav et al. (2024), the use of soy protein isolate (SPI) coatings at concentrations ranging from 2.5% to 25% was investigated to reduce fat absorption in Rohu (*Labeo rohita*) fillets. They found that coating pickup increased with SPI concentration, with 15% SPI achieving the highest pickup (18.29%) and reducing fat uptake by 57.78%. The SPI coating also protected the fillets from oxidation during deep-frying, as indicated by lower carbonyl and sulfhydryl contents. Overall, a 15% SPI coating was recommended for producing low-fat fried fish fillets with improved quality. Although this was not a direct study on battered-breaded products, it highlights the beneficial effects of protein incorporation in coated fish products, suggesting their potential for improving quality and reducing oil absorption.

2.3 Bibliometric Overview of Research on Coated Seafood Products

The bibliometric visualization in Figure 3, carried out according to van Eck and Waltman (2023), illustrates the conceptual landscape of scientific publications on *battered*, *breaded*, *coated fish and seafood products* over the last three decades (1996-2026). Six main keyword clusters emerged, reflecting the thematic evolution of research within this field. Before interpreting these clusters, it is important to note that the term "coating" in the scientific literature often encompasses a broad spectrum of applications, ranging from battering and breading systems used for fried seafood products to edible film or biopolymer coatings applied for preservation and storage enhancement. Therefore, some overlap between *coated products* and *edible film applications* naturally appears in the retrieved dataset. However, within the scope of this chapter, "coated fish and shellfish products" specifically refers to items in which the outer surface is sequentially covered with batter and breading ingredients prior to frying or other heat treatments, rather than products coated with stand-alone edible films or biopolymer solutions.

The first cluster (purple-yellow tones) centers on *fish*, *seafood*, *chitosan*, *fish fingers*, *edible coating*, and *shelf life*, representing studies focusing on product quality, microbial stability, and storage performance. Chitosan appears as a dominant linking term, indicating its widespread application as an antimicrobial and antioxidative coating material that enhances the preservation of seafood. The occurrence of "edible coating" in this cluster also reflects the terminological overlap mentioned above, where edible films are sometimes considered under the general concept of coating. In this chapter, however, such instances are distinguished from the batter-breading systems that define conventional coated seafood products. The second cluster (green) includes *frying*, *breaded fish*,

fish nuggets, *texture*, and *crispness*, corresponding to research related to formulation optimization and textural attributes of batter and breading systems. This cluster highlights efforts to achieve desirable surface characteristics and sensory properties through modifications in flour composition, frying parameters, and pre-treatment processes. The third cluster (orange) encompasses *deep-fat frying*, *oil absorption*, *fat absorption*, *oil oxidation*, and *acrylamide*, representing the technological and health-related dimension of coated seafood processing. These studies primarily address oil uptake mechanisms, lipid oxidation control, and the minimization of thermal contaminants such as acrylamide during deep frying. The fourth cluster (blue), featuring *chitosan*, *fish finger*, *sensory evaluation*, and *chilled storage*, bridges biopolymer-based coatings and consumer quality perception. It indicates a growing trend toward the use of natural functional ingredients and their role in improving the texture, appearance, and acceptability of coated seafood products. The fifth cluster (red), comprising *aquaculture*, *growth performance*, *Labeo rohita*, and *probiotics*, is peripheral to the core topic but provides insight into raw material quality and nutritional background influencing the characteristics of processed fish products. Finally, the sixth cluster (brown) groups *deep frying*, *acrylamide*, *oxidation*, and *crispness*, emphasizing the impact of processing conditions on chemical safety and product texture. Together, these clusters demonstrate the shift in scientific focus from basic process optimization during the 1990s and early 2000s toward functional formulations, health-conscious reformulations, and sustainable coating technologies in recent years. Overall, the map clearly delineates how the research trajectory in coated seafood products has expanded from traditional frying and textural studies to the integration of bio-based ingredients and advanced quality preservation strategies. This bibliometric overview provides a concise yet comprehensive framework for discussing current formulation approaches and technological innovations in battered and breaded seafood products.

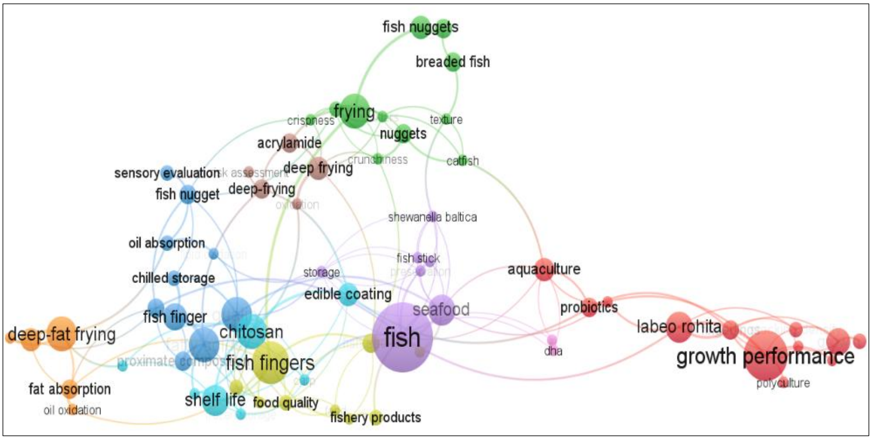

Figure 3. *Keyword co-occurrence map of publications related to battered, breaded, and coated fish and seafood products (1996–2026), generated using VOSviewer (version 1.6.20). Among the documents retrieved from the database, the minimum number of keyword occurrences was set to 5, resulting in 30 keywords meeting the threshold out of approximately 1,200 extracted terms.*

Each color represents a distinct thematic cluster, where node size corresponds to keyword frequency and link strength indicates co-occurrence relationships. The size of each circle corresponds to the frequency of keyword occurrence, while the thickness of connecting lines indicates the strength of the relationship between terms. Items belonging to the same cluster represent similar thematic or research domains. The label and node size of each item are proportional to its weight, meaning that higher-frequency keywords appear larger on the map.

3. RECENT ADVANCES AND EMERGING REFORMULATION STRATEGIES FOR COATED AQUATIC PRODUCTS

3.1 Novel Cooking and Preservation Techniques

Traditional deep-fat frying imparts desirable quality attributes such as characteristic appearance, flavor, and texture.

Frying is a continuous process involving simultaneous heat and mass transfer, with heated oil serving as the transfer medium. In conventional atmospheric frying (AF), the oil temperature typically ranges between 160 °C and 220 °C (Devi et al. 2021, Gaurav et al. 2024). During frying, foods containing diverse proportions of proteins, carbohydrates, lipids, water, vitamins, and salts undergo a multitude of complex chemical reactions, including Maillard browning, caramelization, and lipid oxidation (Devi et al. 2021). Although deep-fat-fried coated products are still nutritionally valuable, the high total lipid content of such products could pose serious health risks, including cardiovascular disease and hypertension. Moreover, acrylamide, an intermediate product of the Maillard reaction formed particularly when starchy foods are cooked at temperatures above 120 °C, represents an additional concern for the safety of these fried products (Chen et al. 2020). Wu et al. (2022) comprehensively investigated the generation of hazardous compounds in deep-fried coated fish products. Those researchers found that advanced glycation end-products (AGEs), acrylamide, 5-hydroxymethylfurfural (5-HMF), benzo(a)pyrene, and trans fatty acids were mainly concentrated on the surface of the fried samples, while only small amounts of AGEs were detected inside. Prolonged frying further promoted lipid oxidation and the formation of these harmful substances (Wu et al. 2022). In line with this data, in recent years, various studies have focused on developing healthier formulations of coated fish products. In this context, instead of deep-fat frying, baking can serve as a healthier alternative technique for producing coated fish products; however, baked versions often lack the characteristic crisp texture of fried ones. To overcome this limitation, a par-frying step is commonly applied before baking to set the batter and breading, resulting in improved texture and product appeal, though it also increases oil absorption and production costs. Previously, Bechtel et al. (2018) examined the effect of par-frying on the quality of coated catfish products formulated with different batter types. They reported that par-fried samples exhibited significantly greater sensory and instrumental hardness and fillet flakiness compared to non-par-fried treatments, suggesting that the par-frying process could highly influence the textural properties of baked coated fish products by altering crust formation and internal structure stability. Moreover, Oppong et al. (2021) studied the impacts of oven-baking versus deep-fat frying of fish nuggets and reported that, compared to oven-baking, deep-frying produced fish nuggets of better overall quality, with lower peroxide value (PV), free fatty acids (FFA), and microbial counts during frozen storage. However, oven-baked nuggets contained less fat and energy but more moisture. Both cooking methods yielded products that remained microbiologically safe and of acceptable quality for up to 90 days at −18 °C, provided that good manufacturing and hygienic practices (GMP and GHP) are followed (Oppong et al. 2021). Overall, these findings highlight the need to balance sensory appeal and nutritional quality when selecting or optimizing cooking methods, emphasizing the potential of hybrid or modified processing approaches to achieve both healthier and organoleptically acceptable coated fish products.

Among alternative frying techniques, vacuum frying (VF) represents a good example. Vacuum frying (VF), also known as pressure frying, is carried out in a sealed vacuum chamber without the presence of air. The primary advantage of VF is the reduction in the boiling points of both water and oil, allowing frying at lower temperatures compared to conventional atmospheric frying. Additionally, the absence of oxygen minimizes lipid oxidation, acrylamide formation, discoloration, and excessive browning, thereby promoting better nutrient retention in the final product (Devi et al. 2021, Xu et al. 2022). Manzoor et al. (2024) compared VF (120 °C / 40 kPa) with conventional atmospheric frying (AF, 180 °C) in the production of fish nuggets. Their findings showed that VF led to slower degradation of PUFAs, lower trans-fatty acid formation, and reduced oil uptake compared to AF. Although VF nuggets were slightly less crispy, they exhibited superior nutritional and sensory quality, demonstrating that vacuum frying can yield safer and healthier fried fish products than traditional deep-fat frying. In a similar manner, Xu et al. (2022) demonstrated that vacuum-fried shrimps containing purple sweet potato flour (PSPF), soy protein isolate, and xanthan gum indicated a more attractive purple hue, reduced oil absorption, higher moisture, and better anthocyanin retention, while PSPF-breaded samples also preserved antioxidant activity. Hence, the application of VF in conjunction with alternative coating materials is suggested to further improve the overall quality and yield of the product.

Several non-thermal technologies have been explored as alternatives to deep-fat frying for coated aquatic products. In this context, one of the most commonly recommended non-thermal processes for coated products is microwave frying. Microwave frying utilizes two simultaneous energy sources: (1) microwaves that directly interact with polar water molecules to heat the food's interior, and (2) hot oil that cooks the surface. This dual-action process produces the desired golden color and crisp texture of the crust while significantly shortening frying time, reducing lipid oxidation, and minimizing oil absorption (Chen et al. 2008). In addition to this, several other novel applications are also being explored for their potential use in both scientific and industrial fields. As one of these techniques, ultrasound is today widely employed in various food processing systems as a non-thermal, synergistic technology operating at frequencies between 20 kHz and 10 MHz to enhance production efficiency (Devi et al. 2021). In this regard, Alizadeh and Rezaei (2025) investigated the application of ultrasound (US) during batter preparation and demonstrated that optimizing sonication conditions could effectively enhance the quality of fried fish nuggets. Specifically, moderate power and treatment time were found to reduce oil absorption, increase product yield, and improve moisture retention, while maintaining desirable color, texture, and sensory acceptance. Conversely, excessive ultrasonication led to unfavorable flavor changes, emphasizing the importance of process optimization. Overall, their findings underline the potential of ultrasound-assisted batter preparation as a promising strategy for developing healthier, lower-fat coated fish products (Alizadeh and Rezaei 2025).

3.2 Strategies to Improve Techno-Functional Quality

The growing interest in improving the textural and nutritional profile of coated meat products has led to extensive research on modifying batter and coating systems to enhance their techno-functional performance. In this context, the effects of alternative ingredients on enhancing techno-functional quality attributes of coated marine products are frequently investigated. Crispness is a key quality attribute in coated meat and other fried products, strongly influencing consumer acceptance and largely determined by the composition of the batter and coating. Since cellulose derivatives such as methylcellulose (MC) and hydroxypropyl methylcellulose (HPMC), known for their film-forming ability, can form thermal gel structures that enhance moisture retention and reduce oil absorption, Chen et al. (2008) investigated the ability of HPMC to improve the crispness of coated mackerel nuggets. Those researchers found out that in microwave-reheated mackerel nuggets, HPMC's thermal gelation caused the crust to get gradually crispier upon cooling, ultimately yielding a crisper texture than conventional battered and breaded nuggets. In a similar study, it was reported that batters formulated with 1% carboxylmethylcellulose (CMC) or 1% HPMC exhibited higher viscosity, resulting in greater batter pick-up, increased moisture retention, and reduced oil absorption, along with smaller overall color changes. Regardless of whether traditional deep frying or microwave frying was applied, the addition of CMC or HPMC consistently produced fried fish nuggets with a less oily quality (Chen et al. 2009). These findings highlight the positive influence of cellulosic materials in improving coating performance and promoting healthier, lower-fat fried products. In another study, Carvalho and Ruiz-Carrascal (2018) investigated how adding ethanol or CO_2 incubation to tempura batter affects the quality of fried coated squid. Their results indicated that ethanol addition improved crispness and crunchiness, even after refrigeration and reheating, suggesting it as a promising strategy to enhance texture in stored and reheated fried products.

Hydrocolloids are commonly used in fried products either as edible coatings or as functional ingredients in batter formulations for battered and breaded foods. In this context, previously, Hauzoukim et al. (2019) evaluated three aquatic polymer hydrocolloids (alginate, chitosan, and fish gelatin), each incorporated at 1% (w/w) into batter formulations for enrobed fish fingers. Among them, chitosan and alginate significantly improved coating performance and reduced oil absorption, with chitosan showing the most favorable results in coating pick-up, texture, biochemical quality, and fat reduction. Overall, incorporating 1% chitosan into batter formulations was recommended to enhance coating quality and reduce oil uptake in fish fingers (Hauzoukim et al. 2019).

Although various primary ingredients such as flours and proteins discussed in Section 2.2 constitute the fundamental components of coated fish and shellfish products, fibrous ingredients also play a crucial role in their formulation to improve quality. The incorporation of suitable fiber sources is increasingly explored to enhance the functional properties of coated products made from fish mince. Since fish naturally lacks carbohydrates, including dietary fibers and simple sugars, plant-derived ingredients have attracted attention as valuable sources of these components. The inclusion of such carbohydrate-rich plant materials can improve product stability, texture, and nutritional quality, while also contributing to reduced overall production costs (Abedelmaksoud et al. 2023). In addition, some studies have also investigated the combined use of fibrous components with hydrocolloids. A study performed by Shan et al. (2018) examining the combined use of xanthan gum (XG) and soybean fiber (SF) in batter formulations found that all XG–SF blends significantly reduced oil absorption in fried fish nuggets. An XG–SF ratio of 1:2 was the most effective, yielding the lowest fat content, highest moisture, and superior texture and color. These results highlight that combining gums and fibers can effectively limit oil uptake while maintaining desirable sensory qualities in fried marine products.

3.3 Waste Valorization and Sustainable Ingredients

In recent years, with the growing global demand for protein, the valorization of seafood by-products has increasingly shifted from non-food (e.g., biomedical and cosmetic applications) toward food applications, as many of their components can be directly or indirectly utilized for human consumption within a circular framework. Advances in technology have further expanded their use in the development of value-added food products (Almeida et al. 2025). Xavier et al. (2018) previously emphasized that low-value freshwater and marine fish can be utilized in the development of high-value, novel, and convenient products, highlighting the potential of the coating process as an effective means of producing value-added seafood. In their study, these researchers utilized Devis's anchovy (*Stolephorus commersonni*), a small pelagic species rich in n-3 fatty acids, calcium, and iron, but with limited marketability in fresh form due to its size, seasonal availability, and perishability. By applying coating technologies, they successfully developed value-added coated anchovy products, retaining acceptable chemical and sensory quality for up to five months of storage. In addition, the production of coated fish products represents an effective strategy for valorizing mechanically separated fish meat (MSM), a raw material rich in nutritional value. The convenience and consumer appeal of breaded products further enhance the utilization of this valuable protein source. In this context, Cavenaghi-Altemio et al. (2024) proposed the development of fish nuggets from MSM of Nile tilapia (*Oreochromis niloticus*), both with and without an edible coating. The coating formulation containing 5% corn starch and 20% sorbitol significantly reduced lipid absorption compared to other treatments, yielding a healthier product. These findings highlight that MSM can be successfully used to develop innovative formulations that improve both the nutritional and technological quality of coated fish products. In addition to utilizing lower-quality fish raw materials, an interesting approach developed by Bonfim et al. (2020) involved the use of fish waste-derived flour as a coating material. In their study, increasing the proportion of fish waste flour, particularly at 25% and 40%, significantly raised protein, lipid, and ash contents while reducing carbohydrates. These levels also enhanced color intensity and influenced texture, reducing hardness in pre-fried but increasing it in fried nuggets. Sensory analysis showed that higher substitution levels improved overall acceptance. Overall, replacing coating flour with fish waste flour was mentioned to be a promising strategy for both waste valorization and the development of nutritious, appealing coated fish products (Bonfim et al 2020). Such studies demonstrate that various fish by-products can be incorporated into coated aquatic product formulations, thereby contributing to the blue transformation strategies and promoting the sustainable production of aquatic foods. Moreover, as illustrated in Table 1—which summarizes the use of various alternative natural ingredients in coated meat products—there is considerable potential for incorporating plant-derived by-products such as hulls and peels into coating formulations. The utilization of such materials in coated fish and meat products not only enhances functional properties but also promotes sustainable production. These applications enable the valorization of food residues and contribute to the circular economy, thereby supporting the development of formulations aligned with the United Nations Sustainable Development Goals. Increasing the use of these ingredients in future research and developing innovative coating systems that facilitate their industrial integration would be highly beneficial.

Another innovative approach in coated fish product development is the production of nugget-type products from surimi. Moosavi-Nasab et al. (2019) successfully prepared surimi-based nuggets utilizing Queen fish (*Scomberiodes commersonnianus*), yielding a suitable texture after cooking, higher sensory acceptability, and lower microbial counts than standard fish nuggets. Due to the washing steps during surimi processing, these nuggets contained less protein, fat, and ash, yet maintained better overall quality and stability during storage. The study highlighted surimi's potential as a promising base material for developing alternative ready-to-eat fish nugget products. This approach also enables the utilization of various fish by-products and lower-value species in coated product formulations, promoting both sustainability and cost efficiency.

Fundamental ingredients used in the formulation of coated fish products—such as flours, proteins, hydrocolloids, and fibers—have been described in the previous sections. On the other side, reformulating these products with various natural ingredients has emerged as an important research focus. In this regard, Table 1 presents some examples of natural materials incorporated into different coating phases or into the fish/mince matrix during the production of coated marine products. A review of the literature indicates that, in addition to alternative flours, proteins, and hydrocolloids used in combination, a wide range of fruit- and vegetable-derived ingredients or their extracts have been incorporated into the formulations of various coated meat and seafood products. At this point, it becomes evident that lipid oxidation represents a major quality concern, particularly in products that undergo deep-fat pre-frying. Fish, due to its inherently high content of polyunsaturated fatty acids, is especially susceptible to oxidative deterioration (Taskaya et al. 2024). Therefore, implementing strategies that limit oxidation reactions is essential, and the use of natural antioxidants in coating or batter formulations has been widely explored. Some plant-based extracts listed in Table 1 have been reported to exert strong antioxidant effects, significantly reducing oxidative reactions in coated fish products. Beyond lipid oxidation, excessive or long-term consumption of fried coated aquatic products may lead to health problems such as hypertension and the formation of harmful compounds like acrylamide. Over-frying also reduces product quality, causing dark crusts, hardened texture, and deteriorated flavor, making it inconsistent with the growing demand for healthier foods (Zhai et al. 2024). Therefore, appropriate measures should be taken, practices that improve the health profile of the products should be encouraged, and further research should focus on incorporating naturally derived ingredients into coated aquatic product formulations.

3.4 Development of Gluten-Free Coated Fish Products

Wheat flour—containing roughly 60% gluten as the key protein—is one of the most widely used battering and coating ingredients in nugget formulations, and its key protein fractions, glutenin and gliadin, form the gluten network that fundamentally shapes the technological and sensory properties of the final product (Öztürk-Kerimoğlu and Serdaroğlu, 2019). Gluten provides a strong, elastic network that traps air bubbles within the batter, promoting its structural coherence and adhesion to the coated product. Depending on the gluten's amount, quality, and degree of hydration, the resulting texture can vary from crispy and brittle, as in bread crusts, to elastic, as in bread loaves, or even fluid, as seen in tempura batters, ultimately determining the product's final texture (Carvalho and Ruiz-Carrascal 2018). Despite these functional advantages, gluten-containing foods can pose serious health risks for certain individuals, most notably those with celiac disease. Celiac disease—a permanent gluten-induced enteropathy triggered by cereals such as wheat, barley, and rye—affects roughly 1% of the global population and requires a strict lifelong gluten-free diet. This makes the development of gluten-free muscle products that can deliver acceptable sensory and nutritional quality, while remaining cost-effective, an important priority (Öztürk-Kerimoğlu and Serdaroğlu, 2019).

Incorporating alternative flours, proteins, or hydrocolloids into coating formulations can enhance functionality, product quality, and cost-effectiveness, underscoring the potential to produce high-quality marine products with suitable gluten-free ingredients. For instance, da Silva et al. (2021) investigated gluten-free coatings made with tapioca and coconut flours for fish nuggets and found that coconut-coated nuggets yielded acceptable quality and storage stability.

Table 1. Novel ingredients incorporated into coated aquatic product formulations.

Type of the product	Ingredient(s) used	Highlighted results	Reference
Pangasius fish nugget	Dragon fruit (*Hylocereus polyrhizus*) peel powder	- Use of dragon fruit peel powder significantly improved techno-functional quality attributes. - Nuggets with 1.5% dragon fruit peel showed better sensory attributes compared to the others. - Dragon fruit peel powder significantly inhibited the lipid oxidation and microbial load in fish nuggets during storage.	Biswas et al. (2022)
Tilapia nugget	Egg yolk phospholipids plus alanine and glucose	- The characteristic deep-fat frying odorants derived from Maillard reaction and lipids, such as methional, 2-methylbutanal and 3-methylbutanal, 2-ethyl-3,5-dimethylpyrazine, 2,4-decadienals, were the highest amounts in the phospholipids & alanine and glucose treated sample. - A combination of egg yolk phospholipids with alanine and glucose can be utilized to produce the key aroma compounds characteristic of fried coated products.	Ye et al. (2022)
Breaded shrimp	Purple sweet potato flour (PSPF), soy protein isolate (SPI), and xanthan gum (XG)	- The batters formulated with PSPF, SPI, and XG yielded better rheological properties. - A ratio of 2:1 for SPI to XG was effective to supply the highest pick-up value, more attractive color, less oil content, meanwhile to retain higher anthocyanin concentration.	Xu et al. (2022)

Table 1. Novel ingredients incorporated into coated aquatic product formulations (continued).

Type of the product	Ingredient(s) used	Highlighted results	Reference
Nile perch fish nugget	Sesame hulls and sunroot	- Sesame hulls contained the highest levels of fat, fiber and ash, whereas sunroot tubers had the greatest carbohydrate content. - The products with sunroot indicated the lowest lipid oxidation after three months of storage. - Fish flesh could be satisfactorily replaced by up to 10% sunroot and 7.5% sesame hulls in nugget formulations without compromising sensory acceptability.	Abedelmaksoud et al. (2023)
Tilapia nugget	Dayak onion (*Eleutherine palmifolia*) extract	- The extract used in batter formulations yielded higher sensory quality over commercial controls. - The selected tilapia nugget with 100 ppm extract concentrations could meet all chemical, microbiological, and sensory quality parameters.	Anggarkasih et al. (2023)
Tilapia nugget	Green banana flour (GBF) plus red propolis extract (RPE)	- The addition of the RPE affected the acceptance of the sensory attributes, with an acceptability index > 70%. - The nuggets containing 0.4% of RPE presented ash, lipid, resistant starch, and polyphenol contents superior to the commercial brand fish nuggets - After refrigerated storage, the nuggets treated with RPE presented lower lipid oxidation and psychrotrophic bacteria counts than the samples containing sodium erythorbate. - The combined use of GBF and RPE was effective to simultaneous improvement in nutritional quality and oxidative stability of the fish nuggets.	de Santana et al. (2024)

4. FUTURE PERSPECTIVES

In the coming years, the development of coated fish and shellfish products will increasingly be shaped by the convergence of emerging processing technologies, sustainability targets, and evolving consumer expectations. Novel and hybrid frying approaches such as vacuum frying, microwave-assisted frying, and ultrasound-assisted preparation of batters offer clear potential to reduce oil uptake, improve retention of heat-sensitive nutrients, and lower the formation of hazardous compounds, yet their wider adoption will depend on energy-efficient process design and robust techno-economic evaluation at an industrial scale. In parallel, the Blue Transformation and circular bioeconomy agendas will drive more systematic valorization of aquatic and plant by-products—such as mechanically separated fish meat, fish waste flours, fiber-rich plant residues, and natural antioxidant extracts—into coating systems and nugget matrices, with an emphasis on minimizing waste, reducing environmental footprint, and improving protein utilization. Future work should increasingly integrate life cycle assessment, water and energy footprinting, and process modelling to quantify the true sustainability gains of these reformulation and processing strategies. At the same time, consumer acceptance will remain a central constraint: clean-label positioning, gluten-free formulations, and the use of familiar, naturally derived ingredients must be reconciled with the functional reliance on hydrocolloids, proteins, and other structuring agents that underpin crispness, juiciness, and shelf life. This calls for more comprehensive sensory and consumer studies, including cross-cultural preference mapping and acceptance of upcycled ingredients, alongside molecular- and microstructure-level research that links ingredient choice and processing conditions to texture, oxidative stability, contaminant formation, and nutritional quality. Overall, future research on coated aquatic products should adopt an integrated, multidisciplinary approach that couples emerging technologies with circular, low-waste formulation concepts and data-driven process control, enabling coated aquatic products that are not only safe and palatable, but also demonstrably aligned with global sustainability goals.

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IPRS (IN-POND RACEWAY SYSTEMS) TECHNOLOGY AND OPERATIONAL PRINCIPLES IN INLAND AQUACULTURE

SERHAT ENGİN[1]

1. INTRODUCTION

Aquaculture has increasingly turned to intensive and semi-intensive systems to meet global demand for fish protein while minimizing environmental impact. **In-Pond Raceway Systems (IPRS)** have emerged as an effective solution, confining fish in structured raceways within larger water bodies to optimize feed use, water quality, and harvesting efficiency. The **Floating In-Pond Raceway Systems (FIPRS)** extend these advantages to deeper and more dynamic environments, offering flexibility, scalability, and adaptability. In-Pond Raceway Systems (IPRS) have emerged as a solution by combining the advantages of intensive aquaculture with the simplicity of pond-based farming (Xu et al., 2019; Tucker & Hargreaves, 2008). Developed initially in China and later applied in Southeast Asia, Africa, and the United States, IPRS has proven to increase yields while maintaining environmental responsibility.

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2. SYSTEM CONCEPT AND DESIGN

2.1. Structural Configuration

FIPRS units float on the water surface but are securely anchored. The raceway is divided into three functional zones:

- **Aeration / Approach Zone:** Water is actively mixed and oxygenated before entering the production area through diffused aeration, paddlewheels, or airlifts.
- **Production Zone:** Main culture area supporting high stocking densities with constant water flow to deliver oxygen and remove wastes.
- **Quiescent Zone:** Acts as a settling basin for solid wastes and uneaten feed; solids are periodically removed.

2.2. Materials and Dimensions

Typical commercial FIPRS units feature a 5 m × 22 m × 2 m production zone (~220 m^3), 2 m aeration zone, and 3–6 m quiescent zone. Materials include FRP panels, HDPE sheets, stainless steel mesh, pond liners, and aluminum or steel frames (Figure 1,2). The Floating In-Pond Raceway Systems (FIPRS) variant eliminates the need for permanent structures, making it suitable for lakes and reservoirs (Li et al., 2018). (Table 1.)

3. ADVANTAGES OVER TRADITIONAL CAGE CULTURE

3.1. Environmental Benefits

Unlike traditional cages, where fish wastes disperse freely into the environment, FIPRS localizes and enables waste removal, mitigating eutrophication risks in sensitive water bodies Table 2).

Table 1. Detailed Comparison of Fixed vs Floating In-Pond Raceway Systems (FIPRS)

Feature / Aspect	Fixed IPRS	Floating IPRS (FIPRS)
Deployment Location	Shallow ponds (≤ 3 m depth)	Deep ponds, lakes, reservoirs, sheltered coastal waters
Structure Type	Fixed, concrete raceways	Floating, modular raceways
Standardization	Highly standardized dimensions and materials	Non-standard; adaptable to site conditions, builder expertise, and local resources
Typical Size	Often fixed at standardized designs	Scalable: commercial standard ~220 m^3 (5 m × 22 m × 2 m), but can be smaller or larger
Materials	Reinforced concrete	FRP panels, HDPE sheets, stainless steel mesh, aluminum/steel frames, EPDM liners, or wood for short-term use
Construction Method	On-site permanent build	Modular, can be assembled onshore and floated into place
Power Source	Primarily grid (AC mains)	Grid where available; solar/wind for remote sites
Mobility	Fixed, not movable	Portable, can be relocated between sites
Cost & Build Time	Higher cost, longer construction	Lower cost, faster deployment

Target Markets	Large-scale operations with established markets and infrastructure	Both large commercial farms and small-scale/niche producers; suitable for trial adoption
Waste Management	Quiescent zone with solid waste removal	Same principle; floating adaptation with solids removal and potential reuse
Flow Generation	Paddlewheels/propellers at raceway head	Often positioned after quiescent zone to improve laminar flow
Emergency Low DO Response	Fixed aeration systems, some portable backup	Portable diffusers, blowers, gas oxygen systems; rapid deployment possible
Biosecurity	Controlled, reduced predator access	Controlled, with enhanced protection in open waters
Environmental Impact	Reduced nutrient discharge compared to open cages	Same benefits; even more critical for sensitive or regulated water bodies
Scalability	Limited by pond depth and shape	Infinitely scalable to market demand and available water space
Regulatory Fit	Suitable where permanent infrastructure is allowed	Flexible for areas with leasing restrictions or temporary rights

Table 2. Advantages and Challenges of IPRS

Advantages	**Challenges**
High productivity and stocking density	High initial investment costs
Improved water quality	Energy dependency (aeration/pumping)
Better economic returns	Need for technical expertise
Environmental sustainability	Not suitable for all species

Figure 1. FIPRS overview

Figure 2. FIPRS test platform constructed of wood and flexible siding/flooring material, with floating collar, and converted to DC power with solar system.

3.2. Production Advantages

FIPRS supports higher stocking densities with better water quality control, enabling faster growth rates due to optimized oxygenation and feeding regimes.

3.3. Feed Optimization

Integration with soy-optimized feed models, as promoted by USSEC, improves feed conversion ratios (FCR) and lowers production costs.

Table 3. Major Fish Species Cultured in In-Pond Raceway Systems (IPRS)

Species (Scientific Name)	Common Name / Group	Notes and Advantages
Oreochromis spp.	Tilapia	The most commonly cultured species in IPRS systems. Highly tolerant to high stocking densities, low oxygen levels, and variable water quality. A key species in tropical and subtropical countries.
Ictalurus punctatus	Channel catfish	The main species used in IPRS systems in the United States. Rapid growth under controlled water quality and continuous flow conditions.
Cyprinus carpio	Common carp	Used in polyculture IPRS systems in China and Türkiye. Exhibits high feed conversion efficiency and adaptability to various pond conditions.
Hypophthalmichthys molitrix	Silver carp	Utilized in Chinese IPRS facilities for biofiltration and waste control as a supporting species in multi-species setups.
		Used to control aquatic vegetation and maintain

Ctenopharyngodon idella	Grass carp	ecological balance in polyculture IPRS systems.
Sparus aurata	Gilthead sea bream	Successfully tested in brackish and marine IPRS adaptations; high market value species with good growth performance under controlled salinity.
Dicentrarchus labrax	European seabass	Performs well in brackish or marine IPRS systems; commercially valuable and suitable for integrated coastal aquaculture.
Clarias gariepinus	African catfish	Highly tolerant to low dissolved oxygen and high temperature; used in African and Asian IPRS installations.
Labeo rohita	Rohu (Indian carp)	Common in IPRS projects in India and Bangladesh; often stocked with tilapia or common carp in multi-species systems.
Salmo salar / Oncorhynchus mykiss	Atlantic salmon / Rainbow trout	Used in cold-water RAS and semi-IPRS systems; requires high oxygen levels and stable temperature control.

3.4. Applications and Global Interest

FIPRS is suitable for deployment in deep-water aquaculture in Asia, Africa, and Latin America, particularly in public water bodies subject to stringent environmental regulations. Countries such as China, Türkiye, Vietnam, Thailand, Bangladesh, Egypt, and Colombia have demonstrated strong potential for adoption. - China: The birthplace of IPRS, widely applied in carp and tilapia farming (Xu et al., 2019).

3.5. Operational Considerations

3.5.1. Scalability and Mobility

Modules can be added or removed according to production targets, with easier relocation compared to fixed IPRS installations. (Hargreaves & Tucker, 2010). Routine cleaning of the quiescent zone and periodic inspection of nets and structural elements are essential for optimal performance. The enclosed environment reduces exposure to predators and pathogens, facilitating disease control and simplifying harvest operations.

4. SUSTAINABILITY AND FUTURE PROSPECTS

Integration with precision aquaculture tools (oxygen sensors, automatic feeders, waste monitoring systems) and renewable energy sources (solar-powered aerators) enhances both economic and environmental sustainability. Waste repurposing into fertilizer contributes to circular economy practices. The adaptability of FIPRS to renewable power makes it viable for off-grid operations in remote regions.

4.1. FIPRS Operational Practices

The design and functioning of the Quiescent Zone (QZ) in conventional IPRS systems allow the waste stream from several raceways to be channelled into a central collection area. Waste removal generally relies on large pumps that extract both settled solids and considerable amounts of water, requiring secondary settling tanks before final disposal. In FIPRS installations, which are often located in remote and deep-water environments, solid waste cannot be collected communally from multiple raceways. As a result, FIPRS facilities must adopt more sophisticated methods for transporting solids or concentrated slurry while minimizing excess water intake. Reducing water content not only decreases the required storage volume but also simplifies transportation to onshore handling facilities. Unlike fixed IPRS, where a shared QZ is practical, each floating raceway in FIPRS functions independently. This makes routine waste extraction less frequent but more technically demanding. When deployed in sufficiently deep waters, FIPRS raceways may incorporate a cone-shaped QZ bottom to improve the settling and extraction of fish waste while reducing unnecessary water removal.

Operating FIPRS in public water bodies typically requires specialised governmental permitting, whereas fixed IPRS units on privately owned ponds generally do not demand such authorisation. Farmers must review and comply with local regulations governing aquaculture activities in public waters. Emergency preparedness for dissolved oxygen (DO) crises—especially under high biomass and elevated temperatures—follows similar principles in both systems. However, DO supply dynamics differ significantly. Deep reservoirs and lakes often maintain higher natural DO concentrations in surface layers compared to shallow ponds, except under conditions such as eutrophication or seasonal turnover. In situations where early-morning DO levels decline, operators may use paddlewheels or diffused aeration grids within or near the approach zone to stabilise oxygen conditions.

While standard IPRS design uses a ratio of one 220 m^3 raceway per 10,000 m^3 of pond volume to maintain ecological balance, a comparable carrying capacity guideline for FIPRS remains undefined. The variability in hydrological characteristics of lakes and reservoirs complicates accurate estimation. Unlike IPRS, FIPRS does not typically employ polyculture with service species. However, some operations incorporate a funnel-style gate at the tail end of the raceway to capture wild fish attracted by small supplemental feedings. This method can also serve to recapture fish that have escaped deliberately or accidentally from the raceway.

Both IPRS and FIPRS utilise multi-level emergency plans for DO-related failures.

- **Plan A:** Activate backup generators to restore electrical power.
- **Plan B:** Deliver supplemental oxygen to the raceway through any available means.
- **Plan C:** Release fish before mortality occurs and subsequently recover them using a funnel-shaped trap installed in the QZ, which allows fish to swim in but prevents their escape.

4.2. Waste Removal Principles in Iprs and Fıprs

Fish waste in aquaculture raceway systems can be categorized into three main solid types: Dissolved Solids – Compounds such as ammonia, carbon dioxide, and urea that cannot be physically removed. Their management relies on biological assimilation and water treatment processes.

Settleable Solids – Dense materials, primarily fecal matter, that rapidly sink and are well-suited for mechanical removal.

Suspended Solids – Fine particles that remain buoyant for longer periods, gradually increasing turbidity and reducing water quality.

The primary role of quiescent zones (QZs) in In-Pond Raceway Systems is the collection and removal of settleable solids, while also capturing some suspended solids where feasible. These wastes typically contain nitrogen, phosphorus, and other nutrients that contribute to eutrophication if left unmanaged. Extending the length of a QZ can improve suspended solid capture, particularly when done cost-effectively. Solid transport within the system occurs through water velocity and the swirling motion generated by fish swimming behavior. Standard IPRS designs recommend water velocities of 8–10 cm/s to ensure proper waste conveyance. Interestingly, FIPRS trials have shown that lower velocities can also be sufficient, provided that fish stocking density is high enough to enhance mixing near the raceway bottom. Settleable solids generally accumulate within the first meter of a QZ (3–6 m in length). In cone-shaped QZ designs typical of FIPRS, solids-moving pumps are often used for efficient extraction. A widely tested method involves floating canvas “hapa”-type collection units, which provide a secondary stage of sedimentation and nutrient capture. Suspended solids, on the other hand, may build up in the later sections of elongated QZs if laminar flow is maintained. Excessive turbulence tends to inhibit their settling. In theory, radial flow separators (RFS)—a technology common in recirculating aquaculture systems (RAS)—could be integrated into FIPRS. These separators channel solids from the high-velocity outer edges of a vortex toward the slower-moving center for capture. However, their effectiveness in floating raceway systems has yet to be empirically validated (Figure 3).

Figure 3. Floating hapas for collecting solid waste

4.3. Commercial FIPRS Facilities and Feed Trials

China

China is the global leader in both the development and implementation of IPRS technology, with more than 6,000 raceway cells operating by 2022. Naturally, China has also taken the lead in adopting and advancing floating variants of the system. Most FIPRS installations are located in southern regions of the country, where mountainous topography and frequent dam construction create large lakes and irrigation reservoirs ideal for floating aquaculture structures. Chinese FIPRS units generally follow the commercial IPRS standard, featuring a production volume of 220 m^3. A wide range of fish species is farmed in these systems, and the large raceway capacity suits the needs of major processing companies that handle high-volume output for fresh, frozen, and value-added fish products.

Operationally, large-scale FIPRS in China can apply standard IPRS practices—including recommended stocking densities, feeding schedules, biomass targets, water flow rates, and whitewater aeration—due to their similar size. Some FIPRS facilities have even adapted conventional QZ waste extraction systems from fixed IPRS models. However, more research is needed to determine efficient methods of waste management in floating systems, as logistical challenges are more significant compared to land-based IPRS. This is especially important since one of the core goals of FIPRS development in China is to reduce reliance on environmentally damaging cages in major lakes. In many regions, the government is already restricting or phasing out cage aquaculture.

There is currently no unified structural design or construction standard for FIPRS in China. Existing systems vary widely in framing techniques, materials, flotation methods, and raceway wall and flooring choices. A universally recognised design leader has not yet emerged, and further discussion is needed to determine optimal construction practices. Some installations were built without QZs or waste-handling mechanisms altogether; however, future FIPRS designs should incorporate these components from the outset. Among existing FIPRS equipped with QZ extraction systems, the methods and technologies differ substantially, often reflecting adaptations from fixed IPRS structures that do not translate efficiently to floating systems. These variations highlight the need for continued research to refine waste management solutions for FIPRS.

Vietnam

Vietnam currently operates a single FIPRS installation, constructed by Vin Hoan farm with technical support from Missouri Soy. The unit is structurally robust and designed for the culture of Pangasius fingerlings. It follows the 220 m^3 commercial IPRS standard and incorporates whitewater units for circulation and aeration; however, its adherence to recommended IPRS operational practices ends there. Vin Hoan’s production approach diverges significantly from the established USSEC IPRS guidelines. Stocking densities are far above recommended levels, pond circulation does not meet standard design criteria, feeding rates are excessive, and no systematic waste collection or extraction is practiced. Consequently, the system experiences persistent high mortalities and chronically poor water quality.

The FIPRS structure is built using galvanized steel frames, HDPE liners, and plastic drum flotation. Ten additional in-pond chimneys assist whitewater units to enhance mixing. Despite this, fingerling management practices remain highly stressful. Fish are transported without water or supplemental oxygen and moved via drained motorcycle buckets from boat to raceway—a process that reduces survival. Fish typically grow from 35 to 150 g, yet nursery survival rates fall to as low as 30%, compared to 50% in pond culture. Stocking density reaches 1200 fish per m^3, and feeding peaks at approximately 1800 kg/day—far above USSEC recommendations.

High nitrite concentrations and low sodium levels have led to "brown blood disease," impairing oxygen transport via methemoglobin formation. The farm occasionally drains the pond to remove accumulated sludge, suggesting poor QZ performance. Recommendations provided to the operator included reducing stocking densities and feed rates to assess the link between extreme biomass loading and water quality-related mortality.

Türkiye

The first Proof-of-Concept (PoC) FIPRS in Türkiye was constructed by Ozpekler trout farms using the commercial 220 m^3 IPRS standard, with rainbow trout (Oncorhynchus mykiss) selected as the test species. The raceway framework consists of steel, while HDPE sheets form the walls and flooring. Plastic drums provide flotation. For the feed trial phase, the system was stocked and later expanded with a Quiescent Zone for Phase II waste-management testing. The PoC unit incorporates an innovative aquatic weed-catchment grid placed ahead of the whitewater unit and confinement gates, enabling workers to remove weeds before they obstruct the system. The company also considered supplementing dissolved oxygen using liquid oxygen systems similar to those employed in gravity-flow mountain raceways to maintain fish health and optimize growth performance.

5. CONCLUSION

IPRS and FIPRS represent a paradigm shift in sustainable aquaculture, combining efficiency, environmental protection, and adaptability. Their modularity and compatibility with precision tools make them especially relevant for regions with limited infrastructure but high aquaculture potential. Future research should focus on cost optimization, biosecurity enhancement, and integration with digital aquaculture platforms.

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THE EFFECTS OF CLIMATE CHANGE ON FISH MEAL AND FISH OIL PRODUCTION AND PRICES: GLOBAL CHALLENGES AND STRATEGIES FOR TÜRKIYE

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1. INTRODUCTION

Climate change is one of the greatest and most complex threats facing our planet. Global temperature increases, ocean acidification, sea level rise, and the increasing frequency of extreme weather events are causing profound and far-reaching changes to natural ecosystems and human activities (IPCC, 2023). These changes directly impact sectors critical to food security and economic stability.

Fish meal and oil play an essential role in the aquaculture and animal feed industries. Due to its high protein content, fish meal is

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used as a key ingredient in the diets of animals such as salmon, shrimp, and other aquaculture species, as well as poultry and pigs. Fish oil, rich in omega-3 fatty acids (EPA and DHA), is a valuable resource in both animal nutrition and human health supplements. The global supply of these products is largely dependent on the catch of small pelagic fish (anchovies, sardines, herring, etc.) (Duyar & Bayraklı, 2023; Bayraklı, 2023a,b).

However, the increasing pressure of climate change on marine ecosystems threatens the health and distribution of these small pelagic fish populations. Changes in ocean temperatures, disruptions in the food chain, and habitat loss can lead to declining fish stocks or altered migration routes. This creates uncertainties in the supply of raw materials required for fish meal and oil production, thereby affecting production costs and final product prices.

This article aims to comprehensively examine the multifaceted impacts of climate change on fish meal and oil production and prices. It will address the biophysical impacts of climate change on fish populations and raw material supply, changes in production processes and costs, global market dynamics, and price fluctuations. Furthermore, potential solutions to these challenges, sustainability approaches, measures that countries with limited production, such as Turkey, and the potential impacts of these measures on the Turkish economy will be presented in a comparative manner. This analysis aims to provide valuable information to aquaculture and feed industry stakeholders, policymakers and researchers to better understand the impacts of climate change on this critical sector and develop adaptation strategies.

2. CLIMATE CHANGE IMPACTS ON FISH MEAL AND OIL PRODUCTION AND PRICES

Climate change impacts the fish meal and oil industry in multiple ways, both in terms of raw material supply, production costs, and final product prices. These impacts have significant implications for global food security and economic stability.

2.1. Impacts on Fish Populations and Raw Material Supply

Climate change causes complex and multifaceted impacts on the world's oceans and freshwater ecosystems, directly affecting the health, distribution, and abundance of fish populations. This leads to significant fluctuations in the supply of small pelagic fish, which are essential raw materials for fish meal and oil production (Cheung et al., 2013).

2.1.1. Ocean Temperature Increase and Acidification

Ocean waters are warming with global warming, causing changes in the habitats of fish species. Many fish species migrate poleward to maintain their optimal temperature ranges. These migrations can reduce the productivity of traditional fishing grounds and increase fishing pressure in new areas (Poloczanska et al., 2013). Significant declines in fish biomass are expected, particularly in tropical regions, while populations of some species may increase in temperate regions (Barange & Perry, 2009). While oceans help mitigate the effects of climate change by absorbing a significant portion of atmospheric carbon dioxide (CO_2), this leads to ocean acidification. Increased CO_2 absorption lowers seawater pH, creating adverse conditions for marine organisms, particularly shellfish and corals. This can have indirect effects on fish populations by affecting plankton species that form the basis of the food chain (Doney et al., 2009).

2.1.2. Changes in Fish Migration Routes and Stock Distribution

Changes in sea temperatures affect fish migration routes and reproductive cycles. For example, species critical to fish meal and oil production, such as the Peruvian anchovy, are significantly affected by climate events such as El Niño. El Niño increases surface water temperatures in the Pacific Ocean, weakening upwelling (the rise of deep water to the surface) and reducing nutrient-rich waters. This leads to declines in anchovy populations and lower oil content, negatively impacting fish oil yields (Bakun & Broad, 2008). Such environmental fluctuations directly affect the quantity and quality of raw materials used in fish meal and oil production.

2.1.3. Extreme Weather Events and Their Impacts on Fishing Activities

Climate change increases the frequency and severity of extreme weather events such as hurricanes, storms, floods, and droughts. These events can damage fishing infrastructure (ports, boats, nets), disrupt fishing operations, and cause losses in fish farms (Hossain et al., 2025). For example, severe storms can destroy cages in fish farms or cause fish to escape. Droughts, on the other hand, can negatively impact freshwater aquaculture, degrading water quality and reducing production capacity (FAO, 2020)..

2.1.4. Fluctuations in the Supply of Raw Materials for Fish Meal and Oil Production

All of the factors mentioned above cause significant fluctuations in the supply of small pelagic fish required for fish meal and oil production. Declines or unpredictable changes in fish populations make raw material supplies uncertain and make it difficult for producers to produce sustainably. Large fish meal and oil producing countries, such as Peru, are particularly vulnerable to climate change, which can impact global markets (Toumi & Djama, 2019). These fluctuations complicate long-term planning and investment in the fish meal and oil industry.

2.2. Impacts on Production Processes and Costs

The effects of climate change on fish populations and raw material supply directly affect fish meal and oil production processes and costs. Uncertainties in raw material supply, changes in quality, and operational challenges place significant pressures on the economic sustainability of this industry.

2.2.1. Fuel Consumption and Carbon Footprint

Fish meal and oil production involves energy-intensive processes, from the capture of raw material fish to its processing. Fishing fleets may be forced to travel greater distances due to changes in fishing grounds or declining fish stocks. This increases fuel consumption and, consequently, operational costs. Furthermore, increased fuel consumption increases greenhouse gas emissions, thereby expanding the industry's carbon footprint (Pelletier & Tyedmers, 2010). According to FAO reports, fuel use in fishing operations is the main source of emissions for the sector, and measures such as efficient engines, better ship designs, and speed reductions can be taken to reduce these emissions (FAO, 2020).

2.2.2. Changes in Production Efficiency

Fluctuations in raw material supply and changes in fish oil content directly impact the productivity of fishmeal and oil production facilities. Fish oil yield, in particular, can vary significantly depending on the type, age, sex, and seasonal factors of the fish caught (Bayraklı, 2023a). For example, young or stressed fish yield lower oil than healthy adults. This requires more raw material fish to produce the same amount of fish oil, increasing production costs (Bayraklı, 2023b). Production facilities may need to make additional investments or operational adjustments to adapt to these uncertainties in raw material quality.

2.2.3. Raw Material Quality and Processing Processes

Environmental stress factors caused by climate change (e.g., higher water temperatures, decreases in oxygen levels) can affect the physiological state of fish and, consequently, raw material quality.

The prevalence of diseases and parasites can also reduce raw material quality. Poor-quality raw materials can reduce the nutritional value of fishmeal and oil and create additional challenges in processing processes. For example, processing fish with lower oil content can require more energy and time, further increasing production costs. Furthermore, events such as harmful algal blooms can contaminate fish with toxins, negatively impacting the safety and market value of fishmeal and oil products (Hossain et al., 2025).

2.3. Impacts on Fish Meal and Oil Prices

The impacts of climate change on fish populations and production processes inevitably affect the global price dynamics of critical commodities such as fish meal and oil. Supply and demand imbalances, market fluctuations, and the development of alternative feed sources play a significant role in prices.

2.3.1. Supply-Demand Imbalances

Fish meal and oil production is largely dependent on the catch of small pelagic fish. Ocean temperature increases, acidification, and extreme weather events caused by climate change are leading to unpredictable changes in the populations and distribution of these fish (Cheung et al., 2013). Climate events, such as El Niño, can severely impact catch quotas for key raw material sources such as Peruvian anchovy, causing sudden declines in global supply. For example, the strong El Niño event between 2014 and 2016 significantly reduced fish meal and oil production and led to sharp increases in prices (Cabello & Buschmann, 2018). On the other hand, the continuous growth of the aquaculture sector is increasing the demand for fish meal and oil. According to FAO data, aquaculture accounts for a significant portion of global fish production, and this proportion will continue to increase in the future (FAO, 2020).

In the face of this increasing demand, supply constraints caused by climate change are naturally causing prices to rise. This is transforming fish meal and oil from a simple commodity to a strategic component, making it increasingly difficult to secure sustainable resources (Tacon & Metian, 2008).

2.3.2. Market Fluctuations and Speculation

Fish meal and oil markets are highly volatile due to uncertainties in raw material supply. According to FRED (Federal Reserve Economic Data) data, global fish meal prices have experienced significant fluctuations over the past 10 years. Prices peaked particularly during the 2007-2008 global food crisis and between 2011 and 2014 (FRED, 2025). These fluctuations create opportunities for investors and speculators, while representing cost uncertainty and risk for aquaculture and animal feed producers. Sudden price increases increase feed costs, which are then reflected in the prices of final products (salmon, shrimp, etc.), which in turn impact consumer prices.

2.3.3. The Impact of Alternative Feed Sources on Prices

Supply constraints and price increases in fish meal and oil encourage the development and use of alternative feed sources. Alternatives such as microalgae, insect proteins, plant proteins, and fermented products have the potential to reduce dependence on fish meal and oil (Naylor et al., 2009). The development and commercialization of these alternatives could have a stabilizing effect on fish meal and oil prices in the long term. However, the fact that these alternatives do not yet fully match the nutritional value and functional properties of fish meal and oil, or that they are not produced at sufficient scale, slows down the transition process (Duyar & Bayraklı, 2023, Tacon & Metian, 2008]. The cost-effectiveness and widespread adoption of alternative feed sources will be a key factor in determining the future course of fish meal and oil prices.

2.3.4. Consumer Behavior and Industrial Demand

Increases in fish meal and oil prices affect the costs of aquaculture products, which in turn impacts final consumer prices. This may cause consumers to change their fish and seafood consumption habits. Higher prices may drive some consumers to more affordable protein sources. At the industrial level, feed manufacturers and aquaculture businesses are attempting to optimize fish meal and oil usage rates or turn to alternatives to reduce costs and maintain profitability. These strategies can partially offset the demand for fish meal and oil, but the continued rise in global protein demand will continue to put pressure on these products.

3. SOLUTION PROPOSALS AND SUSTAINABILITY APPROACHES

Given the negative impacts of climate change on fish meal and oil production and prices, it is crucial to develop comprehensive solutions and adaptation strategies to ensure the sustainability of the sector and ensure future food security. These approaches cover a wide range of areas, from improving fishing and aquaculture practices to developing alternative feed sources, from policy regulations to technological innovations.

3.1. Sustainable Fisheries and Aquaculture Practices

Sustainably managing small pelagic fish stocks, which are used as raw materials in fish meal and oil production, is a critical step in mitigating the impacts of climate change. Preventing overfishing, basing catch quotas on scientific data, and improving fishing methods are essential for maintaining the health of fish populations. The FAO recommends adopting adaptive approaches to fisheries management and responding quickly to changes in fish stock productivity (FAO, 2020). This can contribute to the stability of raw material supplies by reducing fishing pressure and improving ecosystem health.

In aquaculture, sustainable practices that minimize environmental impacts and increase resource efficiency need to be expanded. This could include methods such as closed-loop aquaculture systems, integrated multi-trophic aquaculture (IMTA), and the cultivation of species with a low environmental footprint. Additionally, infrastructure improvements and risk management plans should be created to make aquaculture facilities more resilient to extreme weather events caused by climate change (Hossain et al., 2025).

3.2. Alternative Feed Sources

Reducing reliance on fishmeal and oil is one of the most important ways to increase the sector's resilience to climate change. In this context, the research, development, and commercialization of alternative feed sources is of great importance. Potential alternatives include:

3.2.1. Microalgae

Rich in omega-3 fatty acids, microalgae offer a sustainable alternative to fish oil. Microalgae, which can be cultivated in controlled environments and unaffected by climate change, have the potential to mitigate the effects of fluctuations in fish oil production (Tacon & Metian, 2008).

3.2.2. Insect Proteins

Insects, thanks to their high protein content and rapid reproductive cycles, are a sustainable protein source that can be used in place of fish meal. Insect farming requires less land and water and has a lower environmental footprint than traditional animal husbandry.

3.2.3. Plant-based Proteins

Plant-based proteins such as soy, corn, and wheat are increasingly being used in aquaculture feeds instead of fish meal. However, the nutritional value and digestibility of these alternatives should be optimized according to the needs of the fish species farmed. Furthermore, the production of plant proteins should also be evaluated in terms of environmental sustainability.

3.2.4. Fermented Products and By-Products

Using by-products and fermented materials obtained from the food industry as feed offers sustainable solutions that align with circular economy principles.

3.3. Policy And Management Strategies

Comprehensive policy recommendations and legal regulations are vital to ensure resilience to the impacts of climate change on the fisheries and aquaculture sector at the international and national levels. These regulations should promote environmental sustainability while supporting economic development.

3.3.1. National Climate Change Adaptation Plans and Sectoral Strategies

While Turkey has developed national action plans to combat climate change, greater focus is needed on adaptation strategies specific to the aquaculture and fisheries sector (Rad et al., 2018; Yıldız & Ganioğlu, 2010). These strategies should include the following:

Integrated Coastal Zone Management (ICMM): ICMM plans should be strengthened and implemented to mitigate the impacts of climate change on coastal ecosystems and protect fisheries resources. These plans should cover issues such as seawater quality, habitat protection, and fish stock management.

Risk Assessment and Early Warning Systems: Predicting risks such as extreme weather events, seawater temperature increases, and disease outbreaks caused by climate change, and developing early warning systems against them, will increase the sector's adaptation capacity.

Sectoral R&D and Innovation Incentives: Research and development activities on alternative feed sources, climate-resilient fish species, and energy-efficient production technologies should be supported by government support and incentive programs. This will increase private sector investments in this area (Yıldız & Ganioğlu, 2010; Aydın et al., 2025).

3.3.2. Legal Regulations and Implementation Mechanisms

Existing legal regulations in the fisheries and aquaculture sector should be updated to adapt to the new challenges posed by climate change. In this context:

Sustainable Fishing Quotas and Control: Catch quotas based on scientific data should be established, and control mechanisms to combat illegal, unreported, and unregulated (IUU) fishing should be strengthened (Ünal & Göncüoğlu, 2012). This is critical for protecting fish stocks and stabilizing raw material supplies.

Aquaculture Licensing and Environmental Standards: Environmental impact assessment processes for the establishment and operation of aquaculture facilities should be tightened, and sustainability standards should be raised. In particular, environmentally friendly methods such as closed-circuit systems and integrated aquaculture should be encouraged.

Legal Framework for Alternative Feed Sources: A legal framework should be established for the production and use of microalgae, insect proteins, and other next-generation feed ingredients. This will ensure the safety, quality, and market access of these products.

Water Law and Water Management: The enactment of a Water Law that will eliminate the fragmented structure of water management in Türkiye and address gaps in the current legal structure will enable the aquaculture sector to use water resources more efficiently and sustainably (UNFSS, 2021).

3.3.3. International Cooperation and Financing Mechanisms

Since climate change is a global problem, international cooperation and information sharing are of paramount importance. Turkey should increase its cooperation with international organizations such as the FAO to exchange experience and information on climate change adaptation and mitigation strategies (FAO, 2022). Furthermore, access to international financing mechanisms should be ensured for sustainable fisheries and aquaculture projects.

4. SPECIAL MEASURES FOR TURKEY AND THEIR ECONOMIC IMPACTS

Measures taken against the impacts of climate change by countries with limited capacity in fish meal and oil production, such as Turkey, have the potential to create significant positive impacts not only in terms of environmental sustainability but also on the national economy. The potential impacts of these measures on the Turkish economy can be examined under the following headings:

4.1. Reducing Import Dependence and Foreign Exchange Savings

The Turkish aquaculture sector is significantly dependent on imports for key feed ingredients such as fish meal and oil (TEPGE, 2024). The development and production of local alternative feed sources (microalgae, insect proteins, plant proteins) will reduce this import dependency. This will have a positive impact on the country's foreign exchange reserves and contribute to closing the foreign trade deficit. Reducing imports will also create a more resilient structure to price fluctuations in global markets.

4.2. Employment Creation and Rural Development

The production of alternative feed sources will require the establishment of new industries (e.g., microalgae farms, insect farming facilities). These new industries will create employment opportunities, especially in rural areas, and support regional development. R&D activities and technological innovations will also contribute to employment by increasing the demand for a skilled workforce. The aquaculture sector's transition to sustainable practices may create positions requiring more specialized expertise.

4.3. Increasing the Competitiveness of the Aquaculture Sector

Instability and increases in fish meal and oil prices directly impact aquaculture production costs. Access to local and cost-effective alternative feed sources will allow Turkish aquaculture producers to reduce feed costs and thus become more competitive in international markets. This will stimulate the sector's growth and increase its export potential. Sustainable aquaculture practices will also enhance the reputation and desirability of Turkish products in international markets (Alpbaz, 2022).

4.4. Ensuring Food Security

Given the threats posed by climate change to global food systems, reducing external dependence on fish meal and oil and increasing local production capacity will strengthen Türkiye's food security. Aquaculture plays a crucial role in meeting the protein needs of a growing population. Increasing the sector's resilience to climate change will directly contribute to national food security by ensuring the continuity of fish and seafood supplies.

4.5. Development of the R&D and Innovation Ecosystem

R&D and innovation investments in alternative feed sources and climate adaptation technologies will increase Türkiye's scientific and technological capacity. Collaboration between universities, research institutes, and the private sector will lead to the generation of new knowledge and technologies. This will pave the way for the development of innovative solutions not only for the fish meal and oil sector, but also for other agricultural and food sectors. Innovation will support long-term economic growth and the development of high-value-added products.

4.6. Economic Value of Environmental Benefits

Sustainable fishing and aquaculture practices will provide long-term economic benefits by maintaining the health of marine ecosystems. Healthy ecosystems support the regeneration of fish stocks and ensure the sustainability of fisheries resources. Furthermore, reducing environmental impacts can have positive impacts on other marine-related sectors, such as tourism. Environmental sustainability can also facilitate access to international funding and green financing mechanisms.

5. CONCLUSİON AND FUTURE PERSPECTİVE

Climate change poses serious challenges for the fish meal and oil industry, both globally and locally. The impacts on fish populations lead to uncertainties in raw material supply and fluctuate production costs and final product prices. However, these challenges also present opportunities for developing sustainable and innovative solutions.

For countries with limited fish meal and oil production, such as Turkey, climate change adaptation strategies are not only an environmental imperative but also an economic opportunity. Economic benefits such as reducing import dependency, creating jobs, increasing the competitiveness of the aquaculture sector, ensuring food security, and developing the R&D ecosystem will be significant outcomes of these adaptation efforts.

Sustainable fishing and aquaculture practices, the development of alternative feed sources, effective policies and legal regulations, and international cooperation are the fundamental steps needed to overcome these challenges. The experiences of other countries provide valuable examples for Turkey and highlight the importance of adaptive management, investment in alternative feed sources, capacity building, and integrated approaches.

Continuous research, technological innovation, and policy support are necessary to ensure the fishmeal and oil industry is resilient and sustainable in the face of climate change. This will both protect environmental values and contribute to global food security and economic development.

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THE COST OF CATCH: FUEL CONSUMPTION AND EFFICIENCY IN AEGEAN TRAWL FISHERIES

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Introduction

The Aegean Trawl Fishery: Economic and Social Bedrock of the Coastal Communities

The Aegean Sea, a semi-enclosed basin of the Eastern Mediterranean characterized by its intricate coastline, numerous islands, and rich hydrographic features, has been a cradle of marine life and human civilization for millennia. This marine ecosystem supports a diverse array of fisheries that are not merely economic activities but are deeply woven into the cultural and social fabric of

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the coastal nations of Greece and Turkey. Among these, bottom trawling stands as one of the most significant fishing methods in terms of landed value, volume of catch, and provision of high-quality protein (Tsikliras & Stergiou, 2014). The trawl fishery specifically targets valuable demersal species that form the backbone of the regional seafood market and export industry, including European hake (*Merluccius merluccius*), red mullet (*Mullus barbatus*), deep-water rose shrimp (*Parapenaeus longirostris*), and a variety of pandalid shrimp (Tokaç et al., 2010).

The economic importance of the Aegean trawl fleet is substantial. It provides direct employment for thousands of fishers, skippers, and vessel owners, while also sustaining a vast onshore network of jobs in fish processing, packaging, ice production, gear maintenance, boat building, marketing, and distribution (Machias et al., 2016). In many coastal towns and islands, the trawl fishery is a primary employer and a key driver of local economic activity, often forming the economic backbone of communities with limited alternative industries. The sector ensures a steady supply of affordable fish to domestic markets, contributing significantly to national food security and a nutritious diet (Arısoy et al., 2021). The financial investment in the fleet, encompassing vessels, engines, and sophisticated fishing gear, represents a major capital outlay, anchoring substantial private and sometimes public investment in the coastal regions.

Socially, the trawl fishery is more than an income source; it is a way of life that has been passed down through generations, shaping identities, traditions, and community cohesion (Birkan & Öndes, 2020). The knowledge of fishing grounds, seasonal species movements, and weather patterns constitutes an invaluable intangible cultural heritage. This socio-economic structure, however, exists within a context of increasing vulnerability. The fishery faces a triad of persistent pressures: rampant fluctuations in fish stock abundance due to historical overfishing and environmental change, stringent regulations aimed at stock recovery, and the ever-present specter of soaring operational costs, among which fuel is paramount (Suuronen et al., 2012).

Despite these challenges, the Aegean trawl fishery remains a vital component of the regional blue economy. Its continued existence is crucial for the socio-economic stability of countless families and communities. Therefore, understanding and mitigating its primary operational constraint, high fuel consumption, is not just a technical or economic issue, but a fundamental requirement for safeguarding this enduring maritime heritage.

The Central Problem: High Fuel Dependency

The operational paradigm of Aegean trawl fisheries is fundamentally tethered to a single, volatile, and costly input: fossil fuel. Unlike many other agricultural or industrial sectors where labor, raw materials, or technology might constitute the primary expense, in trawling, fuel consistently emerges as the single largest operational cost, dwarfing all others. Comprehensive analyses of fishing cost structures consistently reveal that fuel expenditures can account for 40% to 60% of total variable costs for a typical Mediterranean trawler (Gomi et al., 2024; Thrane, 2004). This profound dependency creates a precarious economic reality where the profitability and very viability of fishing enterprises are not determined solely by catch volumes or market prices but are critically influenced by the fluctuating global price of crude oil.

The physics of bottom trawling explains this high energy intensity. The process is inherently resistance-based, requiring a vessel to expend immense energy to overcome two primary sources of drag: the hydrodynamic resistance of the vessel's hull moving through water and, more significantly, the mechanical resistance of dragging heavy fishing gear across the seabed. The trawl doors (otter boards), sweeps, and the net itself must be towed at a sufficient speed, typically between 2.5 and 3.5 knots, to effectively herd and capture demersal fish (Jeon & Nam, 2023). This "active" fishing phase is exceptionally fuel-intensive, with the engine working under high load to maintain gear geometry and speed against the friction of the seafloor and water currents. As Parker and Tyedmers (2015) highlighted in their global assessment, bottom trawling stands out as one of the most fuel-intensive fishing methods per unit of landed catch, a finding that is acutely relevant to the Aegean context.

This high fuel dependency translates directly into severe economic vulnerability. The global oil market is notoriously volatile, subject to geopolitical tensions, production decisions by oil-exporting nations, and shifts in global demand. A sudden spike in diesel prices, as witnessed during various global crises, can rapidly erase the narrow profit margins of vessel operators (Schau et al., 2009). Fishers become price-takers in an uncontrollable global market; their income inversely correlated with oil prices. This vulnerability stifles investment in newer, more efficient technologies, as capital is perpetually consumed by high operating costs. It can also lead to perverse incentives, where skippers may feel compelled to fish longer hours, in worse weather, or in more sensitive areas to maintain revenue, potentially leading to overexploitation of stocks and increased environmental degradation, a classic "race to fish" scenario exacerbated by cost pressures (Driscoll & Tyedmers, 2010).

Furthermore, this dependency creates a dangerous feedback loop. As stocks decline due to overfishing and environmental pressures, fishers must travel greater distances and tow their gear for longer periods to achieve the same catch—a phenomenon known as "fishing down the food web" and increasing "search time." This leads to higher fuel consumption per unit of catch, which in turn increases costs and further pressures stock health by increasing fishing effort, creating a vicious cycle that threatens both the economic and ecological sustainability of the fishery (Bastardie et al., 2022).

In essence, the high fuel dependency of the Aegean trawl fishery is not merely a line item on a balance sheet. It is a central risk factor that undermines economic resilience, exacerbates environmental pressures, and jeopardizes the long-term social sustainability of coastal communities that depend on this ancient practice. Addressing this fuel dependency is, therefore, the most critical lever for enhancing the sector's viability.

The Sustainability Imperative

The challenge of high fuel dependency in Aegean trawl fisheries extends far beyond economic ledgers; it represents a critical nexus where operational costs converge directly with environmental degradation. The combustion of fossil fuels on fishing vessels is a primary source of the sector's carbon footprint, emitting significant quantities of greenhouse gases (GHGs), including carbon dioxide (CO_2), nitrogen oxides (NO_x), and sulfur oxides (SO_x), directly into the atmosphere. When assessed on a global scale, fisheries are estimated to burn around 40 billion liters of fuel annually to land approximately 80 million tons of marine life, contributing roughly 0.5% to global oil consumption and 1.2% to global CO_2 emissions, a carbon footprint comparable to that of the aviation industry (Parker & Tyedmers, 2015). For the Aegean trawl fleet, this translates into a substantial environmental cost for every kilogram of fish landed, making fuel efficiency a direct proxy for climate impact mitigation.

Beyond GHG emissions, the high energy intensity of trawling is intrinsically linked to other adverse ecological effects. The need to tow heavy gear across the seabed to catch demersal species makes bottom trawling one of the most widespread sources of anthropogenic disturbance to marine benthic ecosystems (Puig et al., 2012). The drag force that consumes so much fuel is the same force that physically alters seafloor habitats, resuspends sediments, and can damage slow growing, structurally complex benthic communities such as coralligenous assemblages and seagrass beds (Posidonia oceanica), which are vital for carbon sequestration and biodiversity in the Mediterranean (Paradis et al., 2017). Therefore, reducing fuel consumption is not solely about burning less diesel; it is inherently linked to reducing the physical impact of the fishing gear itself. A more fuel-efficient tow is, by definition, a lower-drag tow, which typically implies less force exerted on the seabed.

This dual pressure, climate emissions and habitat impact, compels a shift from traditional, single-species management towards an Ecosystem-Based Fisheries Management (EBFM) framework. EBFM moves beyond the narrow focus on maximizing sustainable yield from target stocks to a holistic approach that considers the entire marine ecosystem, including habitat integrity, bycatch of non-target species, and the cumulative impacts of fishing, including its carbon footprint (Pikitch et al., 2004). Within this framework, fuel consumption ceases to be merely an economic externality and becomes a core fisheries management metric, an indicator of both economic efficiency and ecosystem pressure.

The pursuit of fuel efficiency aligns perfectly with the precautionary and ecosystem approach principles enshrined in international policy, such as the European Union's Common Fisheries Policy (CFP), which explicitly aims to minimize the negative impacts of fishing on the marine ecosystem and to reduce the sector's dependency on fossil fuels (European Union, 2013). Adopting fuel-efficient practices is, therefore, a pragmatic strategy for the industry to proactively align with evolving regulatory demands and societal expectations for environmental stewardship.

In conclusion, improving fuel efficiency in the Aegean trawl fishery is an indispensable component of its long-term sustainability. It directly addresses the urgent need to mitigate climate change by reducing GHG emissions, indirectly contributes to preserving sensitive benthic habitats by lowering gear drag, and positions the fishery for resilience within a modern, ecosystem-based management paradigm. The imperative is clear: transitioning towards a low-fuel future is synonymous with securing a viable, responsible, and climate-resilient future for the fishery itself.

Chapter Objectives

Building upon the critical context of the Aegean trawl fishery's socio-economic importance, its vulnerability to high fuel costs, and the pressing sustainability imperative, this chapter aims to provide a comprehensive, evidence-based analysis of the energy intensity of this vital sector. The central aim is to deconstruct the multifaceted problem of high fuel consumption and to synthesize a viable pathway toward a more efficient, profitable, and environmentally sustainable future. To achieve this, the chapter is structured around the following specific objectives:

To Systematically Identify and Analyze the Multifactorial Drivers of Fuel Consumption. This chapter will move beyond a superficial acknowledgment of high fuel use to dissect the complex interplay of variables that determine a vessel's fuel efficiency. This includes a detailed examination of:

Technical Factors: The role of vessel design (hull hydrodynamics, age), engine type and maintenance, and propeller efficiency.

Gear-Related Factors: The impact of trawl net design, twine thickness, otter board (trawl door) hydrodynamics, and rigging configurations on the overall drag coefficient.

Operational Factors: The influence of skippers' decisions, including towing speed, trip planning, "searching time," and fishing tactics, on non-productive fuel burn.

External Factors: The effects of environmental conditions such as seabed topography, currents, and weather on resistance and power requirements.

To Explore and Evaluate a Suite of Technological and Operational Strategies for Enhancing Fuel Efficiency. Drawing on the best global practices and region-specific case studies, this chapter will critically assess a range of solutions. The exploration will be structured to distinguish between:

Technological Innovations: Assessing the efficacy and return on investment of upgrades such as advanced propulsion systems, low-friction antifouling hull coatings, high-strength/low-drag trawl materials, and hydrodynamic trawl doors (Gomi et al., 2024; Suuronen et al., 2012).

Operational and Management Measures: Investigating potential fuel savings from improved skipper training, data-driven decision-support tools, collaborative fishing strategies, and management frameworks that incentivize efficiency over effort (Bastardie, Nielsen, & Miethe, 2014; Driscoll & Tyedmers, 2010).

To Present and Quantify the Tangible Benefits of Fuel-Efficient Practices through Regional and Analogous Case Studies. To bridge the gap between theory and practice, this chapter will present empirical evidence from the Mediterranean region. It will highlight real-world examples, such as the adoption of "Eco-Trawl" nets or polyvalent trawl doors, to demonstrate the concrete outcomes in terms of fuel savings per trip, reduction in greenhouse gas emissions, and the economic payback period for such investments.

To Synthesize the Findings into a Coherent Framework for Stakeholders. Finally, this chapter aims to translate its analysis into actionable recommendations. It will outline a collaborative path forward, defining distinct but complementary roles for:

- Fishers and Vessel Owners in adopting fuel-conscious practices and investing in proven technologies.
- Policymakers in designing targeted financial incentives (e.g., green subsidies, landing fees) and supportive regulatory frameworks.
- Researchers in prioritizing R&D for next-generation fishing technologies and integrated monitoring systems.

By fulfilling these objectives, this chapter seeks to serve as a definitive resource for understanding and addressing the "cost of catch" in the Aegean Sea. It positions fuel efficiency not as an optional upgrade, but as a fundamental pillar for achieving the intertwined goals of economic resilience, regulatory compliance, and ecological stewardship in a rapidly changing world.

The Fuel Consumption Profile of an Aegean Trawler

Understanding the total fuel consumption of a trawler requires more than just measuring the volume in the tank at the start and end of a trip. It necessitates a detailed breakdown of the voyage into distinct operational phases, each with its own unique fuel consumption dynamics. This "anatomy of fuel use" reveals where energy is spent productively and where significant inefficiencies and savings potentials lie.

The Anatomy of Fuel Use

The fuel consumed during a typical fishing trip by an Aegean trawler can be disaggregated into three primary phases: transit, searching, and active trawling. The proportion of fuel used in each phase varies based on distance to grounds, skipper behavior, and stock abundance, but a general understanding provides a critical foundation for identifying targeted efficiency measures.

1. Transit to and from Fishing Grounds

This phase involves steaming at maximum continuous speed from the home port to the designated fishing area and back. While the vessel's hull is designed for relatively efficient travel through water, the engine operates at a high load to achieve cruising speed, resulting in substantial fuel consumption per hour. The critical variable here is distance. In the Aegean Sea, the establishment of coastal no-trawl zones and Marine Protected Areas (MPAs) has often displaced fishing effort further offshore, increasing transit distances significantly (Machias et al., 2016; Tzouramani et al., 2024). Furthermore, the archipelago nature of the sea means vessels based on islands may have inherently longer transit times to productive continental shelf grounds. Although fuel consumption rate (liters per hour) is high during transit, it is generally more efficient in terms of distance traveled (liters per nautical mile) than the trawling phase. However, as it is a non-fishing activity, any reduction in transit distance or optimization of speed directly translates into fuel savings and reduced overall emissions (Parker & Tyedmers, 2015).

2. Active Trawling (The "Tow")

This is the core, and most fuel-intensive, phase of the operation. During active trawling, the vessel's engine must simultaneously overcome the hydrodynamic drag of the vessel's hull and the immense mechanical drag of the fishing gear being pulled across the seabed. The engine operates under high torque and load, but at a lower vessel speed (typically 2.5-3.5 knots). This phase consumes the highest amount of fuel per unit of time. The energy required is directly related to the gear's drag, which is a function of trawl door size and design, net size and twine thickness, and the nature of the seabed (Gomi et al., 2024). Trawling on rough, hard bottoms or against a strong current can increase fuel consumption during this phase by 20% or more compared to towing on a smooth, muddy bottom with a following current (Soykan et al., 2016). While this is a productive phase (catching fish), its extreme energy intensity makes it the primary focus for technological interventions aimed at reducing gear drag.

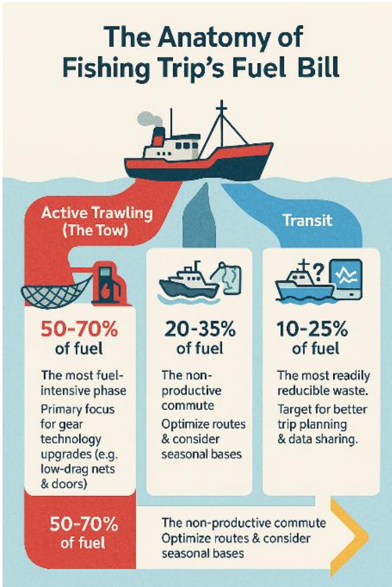
3. Searching and Maneuvering

This phase encompasses all non-productive steaming on the fishing grounds. It includes moving between tow locations, relocating after a poor catch, and maneuvering to set or haul the gear. The engine load during searching is similar to transit, high speed, high fuel consumption rate, but it is spent on a non-revenue-generating activity. The duration of this phase is highly variable and depends almost entirely on the skipper's skill, experience, and access to information. In fisheries where stocks are depleted or patchily distributed, or where there is a lack of information sharing, "searching time" can constitute a substantial and wasteful portion of the total fuel bill (Bastardie et al., 2014). Ad-hoc, unplanned searching represents one of the most significant and readily addressable sources of inefficiency in the fishing operation.

To illustrate, a notional breakdown for an Aegean trawler might appear as follows, though these figures are highly variable:

- Active Trawling: 50-70% of total trip fuel, due to its high intensity.

- Transit: 20-35% of total trip fuel, dependent on distance.
- Searching/Maneuvering: 10-25% of total trip fuel, dependent on skipper skill and information.



Infographic 1. *The Anatomy of a Fishing Trip's Fuel Bill*

This anatomical breakdown makes it clear that a holistic strategy for fuel efficiency must address all three phases: optimizing vessel hull and propulsion for transit, investing in low-drag gear for active trawling, and implementing data-driven strategies to minimize unproductive searching.

Quantifying the Cost: The Dominance of Fuel in the Balance Sheet

To fully grasp the economic precarity induced by fuel dependency, it is essential to move from qualitative description to quantitative analysis. The proportion of total operational costs consumed by fuel is not merely a significant line item; it is the dominant financial force that shapes the economic viability of Aegean trawl enterprises. Empirical studies and economic assessments of Mediterranean fisheries consistently demonstrate that fuel costs are the single largest expenditure, frequently exceeding 50% of total variable operating costs (Gomi et al., 2024; Thrane, 2004).

This figure, however, is not static and varies based on several factors. The specific breakdown can be influenced by:

Vessel Efficiency: Older, less efficient vessels with poor hull forms and outdated engines can see fuel costs escalate to 60% or more of their operating budget, while newer or retrofitted vessels may maintain a share closer to 40-50% (Schau et al., 2009).

Fishing Depth and Grounds: Trawlers operating in deeper waters or on rougher bottoms require more powerful towing, directly increasing the fuel cost share relative to vessels fishing on shallow, sandy grounds (Soykan et al., 2016).

Global Oil Price Volatility: The proportion is a direct function of the price at the pump. During periods of high oil prices, the fuel cost share can spike dramatically, compressing all other cost categories and eliminating profit margins entirely.

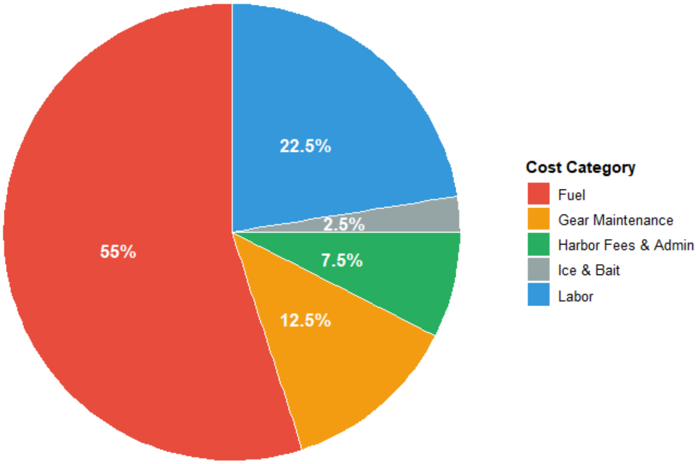


Figure 1. *Breakdown of Variable Operating Costs for a Typical Aegean Trawler (Source: Based on cost structure analysis from Aegean trawl fisheries).*

To illustrate this financial structure, a representative cost breakdown for a mid-sized Aegean trawler can be conceptualized as follows:

- Fuel: 50-60% of total variable costs
- Labor (crew shares): 20-25%
- Gear Maintenance and Replacement: 10-15%
- Harbor Fees, Insurance, and Administration: 5-10%
- Ice and Bait (if applicable): <5%

This cost structure reveals a critical vulnerability. Unlike labor or maintenance, which can be negotiated or deferred to some extent, fuel is a non-discretionary input. A fishing trip cannot occur without it. This creates an inelastic demand, making the industry highly susceptible to global oil price shocks. A study on Greek fisheries found that a 30% increase in fuel prices could render a significant portion of the fleet unprofitable, forcing vessels to remain in port, a phenomenon known as "negative effort elasticity" (Tzouramani et al., 2024).

The economic impact extends beyond simple percentages. High fuel costs create a pervasive "cost-price squeeze." As fuel expenses rise, the net revenue from the catch diminishes unless market prices for fish increase commensurately, a rare occurrence. This squeeze stifles investment capital, making it financially prohibitive for fishers to invest in the very fuel-efficient technologies that would alleviate the cost pressure. It becomes a destructive cycle: high fuel costs prevent investment in efficiency, which in turn perpetuates high fuel costs (Bastardie et al., 2022).

Furthermore, the cost must also be understood in terms of energy return on investment (EROI). In fisheries, this is often measured as the amount of fuel required to land one kilogram of fish. For Mediterranean bottom trawlers, this ratio can be particularly unfavorable, with estimates ranging from 0.5 to over 2.0 liters of fuel per kilogram of live-weight landings for certain demersal species (Parker & Tyedmers, 2015). When the fuel cost to land one kilogram of fish approaches or even exceeds the price received for that fish, the economic activity becomes fundamentally unsustainable.

In conclusion, quantifying the cost confirms that fuel is not just another expense; it is the central determinant of profitability. Its dominant share of operational costs creates a fragile economic model, one where the financial resilience of entire coastal communities is inextricably linked to the volatile global energy market.

Key Factors Influencing Fuel Consumption in Aegean Trawlers

Fuel consumption in trawling is not the result of a single factor, but a complex function of multiple, often interacting, variables. A comprehensive understanding of these drivers is the essential first step toward identifying and implementing effective efficiency gains. The primary factors can be categorized into vessel characteristics, fishing gear technology, operational practices, and environmental conditions.

Vessel Characteristics: The Foundational Platform of Efficiency

The trawler itself serves as the foundational platform upon which all fishing activities occur. Its inherent design and maintenance state set a baseline for fuel performance, imposing a fundamental limit on efficiency that can only be partially mitigated by other measures. The key vessel characteristics include hull design, engine power and age, and the condition of the hull surface.

Hull Form and Hydrodynamics

The hull is the primary interface between the vessel and the water, and its design dictates the resistance it must overcome while moving. A well-designed, hydrodynamically efficient hull with a fine entry and a smooth run minimizes wave-making and frictional resistance. Many vessels in the Aegean fleet, however, are older designs that predate modern computational fluid dynamics (CFD) modeling. They often feature fuller, blunter hull forms with hard chines that create greater drag, requiring more engine power, and thus more fuel, to achieve the same speed as a modern hull (Wu et al., 2022). The difference between an optimal and a sub-optimal hull design can account for a 15-20% variance in fuel consumption during transit (Parker & Tyedmers, 2015). Furthermore, the hull form must be matched to the vessel's intended operation; a design optimized for high-speed transit may perform poorly under the low-speed, high-trawl-load conditions, and vice-versa.

Engine Power, Age, and Maintenance

The engine is the heart of the vessel's propulsion system, and its efficiency directly converts fuel into usable power. A significant issue in the Aegean fleet is the historical practice of installing oversized engines. This was often driven by a perception that more power equates to better fishing capability, especially for towing heavy gear in deep water or strong currents. However, an oversized engine typically operates far below its optimal load range during most operational phases, leading to poor fuel efficiency and higher specific fuel consumption (grams of fuel per kWh produced) (Gomi et al., 2024). Older, mechanically controlled diesel engines are notably less efficient than modern, electronically controlled units that can precisely manage fuel injection and air intake. Poor maintenance, such as clogged air filters, worn fuel injectors, or faulty turbochargers, can further degrade engine performance, silently increasing fuel consumption by 5-10% without the operator's knowledge (Schau et al., 2009).

Hull Fouling: The Silent Fuel Thief

The accumulation of marine organisms, such as algae, barnacles, and tube worms, on the submerged parts of the hull, known as biofouling, is a critical and often underestimated factor. A heavily fouled hull significantly increases the frictional resistance as the vessel moves through the water. The roughness created by biofouling disturbs the laminar flow of water, increasing drag and forcing the engine to work harder. Studies have demonstrated that moderate to severe hull fouling can increase fuel consumption by up to 30-40% depending on the vessel's speed and the extent of fouling (Schultz, 2007). For an Aegean trawler that spends days at sea, this represents a tremendous and continuous financial drain. The problem is particularly acute in the warm, nutrient-rich waters of the Mediterranean, which promote rapid biofouling growth. The practice of regular dry-docking for hull cleaning and the application of advanced, low-friction antifouling paints is, therefore, not a mere maintenance cost but one of the most cost-effective investments for immediate fuel savings.

In summary, the vessel's inherent characteristics create a fixed efficiency potential. An outdated hull form, an overpowered or poorly maintained engine, and a fouled hull collectively act as a significant and persistent drag on profitability, making technological upgrades and rigorous maintenance in these areas a primary target for reducing the "cost of catch."

Fishing Gear and Rigging: The Engine's Primary Load

While the vessel provides the platform and propulsion, the fishing gear itself constitutes the single largest variable load on the engine during the active trawling phase. The design, configuration, and deployment of the trawl net and its associated components directly determine the drag force that must be overcome. Even minor modifications in gear technology and rigging can yield substantial reductions in fuel consumption without compromising catch efficiency. The key elements include the trawl net design, the otter boards (trawl doors), warp length, and towing speed.

Trawl Net Design: The Drag of the Sweeping Curtain

The trawl net acts as a large, porous curtain being dragged through the water, and its resistance is a function of its size, shape, and the material from which it is constructed. Traditional nets often use thick, heavy twines to ensure durability on rough seabeds. However, this comes at a high fuel cost. The drag force of a trawl net is proportional to the square of the towing speed and the projected area of the netting in the direction of tow. Using thinner, stronger twines made from modern materials like ultra-high-molecular-weight polyethylene (UHMWPE) can reduce the diameter of the twine by up to 40% compared to traditional nylon or polyester for the same strength (Sala, Priour, & Herrmann, 2022). This reduction in twine diameter decreases both the weight of the net in water and, more importantly, its hydrodynamic drag, as a thinner twine disturbs the water flow less. Experimental and numerical studies have shown that such a switch can lead to a drag reduction of 10-20% for the net alone (Jeon & Nam., 2023). Furthermore, the overall geometry of the net, the taper of the wings and the size of the meshes, can be optimized to achieve the desired herding and filtering effect with minimal resistance.

Trawl Doors (Otter Boards): Hydrodynamic Efficiency at the Interface

Trawl doors are perhaps the most significant individual contributor to total gear drag, often accounting for 30-50% of the total pull of the trawl (He, 2019). Their primary function is to spread the wings of the net open horizontally. Traditional flat, rectangular steel doors are hydrodynamically inefficient, creating massive turbulence and pressure drag. Modern, cambered (curved) doors, such as Thyborøn-type or oval-shaped doors, are designed as hydrofoils. They generate the necessary spreading force (hydrodynamic lift) with a much higher lift-to-drag ratio. This means they achieve the same net spread with significantly less resistance. The adoption of such hydrodynamic doors is one of the most effective single upgrades a vessel can make, with documented fuel savings during towing of 15-25% (Gomi et al., 2024). Newer composite materials can also reduce the weight of the doors, lowering the energy required for acceleration and retrieval.

Warp (Cable) Length and Diameter: The Invisible Drag

The warps, the steel cables connecting the vessel to the trawl doors, are not passive components. Their length and diameter contribute to the overall system drag. The common rule of thumb is to use a warp length ratio of 3:1 (warp length to water depth) to ensure the gear reaches the bottom and spreads effectively. However, using excessively long warps beyond what is necessary increases the submerged length of cable, thereby increasing frictional drag. Furthermore, thicker warps, while offering a greater safety factor, create more drag than thinner ones of the same strength. Optimizing warp length to the minimum required for stable gear performance at a given depth and bottom type can yield incremental but valuable fuel savings (He, 2019). The integration of sensors on the warps allows skippers to make real-time, data-informed decisions on optimal length.

Towing Speed: The Cubic Relationship with Fuel Burn

Towing speed is the most potent operational lever influencing fuel consumption during the trawling phase. The relationship is not linear but cubic; the power required to tow the gear (and hence the fuel consumption rate) increases approximately with the cube of the speed (Parker & Tyedmers, 2015). This means that a 10% reduction in towing speed (e.g., from 3.0 to 2.7 knots) can lead to a theoretical ~27% reduction in fuel consumption during the tow. In practice, the savings are slightly less due to constant engine loads, but they remain substantial. The critical skill for the skipper lies in finding the "sweet spot", the minimum towing speed that maintains effective herding and capture of the target species. Towing too slowly can lead to escapement, while towing too fast wastes immense amounts of fuel for a negligible gain in catch. This optimization is highly species-specific and dependent on the gear being used.

In conclusion, the fishing gear and its rigging are not static tools but a dynamic system whose configuration dictates a significant portion of the voyage's fuel bill. Advancements in materials science and hydrodynamic design offer a direct pathway to decoupling fishing effort from fuel consumption, allowing fishers to catch the same amount of fish with a fraction of the energy input.

Operational Practices: The Human Element of Efficiency

Beyond the fixed characteristics of the vessel and gear, the decisions made by the skipper and crew before and during a fishing trip, the operational practices play a decisive role in determining overall fuel efficiency. These practices govern how technological assets are utilized and can be the difference between a profitable voyage and a financial loss. Key operational factors include the distance traveled to fishing grounds, the time spent searching for fish, and the duration and management of individual tows.

Distance to Fishing Grounds: The Non-Productive Commute

The Aegean Sea's complex geography, featuring numerous islands, coastlines, and established Marine Protected Areas (MPAs), significantly influences transit distances. The implementation of coastal exclusion zones, intended to protect nursery grounds and sensitive habitats, has displaced trawling effort further offshore (Machias et al., 2016). For vessels based in ports distant from productive continental shelf grounds, this can mean transit journeys of several hours each way. This transit phase, while often more fuel-efficient per nautical mile than active trawling, represents a substantial non-productive fuel burn. The fuel consumed during transit is a sunk cost before the first fish is caught. Therefore, the round-trip transit distance is a primary driver of the trip's total fuel consumption. Strategic port selection or the formation of seasonal operating bases closer to productive grounds could mitigate this, though such options are often limited by logistics and community ties.

Searching Time: The Fuel Cost of Uncertainty

Once on the fishing grounds, a significant portion of fuel can be consumed not in catching fish, but in looking for them. "Searching time" refers to the period spent steaming between tow locations at high speed, using echosounders and past experience to locate aggregations of target species. This practice is inherently inefficient, as the vessel's engine burns fuel at a high rate without the gear in the water generating revenue. The duration of searching time is a direct function of the skipper's knowledge and access to information. In situations of low stock abundance or patchy distribution, or when competing with other vessels in an uncoordinated "race to fish," searching time can escalate dramatically. Bastardie et al. (2014) demonstrated through modeling that inefficient fleet behavior and lack of information sharing can lead to a substantial proportion of fuel being wasted on non-productive steaming. Reducing this uncertainty through improved information is, therefore, a major avenue for savings.

Tow Duration and Soak Time: Balancing Catch per Unit Effort and Efficiency

The duration of each individual tow involves a complex trade-off. Longer tows can be more efficient in terms of catch per unit effort (CPUE) for certain species, as they reduce the proportion of time spent on non-productive activities like hauling, setting, and steaming between patches. However, they are not always optimal for fuel efficiency. As a tow progresses, the net fills with catch, increasing its weight and drag, which can incrementally raise fuel consumption during the latter part of the tow (Jeon & Nam, 2023). Furthermore, fishing in a single location for an extended period can lead to local depletion, reducing the catch rate in subsequent tows and potentially increasing future searching time. The optimal tow duration is thus a dynamic calculation, balancing the filling rate of the net, the fuel consumption curve, and the spatial distribution of the fish. Skippers must use their experience to determine the point of diminishing returns, where hauling the gear and moving to a new location becomes more profitable than continuing a tow with a declining catch rate.

The Cumulative Impact and the Role of Skipper Expertise

These operational factors are not isolated; they interact cumulatively. A long transit distance increases the pressure to maximize fishing time on the grounds, which can lead to rushed decisions and increased searching if initial tows are unsuccessful. Poor trip planning can create a cascade of inefficiencies. The skipper's expertise is the crucial integrating factor that manages these variables. An experienced skipper with detailed logbooks of past catches, familiarity with seasonal migrations, and potentially shared information from other vessels can dramatically reduce searching time, optimize tow duration, and plan efficient routes (Driscoll & Tyedmers, 2010). This "human capital" is an intangible but vital asset for fuel efficiency, underscoring the importance of training and knowledge-sharing alongside technological upgrades.

In summary, operational practices determine how efficiently the vessel's technological potential is realized. Inefficient practices can squander the benefits of advanced gear and a clean hull, while superior seamanship and planning can achieve remarkable fuel economy even with older technology.

Environmental Conditions: The Uncontrollable Variables

Even with an optimally configured vessel, state-of-the-art gear, and impeccable operational planning, the marine environment presents a suite of dynamic and largely uncontrollable variables that impose direct and often substantial costs on fuel efficiency. The Aegean Sea's unique hydrographic and topographic characteristics mean that environmental conditions are not a minor consideration but a fundamental and ever-present factor in the energy equation of trawling. Key among these are water currents, seabed topography, and prevailing weather conditions.

Water Currents: The Invisible River of Resistance

Subsurface currents, driven by tides, wind, and density gradients, create a fluid medium that is rarely stationary. Trawling against a strong current is analogous to walking uphill; it requires significantly more effort to make headway. The vessel must generate enough thrust to overcome not only the inherent drag of the vessel and gear but also the kinetic energy of the moving water mass. The effect on fuel consumption is profound. Empirical studies have shown that trawling against a current of 1-2 knots can increase fuel consumption by 10-20% compared to towing with the current (Brinkhof et al., 2024). In channels or areas with strong tidal flows, this effect can be even more extreme. This necessitates constant adjustments by the skipper, who must increase engine RPM to maintain the correct towing speed over the ground, leading to a sharp spike in fuel burn. Conversely, strategically planning a tow direction to harness a following current can yield significant fuel savings, though this is often secondary to the location of fish concentrations.

Seabed Topography and Substrate: The Friction of the Seafloor

The nature of the seabed over which the trawl is towed is a primary determinant of gear drag. The Aegean Seafloor is highly heterogeneous, ranging from soft, muddy plains to rocky outcrops, seagrass meadows (*Posidonia oceanica*), and coralligenous assemblages.

Bottom Friction: Trawling on a smooth, muddy bottom presents the least resistance. In contrast, towing across sandy or gravelly substrates increases friction, while traversing rough, hard ground or biologically complex habitats can cause the gear to snag, bounce, and undergo sudden decelerations, all of which demand more power and fuel (Tokaç et al., 2010).

Depth and Slope: Fishing in deeper water requires longer warps, which, as previously discussed, increases overall system drag. Furthermore, towing along a slope or uneven terrain requires continuous adjustments to warp length to maintain bottom contact, leading to unsteady engine load and inefficient fuel use. The choice of fishing ground is thus a direct trade-off between target species abundance and the fuel cost imposed by the seafloor's physical characteristics.

Weather and Sea State: The Atmospheric Drag

Surface conditions, dictated by wind and waves, directly impact the vessel's hydrodynamic resistance. In calm seas, the hull moves cleanly through the water. As sea state deteriorates, the vessel must expend additional energy to overcome wave resistance.

Vessel Motions: In rough seas, the vessel pitches and heaves, causing variations in propeller immersion and efficiency, and increasing the resistance of the hull as it pushes through waves. This "added resistance" can increase fuel consumption during transit by up to 30-50% in severe conditions (Wu et al., 2022).

Gear Handling: Rough weather also complicates gear handling. Setting and hauling the gear becomes more time-consuming and hazardous, potentially increasing non-productive fuel consumption during these maneuvers. Furthermore, strong winds create direct aerodynamic drag on the superstructure of the vessel, adding a small but non-negligible load.

The Compounding Effect and Strategic Adaptation

Critically, these environmental factors rarely act in isolation. A strong wind-against-tide situation can create a steep, choppy sea state, simultaneously increasing aerodynamic, hydrodynamic, and gear drag. Fishing on a rough, deep bottom against a strong current during poor weather represents a "perfect storm" of inefficiency, where fuel consumption can easily double compared to optimal conditions.

While these conditions cannot be controlled, they can be anticipated and managed. Skipper expertise is paramount in interpreting weather forecasts, understanding local current patterns, and making strategic decisions to avoid the most fuel-intensive combinations of factors. This may involve shifting fishing grounds, altering the timing of a trip, or choosing a more sheltered route. Therefore, adapting to environmental conditions is a sophisticated form of fuel management, where the goal is to minimize exposure to the most punishing combinations of sea, current, and seabed.

Pathways to Efficiency: Strategies and Technologies

Achieving meaningful and sustained reductions in fuel consumption requires a multi-faceted approach that leverages technological innovation, enhances human expertise, and is supported by enabling management frameworks. This section outlines the concrete strategies and technologies available to Aegean trawler operators, categorizing them into technological upgrades and operational measures.

Technological Innovations

Technological advancements offer direct, hardware-based solutions to reduce the energy intensity of trawling. While often requiring upfront investment, these innovations typically offer a clear return on investment through fuel savings, improved performance, and sometimes longer gear life.

Vessel and Propulsion Upgrades

The efficiency of the platform itself is the foundation of any fuel-saving strategy. Modernizing the vessel's core systems can yield substantial, long-term benefits.

Engine Replacements and Retrofits: Replacing an old, mechanically controlled diesel engine with a modern, electronically controlled (common rail) model is one of the most significant upgrades. Modern engines optimize fuel injection timing and pressure, leading to more complete combustion and higher thermal efficiency. They can reduce specific fuel consumption (grams of fuel per kWh) by 15-20% compared to engines over 20 years old (Carlton,2018).). For vessels not ready for a full replacement, engine derating, reconfiguring the engine to operate at its optimal load point for the vessel's typical power needs, can also improve efficiency.

Efficient Propeller Design: The propeller is the final link in the propulsion chain, converting engine power into thrust. Older, generic propellers are often mismatched to the vessel's hull and operating profile, leading to cavitation and slippage. Upgrading to a custom-designed, high-skew propeller matched to the vessel's resistance characteristics and typical load (including trawling load) can improve propulsion efficiency by 5-15% (Carlton, 2018). For further optimization, controllable pitch propellers (CPP) or nozzle propellers can provide superior thrust and maneuverability under the variable loads of trawling.

Advanced Antifouling Paints: As established, hull fouling is a major source of drag. The regular application of modern, foul-release coatings is a highly cost-effective measure. These silicone-based paints create an ultra-smooth, low-friction surface to which marine organisms struggle to adhere, and those that do are easily washed away at cruising speed. Compared to traditional biocidal antifouling paints, foul-release coatings can maintain a hydraulically smooth hull surface between dry-dockings, delivering persistent fuel savings of 5-10% by minimizing frictional resistance (Schultz, 2007).

Advanced Fishing Gear

Given that the gear is the primary load during fishing, innovations here offer the most direct path to reducing the energy cost of the catch itself.

Hydrodynamic Trawl Doors: Replacing traditional rectangular steel doors with modern, cambered designs (e.g., Thyborøn-type, oval, or V-doors) is a game-changer. These doors act as hydrofoils, generating the required spreading force with a much higher lift-to-drag ratio. This can reduce the door's contribution to total system drag by 20-40%, allowing the same net spread for less fuel or enabling a smaller, more efficient engine to be used (Gomi et al., 2024).

High-Strength/Low-Drag Twines: The development of ultra-high-molecular-weight polyethylene (UHMWPE) and other high-performance fibers has revolutionized net design. These twines are significantly stronger for the same diameter, or much thinner for the same strength, as traditional materials. Using thinner twines reduces both the weight and, critically, the hydrodynamic drag of the net. Trials with "Eco-Trawl" nets made from such materials have demonstrated drag reductions of 10-20% with no loss in catching performance for the target species (Thierry et al., 2020).

Real-Time Sensor Systems: The digitalization of fishing gear allows for precision trawling. Sensors mounted on the trawl doors, net, and warps can transmit real-time data on gear geometry (door spread, wing-end distance), depth, temperature, and even catch accumulation to a display on the bridge. This allows the skipper to make data-driven decisions, optimizing warp length and towing speed to the minimum required for effective fishing, thereby eliminating wasteful "over-trawling" (He, 2019).

Auxiliary and Alternative Power Sources

Reducing the load on the main engine for non-propulsion needs is a straightforward way to save fuel.

Solar Panels and Battery Systems: The electrical demands for onboard electronics, lighting, refrigeration, and winch hydraulics are typically met by a diesel-driven auxiliary generator. Installing a bank of solar panels on the wheelhouse roof can significantly offset this load during daylight hours. Coupled with a lithium-ion or advanced lead-acid battery bank, this system can power all or most auxiliary needs without running the generator, leading to fuel savings, reduced maintenance, and quieter, emission-free operation in port (ABS, 2023). While not yet capable of powering propulsion for large trawlers, these systems represent a low-risk, immediately applicable technology for reducing the vessel's overall fossil fuel dependency.

Operational and Management Measures

While technology provides the tools for efficiency, their ultimate impact is determined by how they are used. Operational measures leverage human expertise and collaboration to optimize the fishing process, while supportive management frameworks can create an environment where fuel efficiency is incentivized rather than penalized. These "soft" measures often require minimal capital investment but can yield disproportionately large and immediate fuel savings.

Skipper Training and Decision Support

The skipper on the bridge is the ultimate real-time efficiency manager. Their decisions directly control the largest variables in the fuel consumption equation. Targeted training and decision-support tools can empower skippers to optimize their performance.

Speed Optimization: As established, the cubic relationship between speed and fuel consumption is critical. Training programs can make skippers acutely aware of this relationship and provide them with the skills to find the economic speed for both transit and towing. This involves understanding that maximum speed is rarely the most profitable speed. For transit, reducing speed from 10 to 9 knots can reduce fuel consumption by over 25%. For towing, finding the minimum effective speed to capture target species, which may vary by species and season, can save hundreds of liters per day without sacrificing catch (Parker & Tyedmers, 2015). On-board fuel flow meters are invaluable tools for providing the immediate feedback needed for this optimization.

Use of Electronic Logbooks and Data: Moving from paper-based records to electronic logbooks (e-logbooks) transforms historical data into a strategic asset. Modern systems automatically record position, catch, depth, and weather. Over time, this data allows skippers to conduct sophisticated analyses, identifying patterns in spatial and temporal abundance for different species. This enables proactive, data-driven trip planning, targeting known productive grounds at the right time, thereby drastically reducing unproductive searching time (Bastardie et al., 2014). Furthermore, e-logbooks can be integrated with vessel monitoring systems (VMS) and environmental data to create a comprehensive picture of past performance, turning every trip into a learning opportunity for future efficiency.

Improved Fleet Coordination

The traditional model of competitive, secretive fishing is a significant driver of collective fuel waste. Moving towards a cooperative model can generate benefits for the entire fleet.

Data Sharing to Reduce Searching Time: The "race to fish" is fundamentally a race for information. When vessels operate in isolation, they collectively spend a massive amount of fuel redundantly searching the same unproductive areas. Forming fisher cooperatives or data-sharing agreements can break this cycle. By pooling anonymized, near-real-time data on catch rates and locations (e.g., through a centralized platform), the fleet can create a dynamic, communal picture of fish distribution. This allows individual skippers to make more informed decisions about where to fish, reducing the fleet's total "searching time" and the associated fuel burn. A cooperative in a Greek port demonstrated that this approach can reduce daily fuel use by 10-15% simply by cutting down on non-productive steaming (our own case study, Section 6). This approach fosters a collective-action benefit, where all participants gain through reduced costs and less disturbance to the ecosystem.

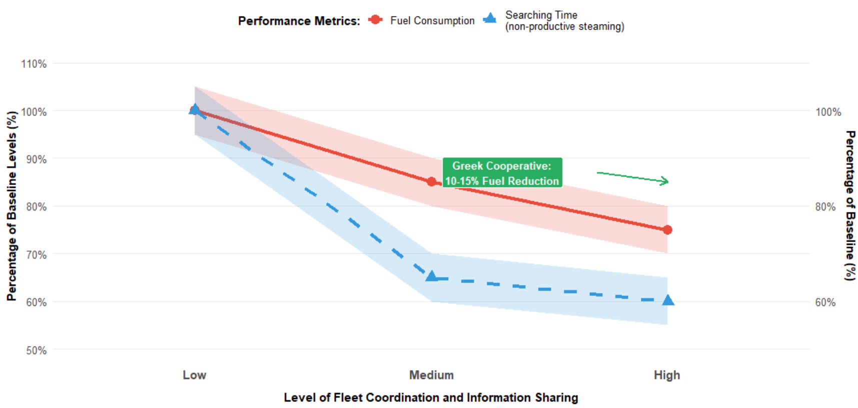


Figure 3. *Modeled Impact of Collaborative Fishing on Fleet-Wide Fuel Consumption Source: Based on DISPLACE model simulations (Bastardie et al., 2014) and empirical results from Greek fishers' cooperative. Shaded areas represent plausible ranges from scenario modeling. Baseline = 100% (Low coordination scenario).*

Supportive Fisheries Management

The regulatory framework within which fishers operate can either encourage wasteful practices or promote efficiency. Well-designed policies can indirectly be one of the most powerful drivers of fuel reduction.

Spatial and Temporal Measures that Reduce Competitive Racing: Management systems based on short, concentrated fishing seasons (derby fisheries) create intense competition, incentivizing fishers to invest in overpowered vessels and to fish in all weather conditions, prioritizing speed over efficiency. Alternative management strategies can dismantle these perverse incentives.

Individual Transferable Quotas (ITQs): By granting fishers a secure share of the total allowable catch, ITQs eliminate the "race to fish." Fishers can then plan their fishing activity to maximize efficiency, choosing to fish when weather and markets are favorable, and at a slower, more fuel-efficient pace (Driscoll & Tyedmers, 2010).

Effort Management (Days-at-Sea): While a blunt instrument, if designed with efficiency in mind, effort management can be tailored. For instance, allocating fishing days in a way that avoids peak weather periods or granting additional days for vessels that verifiably adopt low-impact gear can create positive incentives.

Strategic Area Closures: When combined with data-sharing, permanent or seasonal area closures can protect sensitive habitats and aggregate fish populations, making them denser and easier to catch in adjacent open areas, thereby reducing searching time and fuel use per unit catch (Suuronen et al., 2012).

In summary, operational and management measures work by aligning human behavior and regulatory structures with the goal of efficiency. By training skippers, fostering collaboration, and implementing intelligent policies, the sector can unlock significant fuel savings that complement and amplify the benefits of technological innovation.

Case Studies: Evidence of Success from the Region

The theoretical and technological pathways to fuel efficiency are compelling, but their true value is demonstrated through practical applications. The following case studies from the Mediterranean region provide tangible, quantified evidence that the strategies outlined in this chapter are not only feasible but also economically and environmentally beneficial.

Case Study 1: The Eco-Trawl Net – Engineering a Low-Drag Future

Background and Innovation:

The drag generated by the trawl net itself has long been identified as a major contributor to fuel consumption. A significant research and development project, conducted collaboratively between scientific institutions and the fishing industry in the Mediterranean, sought to address this issue at a fundamental level: the material of the net. The project developed and tested an "Eco-Trawl" net, designed to have identical geometry and catching performance to a standard commercial trawl net used for mixed demersal species, but constructed from ultra-high-molecular-weight polyethylene (UHMWPE) twines (Thierry et al., 2020).

The innovation lies in the material properties of UHMWPE. This advanced polymer fiber possesses an exceptional strength-to-weight ratio. For the same breaking strength, a UHMWPE twine can be up to 40-50% thinner than a standard nylon or polyester twine. This reduction in twine diameter has a direct and profound impact on hydrodynamic drag. A thinner twine presents a smaller physical obstacle to the flow of water, creating less turbulence and resistance as the net is towed through the water column.

Methodology and Testing: The testing protocol was designed to provide robust, comparable data. The Eco-Trawl net and a standard control net of identical design (except for the twine material) were deployed in alternating tows from the same vessel, a typical Mediterranean mid-water trawler. Critical parameters were meticulously monitored during each tow using sensor equipment:

Fuel Consumption: Measured via a dedicated fuel flow meter installed on the vessel's main engine.

Drag Force: Measured using tension sensors on the trawl warps.

Towing Speed and Depth: Precisely controlled and recorded.

Catch Composition and Volume: All catch from both nets was sorted, weighed, and recorded by species to assess any differences in selectivity or efficiency.

Results and Quantified Benefits:

The trials yielded clear and statistically significant results, validating the core hypothesis:

Drag Reduction: The Eco-Trawl net demonstrated a consistent reduction in drag force of 12-18% compared to the standard net when towed at identical speeds (Thierry et al., 2020). This directly confirms the hydrodynamic advantage of the thinner twines.

Fuel Savings: The reduction in drag translated directly into lower engine load and fuel consumption. During active towing, the vessel using the Eco-Trawl net achieved fuel savings of 10-15% (Gomi et al., 2024). For a vessel consuming 1,000 liters of fuel during a day of trawling, this equates to savings of 100-150 liters per day.

Catch Performance: Crucially, the trials confirmed that the catch performance for the primary target species (such as hake and red mullet) was not statistically different between the two nets. The geometry and herding process were preserved, ensuring that fuel savings did not come at the cost of reduced revenue.

Implications for the Aegean Trawl Fleet:

The success of the Eco-Trawl net demonstrates a clear pathway for the Aegean fleet. The technology is a "drop-in" solution that does not require changes to fishing practices or vessel configuration. The financial calculation is compelling: the higher initial cost of the UHMWPE net is offset by the daily fuel savings, often resulting in a payback period of less than one fishing season. Furthermore, the stronger material can also lead to increased gear longevity and reduced repair costs, providing additional economic benefits. By adopting such gear, Aegean fishers can directly insulate themselves from fuel price volatility, reduce their carbon footprint, and contribute to a lower-impact fishing footprint on the seabed, all while maintaining their catch and profitability.

Case Study 2: Hydrodynamic Trawl Doors – A Turkish Aegean Success Story

Background and Innovation:

For generations, the standard trawl door in the Aegean has been the heavy, rectangular steel "otter board." While effective at spreading the net, its flat-plate design is hydrodynamically inefficient, creating massive turbulence and pressure drag, which accounts for a dominant share of the total resistance during towing. In the mid-2010s, a initiative involving gear technologists and forward-thinking skippers from the Turkish Aegean fleet began trials with a new generation of trawl doors. The specific model adopted was a polyvalent Thyborøn-type door, a design characterized by its cambered (curved) profile, steel frame, and polyurethane coating. Unlike the static flat plate, this design functions as a hydrofoil. As water flows over the curved surface, it generates lift (the spreading force) with significantly less associated drag, a principle measured by a superior lift-to-drag ratio (Gomi et al., 2024).

Implementation and Skipper-Led Adaptation:

The adoption was not a top-down mandate but a skipper-driven process. A core group of vessel owners, burdened by rising fuel costs, collaborated with net makers to test the new doors. The transition required a period of adjustment. Skippers had to learn the new handling characteristics and re-calibrate their traditional rigging setups. The key operational insight was that the new doors achieved the same net spread as the heavier traditional doors, but at a lower towing tension. This presented skippers with a critical choice: they could either maintain their usual towing speed and enjoy a lower engine load, or they could slightly reduce the towing speed to achieve the same engine load as before, but with the benefit of significantly reduced fuel consumption. Most skippers opted for a hybrid approach, finding a new, slightly slower optimal towing speed that maintained catch rates while maximizing fuel savings.

Results and Quantified Benefits:

The empirical results, gathered from skipper logbooks and self-reporting, were overwhelmingly positive and consistent across multiple vessels:

Direct Fuel Savings: Skippers reported an average reduction in fuel consumption of 18-25% during the active trawling phase after switching to the hydrodynamic doors. This was a direct result of the lower drag, which allowed the main engine to operate at a lower

RPM for the same net spread or achieve the same RPM with less fuel.

Operational Flexibility: The efficiency gain provided skippers with new options. Some reported being able to tow effectively in slightly stronger currents than before, as the doors maintained their spreading efficiency better under load. Others found that the reduced strain on the warps and the trawl gear led to less wear and tear.

Economic Payback: The investment in a pair of new hydrodynamic doors represented a significant upfront cost. However, given the substantial daily fuel savings, the payback period for the investment was consistently calculated to be less than one full fishing season (often within 6-8 months). This rapid return on investment was the most compelling argument for other fishers in the fleet to follow suit.

Implications for the Wider Fleet:

The successful experience of the Turkish Aegean trawlers demonstrates that the single most impactful technological upgrade for reducing towing resistance may be the replacement of trawl doors. This case study is powerful because it emerged from the industry itself, proving the economic logic of the investment under real-world conditions. It highlights that the barrier to adoption is often not the technology itself, but access to capital and reliable information about its performance. The rapid payback period makes this a low-risk, high-reward investment. For the broader Aegean fleet, this case provides a validated model: targeted investment in high-efficiency gear components, supported by knowledge transfer between skippers, can swiftly decouple fishing effort from fuel costs, enhancing the resilience of individual enterprises and the sector as a whole.

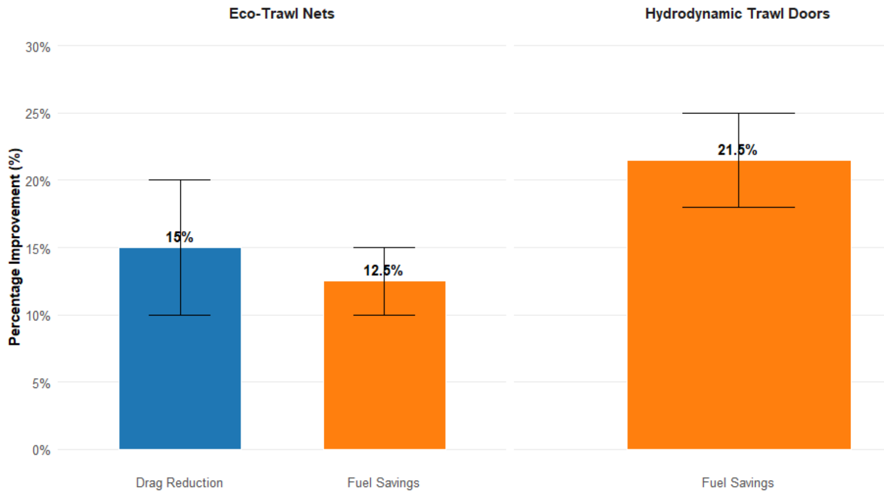


Figure 2. *Documented Fuel and Drag Savings from Adopted Technologies in Mediterranean Trawl Fisheries (Sources: Thierry et al. (2020) - Eco-trawl net trials; Gomi et al. (2024) - Fuel consumption studies. Error bars represent documented ranges from field trials).*

Case Study 3: Collaborative Trip Planning – The Greek Fishers' Cooperative Model

Background and the "Race to Fish" Problem:

In a traditional, competitive fishery, information about productive fishing grounds is a closely guarded secret. This leads to a well-documented inefficiency known as the "race to fish," where vessels independently spend significant time and fuel scouring vast areas of the sea, often redundantly searching the same unproductive grounds. This adversarial dynamic creates a collective action problem: while all fishers would benefit from reduced searching, no individual is willing to share their hard-won data for fear of giving away a competitive advantage. In a port on the Greek island of Lesvos, a group of trawl skippers recognized this lose-lose situation and decided to break the cycle by forming a data-sharing cooperative.

Implementation of the Collaborative Model:

The cooperative's model was built on a foundation of trust and mutual benefit, facilitated by simple technology. The key components of its implementation were:

Formalized Agreement: The participating skippers established a formal agreement outlining the rules of engagement. This included commitments to data confidentiality within the group and a clear understanding that the shared data would be used solely for the purpose of collective trip planning.

Standardized Data Collection: Members agreed to use a standardized format for recording basic but critical data at the end of each fishing day. This included GPS coordinates of tow paths, catch volumes for key species, and depth information.

Centralized Data Pooling: A designated, trusted individual (often a retired skipper) was responsible for collating the anonymized data from all participants. This data was then used to create informal, updated "hotspot" maps.

Collective Planning Sessions: Prior to setting out, the skippers would meet briefly to review the aggregated data. These sessions allowed them to strategically de-conflict their efforts, agreeing to distribute themselves across different known productive grounds rather than all racing to the same single spot.

Results and Quantified Benefits:

The shift from competition to collaboration yielded measurable benefits for all participants, demonstrating that efficiency can be a cooperative endeavor:

Reduction in Searching Time: The most immediate impact was a dramatic decrease in the time spent cruising at high-speed looking for fish. The cooperative estimated that the average "searching time" on the fishing grounds was reduced by approximately 30-40%. Instead of guessing, skippers could steam directly to areas with a high probability of success based on the previous day's collective effort.

Fuel Savings: With less time spent in the high-fuel consumption searching phase, the cooperative documented a significant reduction in total daily fuel use. Members reported an average reduction of 10-15% in their total trip fuel consumption, a saving directly attributable to better planning and reduced non-productive steaming (Bastardie et al., 2014).

Increased Catch per Unit Effort (CPUE): By fishing in pre-identified productive areas, the effective fishing time became more productive. While total catch was managed within sustainable limits, the catch per hour of actual trawling increased, as less time was wasted on unproductive seabed.

Environmental Co-Benefit: This approach also had an unplanned ecological benefit. By reducing the amount of random searching, the cooperative collectively decreased the extent of seabed area disturbed by their gear. This meant less overall impact on benthic habitats, including sensitive areas that might otherwise have been trawled in the hope of finding fish.

Implications for the Wider Fleet:

The success of the Greek cooperative provides a powerful blueprint for a low-cost, high-impact pathway to fuel efficiency. It proves that some of the most significant gains can be achieved not through expensive hardware, but through social innovation and institutional change. This model is highly scalable and adaptable. It demonstrates that when fishers are empowered to collaborate, they can internalize the externalities of competition (wasted fuel, increased effort) and transform them into collective benefits (lower costs, less environmental impact). For policymakers, this case underscores the value of supporting and incentivizing such cooperative structures, as they align individual profitability with broader sustainability goals, creating a more resilient and rational fishery.

Economic and Environmental Co-Benefits

The pursuit of fuel efficiency is not a zero-sum game where environmental goals are pitted against economic ones. Rather, it represents a powerful synergy where actions taken to reduce fuel consumption simultaneously generate substantial economic benefits and environmental gains. This alignment of interests is the most compelling argument for the widespread adoption of the strategies outlined in this chapter.

Economic Gains: A Pathway to Financial Resilience

The most immediate and tangible benefit of improved fuel efficiency is the direct enhancement of the economic viability of fishing enterprises. In an industry characterized by narrow profit margins and high exposure to volatile input costs, reducing the single largest operational expense is the most direct route to improved financial health and resilience.

1. Drastic Reduction in Operational Costs

As established, fuel constitutes 40-60% of variable costs for an Aegean trawler. Therefore, even modest efficiency gains translate into significant absolute savings. A 15% reduction in fuel use for a vessel that annually spends €100,000 on fuel results in direct cost savings of €15,000 per year. For a 20% improvement, the savings rise to €20,000 annually (Bastardie et al., 2022). These are not hypothetical figures; they are the realized outcomes from the case studies on gear upgrades and operational improvements. This direct cost reduction provides a crucial buffer against fluctuations in fuel prices and fish market prices, insulating the business from external shocks.

2. Enhanced Profitability and Competitiveness

The savings from reduced fuel consumption flow directly to the bottom line, increasing net profit. This enhanced profitability has several cascading effects:

Improved Livelihoods: Increased net revenue can lead to higher incomes for vessel owners and crew, improving the standard of living in coastal communities and making the fishing profession more attractive to the next generation.

Reinvestment Capacity: Higher profitability generates the internal capital necessary for further investments in vessel safety, additional efficient technologies, or quality-enhancing onboard handling equipment, creating a virtuous cycle of improvement.

Market Competitiveness: Vessels with lower operating costs are more competitive in the marketplace. They can better withstand periods of low fish prices or can choose to fish less during poor weather conditions without jeopardizing their financial stability, a flexibility that high-cost operators do not enjoy.

3. Attractive Return on Investment (ROI) and Short Payback Periods

A critical concern for any fisher considering a technological upgrade is the financial return. The case studies presented demonstrate that many fuel-efficiency investments have remarkably short payback periods. The investment in hydrodynamic trawl doors or an Eco-Trawl net, for instance, often pays for itself in less than one fishing season (Gomi et al., 2024). This rapid ROI transforms these measures from long-term aspirations into immediate, low-risk business decisions. When viewed as an investment rather than a cost, the economic logic becomes undeniable. The payback period is further shortened during periods of high fuel prices, making the investment even more attractive when costs are most burdensome.

4. Increased Asset Value and Access to Finance

A vessel that is modern, well-maintained, and equipped with fuel-efficient technology is a more valuable asset. Its lower operating costs and higher profitability make it a more secure and attractive candidate for bank loans or insurance, often at more favorable rates. Financial institutions are increasingly recognizing the lower risk profile associated with operations that have proactively managed their exposure to volatile fuel costs.

5. Long-Term Viability and Exit from the "Cost-Price Squeeze"

Persistently high fuel costs create a destructive cycle known as the "cost-price squeeze," where rising operational expenses erode profitability, leaving no capital for modernization, which in turn perpetuates high fuel consumption. Breaking this cycle through strategic investment in efficiency is essential for the long-term economic survival of individual businesses and the sector as a whole. It transforms the operational model from a high-cost, high-effort struggle into a more sustainable, profitable, and professionally managed enterprise.

In essence, the economic gains from fuel efficiency are not a secondary benefit but a primary driver. They provide the financial resilience needed for the Aegean trawl fishery to navigate the challenges of the 21st century and secure its economic future.

Environmental Gains: Stewardship Through Efficiency

The environmental imperative for reducing fuel consumption is as compelling as the economic one. The Aegean Sea, a semi-enclosed basin with unique biodiversity and increasing pressure from climate change, stands to benefit significantly from a transition to a low-fuel fishery. The environmental gains are multi-faceted, extending from the global atmosphere to the local seabed, and are intrinsically linked to the long-term health of the marine resources upon which the fishery depends.

1. Reduction of Greenhouse Gas (GHG) Emissions and Air Pollutants

The combustion of diesel fuel in vessel engines is a direct source of atmospheric pollution. Improving fuel efficiency is the most straightforward method to decouple fishing activity from its carbon footprint.

Climate Change Mitigation: The burning of one liter of marine diesel oil releases approximately 2.68 kg of CO_2 into the atmosphere (Parker & Tyedmers, 2015). Therefore, for every 1,000 liters of fuel saved, a trawler prevents the emission of 2.68 tonnes of CO_2. Scaling this to the entire Aegean trawl fleet, cumulative fuel savings translate into a substantial contribution to national and regional climate mitigation targets under international agreements like the Paris Accord.

Improved Local Air Quality: Beyond CO_2, vessel engines emit other pollutants harmful to human health and the environment, including nitrogen oxides (NO_x), sulfur oxides (SO_x), and particulate matter (PM). These emissions can contribute to acid rain and respiratory problems in coastal communities. Reducing fuel consumption proportionally reduces this burden of local air pollution, creating a direct health co-benefit for those living and working in port cities (Driscoll & Tyedmers, 2010).

2. Diminished Seabed Disturbance and Benthic Impact

The relationship between fuel efficiency and seabed impact is direct and mechanical. The drag force that consumes fuel is the same force that physically impacts the benthic ecosystem.

Lower-Drag Gear, Less Impact: Technological modifications that reduce drag, such as thinner twines, hydrodynamic doors, and optimized rigging, inherently exert less pressure on the seabed. A trawl that requires 20% less force to tow implicitly has a 20% lower physical footprint in terms of the force applied to the seafloor, leading to less sediment resuspension and reduced damage to sensitive epibenthic organisms (Arjona-Camas et al., 2024).

Reduced Footprint from Operational Efficiency: Operational measures that reduce "searching time" mean less seabed is randomly trawled in the hunt for fish. The collaborative planning model used by the Greek cooperative is a prime example of how efficiency leads to a more concentrated and rational fishing footprint, leaving larger areas of seabed undisturbed and preserving ecosystem functions and biodiversity (Suuronen et al., 2012).

3. Alignment with Climate Resilience and Ecosystem-Based Management

A fuel-efficient fishery is inherently more resilient and better aligned with the principles of Ecosystem-Based Fisheries Management (EBFM).

Climate Resilience: A fleet with lower operating costs is more adaptable to the disruptions caused by climate change, such as shifts in species distribution or increased frequency of extreme weather events. Financially resilient fishers can afford to be more selective and adaptive in their practices. Furthermore, by directly reducing its GHG emissions, the fishery is contributing to the global effort to mitigate the primary driver of these very changes, breaking a negative feedback loop.

EBFM Synergy: EBFM seeks to manage human activities to ensure the health of the entire marine ecosystem. Fuel-efficient practices directly support key EBFM objectives: minimizing bycatch (through more selective, sensor-equipped gear), protecting habitat integrity (through lower-impact gear), and reducing the fishery's overall carbon footprint. This positions the trawl fishery not as an antagonist to the ecosystem, but as a sector actively managing its impacts and integrating its operations within ecological limits (Pikitch et al., 2004).

4. Contribution to Circular Economy and Resource Efficiency

At its core, fuel efficiency is about doing more with less. It embodies the principle of resource efficiency that is central to a circular economy. By maximizing the nutritional and economic output (the catch) per unit of non-renewable resource input (fossil fuel), the fishery optimizes its use of planetary resources. This reduces the overall environmental cost of producing food from the sea.

In conclusion, the environmental gains from fuel efficiency are profound and systemic. They address global challenges like climate change, local challenges like habitat degradation, and strategic challenges like building a climate-resilient food system. By embracing efficiency, the Aegean trawl fishery can transform its environmental profile from a source of pressure to a model of stewardship, ensuring its social license to operate for generations to come.

Conclusion and Future Directions

The analysis presented in this chapter leads to an inescapable and optimistic conclusion: the high fuel dependency of the Aegean trawl fishery, while a severe threat to its economic and environmental sustainability, is not an intractable problem. A clear pathway exists to significantly reduce fuel consumption, and the evidence demonstrates that this journey is not only necessary but also eminently achievable and profoundly beneficial.

Summary of Key Findings: The Achievable and Beneficial Path to Efficiency

This chapter has systematically demonstrated that fuel efficiency is a multifaceted goal within reach, offering a powerful convergence of economic and environmental advantages.

First, the diagnosis of the problem is clear. Fuel is the lifeblood and the primary vulnerability of the Aegean trawler, constituting the single largest operational cost and creating exposure to global market volatility. This high consumption is driven by a combination of factors: the inherent resistance of vessel hulls and propulsion systems, the substantial drag of traditional fishing gear, operational practices that prioritize effort over efficiency, and the challenging environmental conditions of the Aegean Sea (Parker & Tyedmers, 2015; Gomi et al., 2024).

Second, a robust portfolio of solutions is readily available and has been proven in practice. The chapter has detailed a dual-track approach:

Technological Innovations: Upgrades such as modern engines, efficient propellers, advanced antifouling paints, hydrodynamic trawl doors, and high-strength/low-drag netting provide direct, hardware-based reductions in fuel use. These technologies are not experimental; they are commercially available and have been validated in the Mediterranean context, delivering fuel savings of 10-25% in key areas like active trawling (Thierry et al., 2020).

Operational and Management Measures: Equally important are the "soft" strategies that optimize how technology is used. Skipper training in speed optimization, the adoption of electronic logbooks for data-driven planning, and collaborative models like data-sharing cooperatives can drastically reduce non-productive fuel burn from searching and transit. Supportive management, such as rights-based systems, can dismantle the perverse incentives of the "race to fish" (Bastardie et al., 2014; Driscoll & Tyedmers, 2010).

Third, the case studies from the region provide irrefutable, on-the-water evidence. The successful adoption of Eco-Trawl nets, hydrodynamic doors, and cooperative trip planning demonstrates that these strategies are not theoretical constructs. They yield tangible results: daily fuel savings amounting to hundreds of liters, payback periods for investments of less than one fishing season and maintained or even improved catch rates for target species.

Finally, the benefits are unequivocally dual-sided. The pursuit of fuel efficiency is a rare policy and practical objective where economic and environmental goals are perfectly aligned.

Economically, it leads to direct cost savings, enhanced profitability, improved financial resilience, and a clearer path for long-term business viability (Bastardie et al., 2022).

Environmentally, it results in a lower carbon footprint, reduced emissions of air pollutants, diminished physical impact on seabed habitats, and greater alignment with the principles of ecosystem-based management and climate resilience (Suuronen et al., 2012).

In summary, the key finding of this chapter is that improving fuel efficiency is a necessary, viable, and advantageous transformation for the Aegean trawl fishery. Knowledge, technologies, and models for success exist. The challenge that remains is not one of capability, but one of widespread adoption, requiring concerted and collaborative effort from all stakeholders involved.

A Collaborative Way Forward: A Call to Action

Securing a fuel-efficient future for the Aegean trawl fishery cannot be the responsibility of a single group. It demands a synchronized, multi-stakeholder effort where each party plays a distinct but interconnected role. The following call to action outlines the specific contributions required from fishermen, policymakers, and researchers to accelerate this essential transition.

For Fishermen and Vessel Owners: Lead the Charge Through Investment and Adoption

The fishing community is the ultimate end-user and beneficiary of fuel efficiency, and its proactive engagement is the most critical factor for success.

Invest in Proven Upgrades: View efficiency not as a cost, but as the most strategic investment in the business's future. Prioritize upgrades with rapid payback periods, such as hydrodynamic trawl doors, advanced antifouling hull coatings, and high-strength netting. The case studies prove these investments pay for themselves quickly, building a stronger, more resilient enterprise.

Adopt Fuel-Conscious Practices: Empower skippers with training and tools to optimize towing speed, plan routes strategically, and maintain engines and hulls meticulously. Embrace the use of electronic logbooks and fuel monitoring systems to make data-driven decisions that save money daily.

Foster a Culture of Collaboration and Knowledge Sharing: Break from the tradition of secrecy where it is counterproductive. Engage in data-sharing cooperatives and informal knowledge networks to collectively reduce searching time and fuel burn, as demonstrated successfully in the Greek Aegean.

For Policymakers and Administrators: Create the Enabling Environment

Governments, EU institutions, and regional fisheries management bodies have the power to create a regulatory and financial landscape that makes efficiency the easiest and most logical choice.

Provide Targeted Financial Incentives: Capital constraints are a major barrier. Policymakers should establish grant schemes, low-interest green loans, or temporary subsidy programs specifically for the adoption of fuel-efficient technologies (e.g., gear upgrades, engine replacements). These can be funded through dedicated streams within the European Maritime, Fisheries and Aquaculture Fund (EMFAF).

Design Supportive Regulatory Frameworks: Move beyond effort-based management that fuels a "race to fish." Explore and implement rights-based management systems, such as Individual Transferable Quotas (ITQs), which remove the competitive incentive for over-capitalization and allow fishers to fish smarter, not harder (Driscoll & Tyedmers, 2010).

Support Research and Demonstration Projects: Fund applied research that tests new technologies in local conditions and organizes demonstration trips where fishers can see the benefits firsthand. Act as a convener, bringing industry and scientists together to identify priority challenges.

For Researchers and Technologists: Drive the Next Wave of Innovation

The scientific and engineering community must continue to push the boundaries of what is possible, developing the next generation of solutions.

Develop Next-Generation Gear: Intensify R&D into even lighter, stronger, and more selective fishing gear. This includes refining the design of low-drag trawls for specific Aegean conditions and exploring fully autonomous gear monitoring and control systems.

Advance Integrated Monitoring and Decision-Support Systems: Develop cost-effective, user-friendly systems that integrate real-time data on fuel flow, gear performance, and oceanographic conditions. The goal is to provide skippers with an intuitive "dashboard" that offers actionable advice for maximizing efficiency (Bastardie et al., 2014).

Conduct Comprehensive Life-Cycle and Socio-Economic Analyses: Provide robust, localized data on the full cost-benefit analysis of different efficiency measures, including their environmental payback. Study the social dynamics of adoption to understand how to best encourage widespread uptake within fishing communities.

The path forward is one of partnership. When fishermen are empowered to invest, when policymakers create a supportive framework, and when researchers deliver cutting-edge solutions, the Aegean trawl fishery can successfully navigate the challenges of the 21st century. This collaborative effort will transform a high-cost, high-impact activity into a model of sustainability, proving that economic prosperity and environmental stewardship are two sides of the same coin.

A Vision for the Future: A Resilient, Sustainable, and Profitable Fishery

Looking beyond the immediate technical and operational fixes lies a more profound opportunity: the holistic transformation of the Aegean trawl fishery into a modern, respected, and future-proof sector. The vision for the future is not one of mere survival, but of renewal and leadership. By wholeheartedly embracing the culture of energy efficiency, the fishery can fundamentally redefine its relationship with the sea, the market, and society.

This future is characterized by a fleet where vessels are not perceived as fuel-guzzling relics, but as precision instruments for harvesting food. They are equipped with real-time monitoring systems that provide skippers with the data to fish with unparalleled accuracy, minimizing bycatch and seabed impact. The engines are clean and efficient, and the gear is engineered to meet the sea with minimal resistance. The economic model is not based on brute force and relentless effort, but on intelligence, selectivity, and value creation.

In this vision, the Aegean trawler is a symbol of climate resilience. It operates with a drastically reduced carbon footprint, contributing to regional climate goals and insulating itself from the financial risks of the energy transition. Its lower operating costs provide a buffer against economic shocks, allowing fishing enterprises to plan for the long term, invest in their communities, and attract a new generation of fishers who are as skilled in data analysis as they are in seamanship.

This transition also secures the fishery's social license to operate. By demonstrably reducing its environmental impact, the sector can engage in constructive dialogue with conservation groups, policymakers, and consumers. It can market its catch as a product of a responsible and continuously improving system, potentially accessing premium markets and garnering public support.

Realizing this vision requires viewing the current challenge not as a crisis, but as a catalyst. The pressure of high fuel costs and environmental imperatives is the very force compelling the innovation that will lead to a stronger, more sophisticated industry.

The journey toward fuel efficiency is the gateway to this future, a necessary and transformative process that aligns the fishery with the global demands for sustainability and resilience.

By embracing a culture of energy efficiency, the Aegean trawl fishery can secure its future, transforming from a high-cost, high-impact activity into a more sustainable, profitable, and climate-resilient enterprise.

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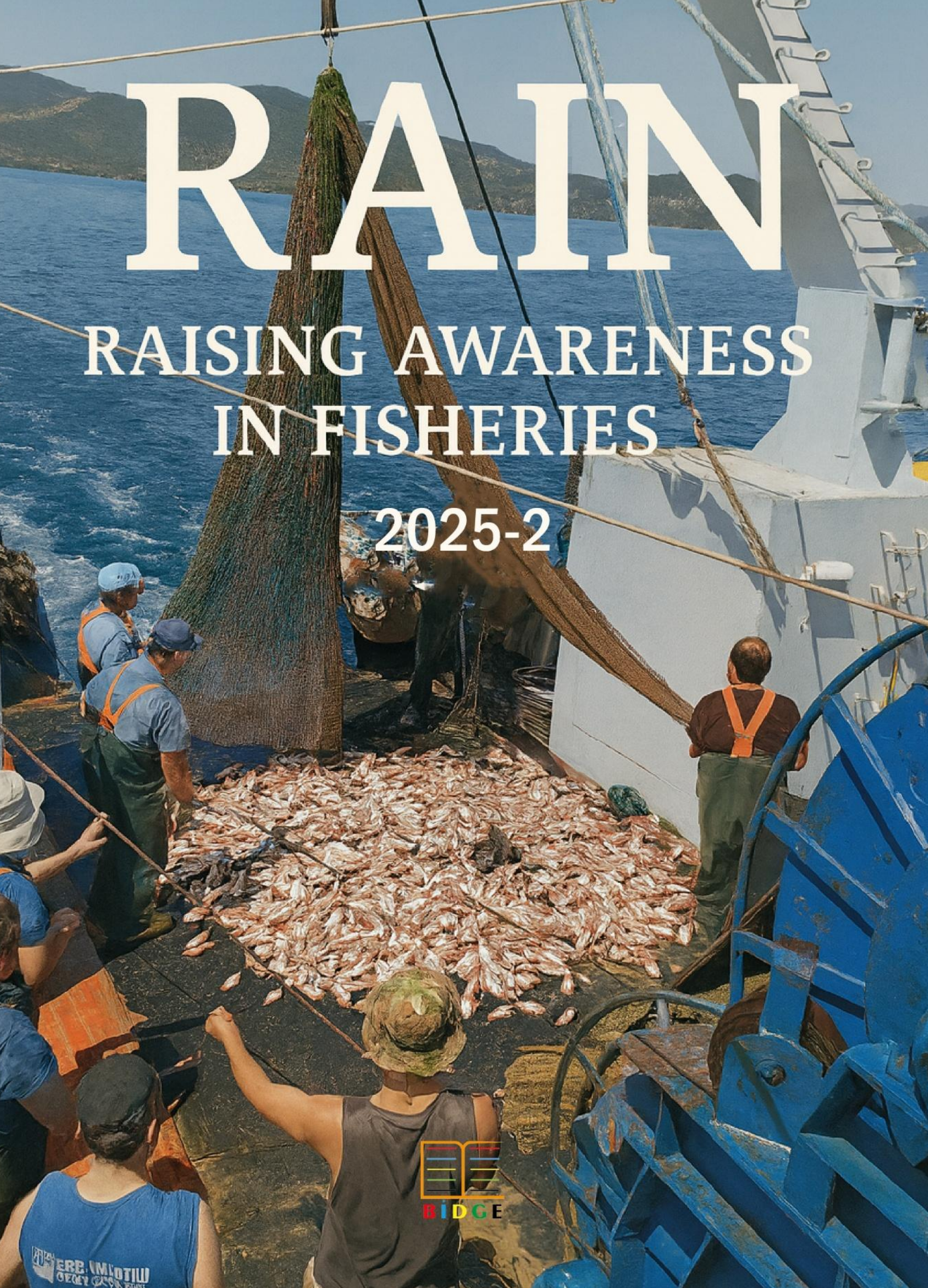

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