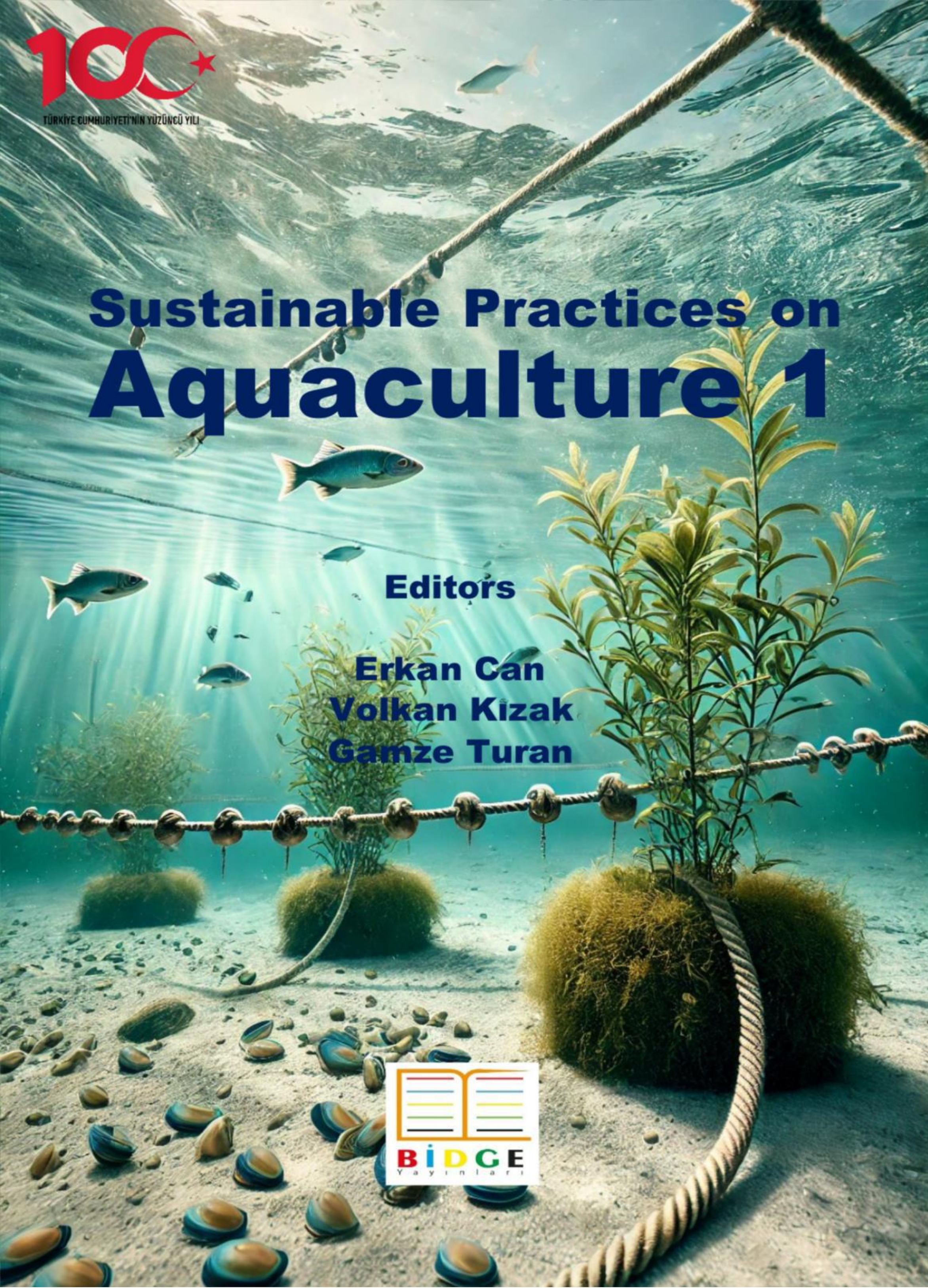

TÜRKİYE CUMHURİYETİ'NİN YÜZÜNCÜ YILI

Sustainable Practices on Aquaculture 1

Editors

Erkan Can
Volkan Kızak
Gamze Turan

BİDGE Yayınları

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Content

PREFACE

In today's world, sustainability is no longer a choice but an imperative for humanity. The rapid growth of the global population, the depletion of natural resources, and increasing environmental challenges highlight the need for innovative and sustainable approaches in various fields, from food production to ecosystem conservation. Aquaculture and marine ecosystems hold critical importance in this regard, as oceans and seas are vital resources for both food security and biodiversity.

This book has been prepared to compile the latest advancements and studies on sustainable practices in aquaculture and marine ecosystems. ***Sustainable Practices on Aquaculture 1*** underscores innovative approaches and multidisciplinary solutions while offering practical examples of how sustainability principles can be implemented effectively.

The chapters in this book address diverse aspects of sustainability in the aquaculture sector:

- Integrated Multi-Trophic Aquaculture (IMTA) Case Studies in Türkiye focus on local dynamics within the sector,
- Sustainable Practices in Trout Farming provide a guide for improving current practices,
- Disinfection of Fish Eggs with Medicinal Aromatic Plants introduces an innovative alternative to traditional methods,

- Sustainable Developments in Offshore Aquaculture explore how future technologies can merge with environmentally friendly production, and
- Nanotechnology and Blue Crabs: Carbon Quantum Dots in Marine Conservation highlights pioneering research on the role of technology and innovation in marine conservation.

I would like to extend my gratitude to all the authors and researchers who contributed to the preparation of this book. Their work significantly enhances awareness of sustainability and brings forward practical solutions in this field. I also wish to thank the editorial team and supporters who have played an essential role in bringing this publication to fruition.

Sustainable Practices on Aquaculture 1 aims to inspire researchers, industry professionals, and all readers interested in sustainability. I believe this work will not only serve as an academic resource but also contribute to shaping future policies for sustainable aquaculture practices.

With warm regards,

Editors

CHAPTER I

Integrated Multi-Trophic Aquaculture (IMTA) Case Studies in Türkiye

Gamze TURAN[1]

1.Introduction

Aquaculture is the fastest growing food industry in the world with values more than 5% per year according to FAO statistics and this trent will probably continue as capture fisheries are in global decline (FAO 2009a).

Today, more than 50 % aquatic products consumed is cultured and total aquaculture production reached over 52 million tonnes in 2007 and it may reach 80 million tonnes or more by 2030 depending on demand assuptions (Muir et al. 2010).

An example of this rapid development can be seen also in Turkey where seabream (*Sparus aurata*), seabass (*Dicentrarchus labrax*), bluefin tuna (*Thunnus thynnus*) and rainbow trout

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(*Oncorhynchus mykiss*) farming have become major economic activities with an annual production of 90,000 tonnes in 2008 at 356 sea-based marine fish farms on 8,333 km of coast line and 177,714 km of rivers (Deniz 2010). According to FAO most recent tables, in 2008 Turkiye was the third Europe-leading fisheries nation after Norway and Spain in both culture (152,000 tonnes) and total fisheries (647,000 tonnes culture + capture) production, including marine, brackish and freshwater species and the second World-leading country on seabream and seabass aquaculture (FAO 2009b). The nation holds a 25% share of the European sea bream and sea bass market and occupies the first place in trout production among European countries (Deniz 2010). The country has a total of 24.6 million ha coastal zone, of which 1.5 million ha area, called "economic coastal zone", has a high potential for IMTA (Turan 2009).

Turkish Aquaculture is, however, now at a crossroad and there are many critical aspects of its sustainability that need to be addressed. Because of the recent regulations made by the Turkish Ministry of Environment and Forestry, the marine cage farms produce 90,000 tonnes of marine fish with 250,000 employee were forced to leave their operations from the shores to either on-land or off-shore areas due to their negative ecological impacts (Turan 2009). Today, there are approximatelly 150 sea-based farms are able to continue their operations at offshore, the rest started to grow fish in land-based ponds. Addition to this problem, the marine aquaculture sector has increasingly to deal with conflicts over space with other sectors, namely tourism, environmental protection, maritime, recreation, etc.

The challenge faced by the Turkish aquaculture industry is how to maintain previuos production levels and even expand them without exceeding assimilative capacity of the ecosystem. This is where Integrated Multi-Trophic Aquaculture (IMTA) can become important to the industry.

IMTA is an innovative solution being proposed for environmental sustainability, economic diversification, and social acceptability and IMTA can be applied to on-land and off-shore aquaculture systems. This practice combines the cultivation of finfish with shellfish and seaweed species for an ecologically-balanced aquaculture management approach. IMTA increases the long-term sustainability and profitability per cultivation unit as the wastes of the main cultured species are biomitigated through conversion into fertilizer, food, and energy for additional commercially valuable species. In this way, otherwise costly waste mitigation processes become revenue-generating cultivation components, which by their harvest export nutrients outside of the coastal ecosystem (Troell et al. 2003).

Actually, IMTA is not a new concept. For example, Asian countries have been for centuries practising the precursor of IMTA, polyculture, which produces a large fraction of the world's freshwater fish (Edwards 2004). In recognition of growing interest, the Aquaculture Europe 2003 Conference in Trondheim, Norway, whose theme was 'Beyond Monoculture', was the first large international meeting with IMTA as its main topic. In 2006, at the joint European Aquaculture Society and World Aquaculture Society Conference in Florence, Italy, IMTA was recognized as an emerging research priority and alternative to consider for the future development of aquaculture practices. The determination to develop IMTA systems will, however, only come about if there are some visionary changes in political, social and economic reasoning. Sustainability, long-term profitability and responsible management of coastal waters will be accomplished by a regulatory internalization of the total environmental cost of the aquaculture operation and enforcement of the polluter pays principle (Chopin 2006).

IMTA is already developed and practiced semi commercially and commercially in several places in the world, such as in Canada Canada, South Africa, Israel, Chile, and China (Buschmann et al. 1994, 1996, 2001, 2005; Carmona et al. 2006; Chopin 2006; Chopin et al. 1999, 2001, 2008; Troell et al. 1997, 2006; Whitemarsh et al. 2006; Yang et al. 2004) have demonstrated that land-based and off-shore IMTA systems are technically feasible and economically profitable. And, many pioneer studies have been conducted in the United States of America, Spain, Portugal, France, United Kingdom of Great Britain, Ireland, Norway, Sweden, Finland (Barrington et al. 2009) and Turkiye (Cirik et al. 2006; Osinga et al. 2010; Turan, 2009; Turan et al. 2006, 2007, 2009, 2010).

Presently, the most advanced IMTA systems in open marine waters have three components (fish, suspension feeders such as shellfish, and seaweeds in cages and rafts), but they are admittedly simplified systems. More advanced systems will have several other components, such as crustaceans in mid-water reefs; deposit feeders such as sea cucumbers, sea urchins and polychaetes in bottom cages or suspended trays; and bottom-dwelling fish in bottom cages.

IMTA provides exciting new opportunities for valuable crops of aquatic species and for Turkish IMTA approaches, the IMTA component may include species of :

- *Gracilaria*, *Gelidium*, *Gigartina*, *Hypnea*, *Porphyra*, *Asparagopsis*, Juvenile *Laminaria*, *Sargassum*, *Cystoseira*, *Dictyopteris*, *Ulva* and *Caulerpa* (seaweeds).
- *Dysidea avara* and *Chandrosia reniformis* (sponges).
- *Ostrea*, *Crassostrea*, *Pecten*, *Mytilus*, *Tapes*, and *Haliotis*, (molluscs).
- *Paracentrotus*, *Arbacia*, and *Holothuria* (echinoderms).
- *Nereis*, *Arenicola*, *Glycera* and *Sabella* (polychaetes).

- *Penaeus* and *Homarus* (crustaceans).
- *Sparus, Dicentrarchus, Oncorhynchus, Salmo, Thunnus, Scophthalmus*, and *Mugil* (fish).

In order to ensure the further development of IMTA systems in Turkiye, several steps should be taken by government, industry, academia, community and non-governmental organizations. These steps can include (1) establishing the economic value of IMTA systems and their co-products, (2) developing bio-economic models for IMTA systems, (3) exploring additional economic value for IMTA co-products, (4) exploring CO_2 Utilization against global warming by IMTA coproducts, (5) Selecting the right species and habitats, (6) promoting effective government legislation/regulations and incentives for IMTA developments and the commercialization of IMTA products, (7) recognizing the benefits of IMTA and educating stakeholders about this practice, and (8) establishing the Research & Development & Commercialization for IMTA

IMTA provides exciting new opportunities for valuable crops of aquatic species and for Turkish IMTA approaches, the IMTA samples may include case studies of :

2.Mussels-Finfish IMTA at Pinar Deniz Sea Products (Mersin Bay, Izmir)

Pinar Deniz Sea Products is the pioneer of a modern and integrated fish farming in Türkiye which has been established as a first marine aquaculture facility in 1985 with a production capacity of 1 million fry seabream (*Sparus aurata*) and 300 tonnes market-size seabream annually. In 1995, seabass (*Dicentrarchus labrax*) production has been introduced into the company and production capacity has reached 60 million seabream and seabass fry and 2,440 tonnes market-size fish in 2006. In coming years, the company is aiming to produce alternative new finfish species such as dentex, lear fish, mullet, sharp-snout bream and striped bream whose production protocols already well established by the R&D team of the company.

Today, the company continous its production in two facilities: a hatchery located in Ildiri (Cesme, Izmir) on 11,742 m^2 land-based aquaculture system and an offshore farm located 1,5 miles away from the shore and 50 meters deep.

Before the last regulations made by the Turkish Ministry of Environment and Forestry and before the cages had to move to the offshores, the company was producing market-size marine fish in Mersin Bay (Izmir) on 36,500 m^2 sea-based netcage systems. In 2000, the company integrated the Mediterranean mussels (*Mytillus galloprovincialis*) cultivation to the marine fish monoculture system and developed a Mussels-Finfish IMTA system (Figure 1) where the mussels were producted in raft and long-line culture system and when it was active it was opeating with a production capacity of 1,000 tonnes annually.

Today, the R&D&C activities of the company go on for improving existent systems and developing new systems, such as land-based and sea-based IMTA systems and production of new marine species, such as seaweeds addition to new alternative finfish species.

Figure 1. Mussels production at Mussels-Finfish IMTA system at Pinar Deniz Sea Products.

3.Seaweed-Finfish IMTA at Hunkar Su Urunleri Marine Farm (Seferihisar, Izmir)

Hunkar Su Urunleri Marine Farm Ltd., was located in Sigacik Bay (Seferihisar, Izmir), was producing 100 tonnes market size of seabream (*Sparus aurata*) and seabass (*Dicentrarchus labrax*) and use on avarage 30 tonnes of fish feed annually in fishcages (Figure 2). Before the last regulations made by the Turkish Ministry of Environment and Forestry in 2008 and before the cages had to move to the offshores in 2009, Beginning from 2002, the company performed a series of research experiments to integrate agarofit seaweed (*Gracilaria verrocosa*, or its new name *G. viridis*) into the finfish production system with colloboration with Ege University. Due to intensive finfish aquaculture activities cause significant loading of inorganic nutrients, especially nitrogen (N) and phosphorus (P), into coastal waters. The experiments were aimed to cultivate of *Gracilaria* near marine fish cages facilitates utilization of the nutrients loaded into the water by the fish farms; those nutrients then become valued resources as fertilizer, animal feed and biofuel. This approach also reduces the risk of eutrophication, diseases, harmful algal blooms, and green tides in the vicinity of finfish aquaculture operations.

During the studies, *Gracilaria* was cultured in the seaweed nets (Figure 3) at different experimental stations at and around the fish farm. Result of the study which was done in 2005 showed that the slower-growing *Gracilaria* with 3% daily growth rate, collected from the site where average N and P were 4.32 and 0.82 μg.at per l, respectivelly. The faster-growing *Gracilaria* with 5% daily growth rate, collected from a site near the farm where average N and P values were 31.34 and 3.03 μg.at per l, respectively. And, it was concluded that *Gracilaria*-finfish IMTA represents An important benefit to farmers of this approach is that released dissolved N and P, which represent a loss of money, can be captured and converted into the production of commercial *Gracilaria* and agar-agar, thus generating economic value that more than compensate for the expenses. For example, a 1- ha *Gracilaria* culture with avarage 5 % daily growth rate close to the fish cages has the potential to remove dissolved inorganic N and dissolved P from the fish farm and such cultivation would give an annual harvest of 24 dry tonnes of *Gracilaria*, worth 24,000 US$ (Cirik et al. 2006; Turan, 2009; Turan et al. 2006, 2007, 2009, 2010). These numbers are manageable over a year when one considers several harvests over a growing season. Additionally, as legislative guidelines, standards, and controls on the effluents from aquaculture operations into aquatic ecosystems become more stringent, bioremediation by the production of *Gracilaria* could help the aquaculture industry in Türkiye avoid noncompliance problems. With CO_2 being the main nutrient for seaweed growth, CO_2 credit trade may constitute a revenue source of a IMTA seaweed farming (Turan and Neori, 2010).

(a) (b)

Figure 2. Seaweed-Finfish IMTA approach (a) and the seaweed Gracilaria nets (b).

4.Seaweed-Marine Ornamental Fish IMTA at TDE Ltd. (Guzelbahce-Izmir)

TDE, or Tropical Marine Ecosistems, Ltd. is an aquatic habitat design and construction company that specialized in planning, designing, engineering for aquatic filtration systems and life support systems. Aquatic filtration specialists of TDE, design, produce and support, setup of filtration systems by using the last innovations in technology. The company focus on all needs of costumers in a huge scale from standard assembled to special assembled systems. Their work also covers the areas of live organisms supply, including fish, shellfish, corals, sponges, seaweeds, to the customers all over the country.

Beginning from 2007, a series of research experiments were conducted collaborated with Ege University Fisheries Faculty to determine value of a green seaweed, *Ulva rigida* or it is commonly known as Sea lettuce, in bioremediation of inorganic nutrients in fish effluents and to evaluate the potential for incorporating seaweeds into a land-based IMTA system. During the studies, *Ulva* was cultured in fish effluent concreate pond (Figure 4) at the Universities Marine Center located in Urla Harbor (Urla, Izmir). Result of the experiments showed that *Ulva rigida* reduced the nutrient content of the fish effuent by up to 50% and individual plants of *U. rigida* grown in fish effluents in land-based system increased in weight by about 15 % per day in spring and 20% per day in summer (i.e. plants doubled in a few days). This growth rate was sustained during the experiments. In feeding trials with marine aquarium fish species, *U. rigida* was consumed well by the fish (Figure 5). Futher detailed studies with these fish on the stimulating appetite and health improving effects of *U. rigida* are planned (Turan, et al. unpublished data).

While the market for *Ulva rigida* as human food can become significant, the value of the seaweed as a food source for marine tropical aquarium fish is established in this study, like it has been shown for abalone in previous studies (Spigel and Neori, 1993; Troell et al. 2006). It is also a valuable species to use for the removal of the excess nutrients being released from fish farms. The techniques developed for its cultivation in land-based IMTA systems would make it suitable deployment in and around fish farms, where the seaweed could reduce the environmental impact of excess feed and excretory products from the fish. The benefits of using seaweed species to reduce the eutrophication of coastal waters resulting from waste water discharge would be increased if species of greater commercial value were to be used. Thus, the use of *Ulva* in integrated aquaculture schemes in Türkiye has a potential (Turan, 2009).

(a) (b)

Figure 3. Ulva cultivation in fish effluent (a) and feeding trials of the ornemental fish with Ulva (b).

5.Sponge-Finfish IMTA at Labraks Ltd. (Bodrum, Türkiye)

Labraks Su Urunleri Marine Farm Ltd., was located in Bodrum (Mugla), was producing market size seabream (*Sparus aurata*) and seabass (*Dicentrarchus labrax*) in fish cages, before they closed their operations due to the last regulations made by the Turkish Ministry of Environment and Forestry in 2008. When the company was exist, beginning from 2006, a series of research experiments were performed to integrate two Mediterranean Demospongiae species: *Dysidea avara* and *Chondrosia reniformis* into the finfish production at the company by Osinga et al. (2010) with the idea of culturing sponges in the vicinity of fish farms may have two benefits: the sponges may grow faster due to an increased availability of organic food and the pollution caused by the fish farms is remediated by the filtering activities of the sponges.

Aquaculture trials between 2006 and 2007 were conducted and funded by the European Commission (Project SPONGES-017800) to test the possibility of growing these sponges in the vicinity of sea-based fish farms (Figure 6). And, the resuls of the study showed that after being one year in culture, nearly 100% of all explants of *D. avara* survived and their growth was highest underneath the fish cages. For *C. reniformis* survival at the pristine site was 100%, and growth was estimated at 800% per year. And, it was concluded that the aquaculture trials gave promising results and represent significant progress towards feasible aquaculture of *Dysidea avara* and *Chondrosia reniformis*. For this study, the production cost of the sponges was estimated as 36 euro per kg sponge (wet weight) and concluded that it is highly profitable since a cost price for sponges below 50 euro.kg^{-1} is accepted as profitable. It is also important to note that the sponges in the culture had an avarol content that did not differ from naturally growing specimens (Osinga et al. 2010).

Sponges are very efficient filter feeders. A large-scale sponge-finfish IMTA which combines the production of sponges with remediation of pollution, particularly pollution caused by sea-based fish farming culture have a profound effect on the water quality in the vicinity of fish farms. Conversely, the organic enrichment originating from the fish may stimulate sponge growth, thus making sponge aquaculture more efficient. Both species have potential commercial interest. *D. avara* is known for its secondary metabolite avarol, which has been in clinical trials as a potential HIV inhibitor. It was also discovered that avarol can also be effective against skin diseases such as psoriasis. *C. reniformis* is of interest as a producer of collagen, particularly collagen for cosmetic and biomedical applications. Since both avarol and collagen are produced in relatively large quantities by the sponges, aquaculture appears to be a feasible alternative for production of the compounds through chemical synthesis or recombinant production (Osinga et al. 2010). Analogous to this view is the successful culture of corals that has been achieved in the vicinity of fish cages in the Gulf of Eilat (Israel).

Figure 4. Stainless steel frame hosting ten explants of D. Avara under fish cages.

6.IMTA Research Activities at Ege University Fisheries Faculty (Izmir)

Aquaculture is one of seven Strategic Areas at Ege University Fisheries Faculty and it is devoted to interdisciplinary research for a sustainable aquaculture cultivation of the marine, brakish and freshwater based on industrial challenges and expertise in the involved research teams. A strong expansion of the activities and the Faculty’s national position as capital for research and development resulted in the establishment of Urla Marine Center with aquaculture facilities (1982) and Dalyan Homa Lagoon Marine Center (1988). Together, they provide a stimulating and integrated environment for applied research in the field of marine aquaculture technology and environment related issues. Urla Marine Center located in Urla-Iskele (Izmir) has a hatchery and a nursey with the capacity to produce one million fish fingerlings and market-size fish of 300 kg. Dalyan Homa Lagoon Marine Center has a mean depth of 1.09 m, a maximum depth of 2.0 m, and an area of 1,800 hectares.

Both Centers have been widely used by external and international users through the projects. During recent years, the facilities have contributed significantly in achievements on seaweed aquaculture, seaweed-based integrated aquaculture systems, the role of seaweeds as bio-filter systems in the treatment of fish effluents at land-based and sea-based aquaculture systems.

7.Land-based Research Activities

A simple land-based IMTA experiment where *Ulva lactuca* was integrated into freshwater fish tilapia (*Oreochromis liloticus*) culture was performed in 2006 in Urla Marine Center. In the study, the effect of *U.lactuca* on N and P and turbility levels in the tilapia tanks where no water exchange applied during the experiment was investigated. Before the integration of the *Ulva* into the system, they were collected from outdoor seaweed tanks and acclimated to the freshwater. After the acclimation process, *Ulva* was stocked at the density of 1 kg *Ulva* per 2 kg fish (wet weight) in the Tilapia tanks (Figure 7a). 24 hr later, it was observed that *Ulvas* almost clean up the whole tank system (Figure 7b). And, results of the water quality showed that seaweeds removed more than 90% of the nutrients and turbility was also reduced to 5 mg per l from 100 mg per liter (Turan et al. 2007).

After this exciting effect of *Ulva* on the water quality in Tilapia fish tanks it was decided to re-examine the potential of *Ulva* also in the land-based IMTA with marine fish mullet, *Mugil cephalus*, at Urla Marine Center. And, the results of the study which was aimed to find out the best model for stocking densities for possible IMTA development in Türkiye. When the daily growth rate of *Ulva* was found to be approximately 20% per day with 200 $g.m^-$

^{2}.day^{-1} fresh biomass yield, N and P uptake rates were found to be nearly 50% and weakly harvesting frequency of *Ulva* to optimize its bioremediation capacity for possible IMTA systems was suggested (Turan et al. unpublished data).

(a)

(b)

Figure 5. Before (a) and after (b) stocking seaweed Ulva into the tilapia fish tank.

Beginning from 2007, a series of research experiments were conducted at Urla Marine Center collaborated with marine ornamental fish producer company called TDE Ltd. to determine value of a green seaweed, *Ulva rigida* or it is commonly known as Sea lettuce, in bioremediation of inorganic nutrients in the fish effluents and to evaluate the potential for incorporating seaweeds into a land-based seaweed-ornamental finfish IMTA system. The study and its results were explained in the previous pages.

8.Sea-based Research Activities

Dalyan Homa Lagoon Marine Center (Figure 8) is an 1,800 ha land-locked sea area where seaweeds constitute an important autotrophic community. The biomass density in the Lagoon calculated for unatteched seaweeds between November and December 2006 showed ranged from 172 to 510 g dry weight.m^{-2} and a total of eight potentially commercial species of *U. lactuca, U. rigida*, , *Enteromorpha (=Ulva) intestinalis, Chaetomorpha aerea,* *Gracilaria verrucosa (= G. gracilis), Hypnea musciformis, Laurencia papillosa* and *Cystoseira barbata* were identified. The high biomass yield and species variety indicate that seaweeds as nutrient and energy reservoirs are an important biological compartment in the structure of the lagoon (Acarli and Turan, unpublished data).

We are presently developing an IMTA model at the Marine Center where seaweeds *Gracilaria* and *Ulva* grown in seaweed nets (Figure 9) with fish (mullet, seabream, seabass and eel) and mollucs (*Ostrea*, *Crassostrea*, *Mytilus, Tapes*, and *Haliotis)* naturally grown together in a good balance in the Lagoon. If yield of seaweeds, fish and mollucs biomass and quality could be improved, this approach could become economically competitive with high-tech mechanical systems developed for water treatment. Moreover, because the food and phycocolloid industry presently wants unlimited supply of seaweed raw material, there is a renewed interest in cultured seaweed species of agarophytes.

The agarophyte *Gracilaria* culture could also serve as an alternative source of *Gracilaria* that would complement the declining harvest of wild *Gracilaria*, a source of high-quality agar-agar and a component of the economic diversification of the shellfish and finfish aquaculture industry, which could integrate it as a complementary activity that would provide additional income and serve as a natural scrubbing system for excess N and P. If yield of *Ulva* biomass quality could be improved, this approach could generate economic value that more than compensate for the expenses by capturing released dissolved N and P and converting into the production of commercial *Ulva*. Additionally, as legislative guidelines, standards, and controls on the effluents from aquaculture operations into aquatic ecosystems become more stringent, bioremediation by the production of seaweeds could help the aquaculture industry in Türkiye avoid noncompliance problems (Turan 2009).

(a)

(b)

Figure 6. Dalyan Homa Lagoon Marine Center (a) and Preparing seaweed nets (b).

9.Conclusions And Recommendations

IMTA has enormous potential for growth in Türkiye where there are direct groundworks toward the development of IMTA and active research programs gaining knowledge about their regions potential for development of IMTA.

In summary,

- Turkish Aquaculture is now at a crossroad and there are many critical aspects of its sustainability that need to be addressed. Because of the recent regulations made by the Turkish Ministry of Environment and Forestry, the marine cage farms produce 90,000 tonnes of marine fish with 250,000 employee were porced to leave their operations from the shores to either on-land or off-shore areas due to their negative ecological impacts.

- The challenge faced by the Turkish aquaculture industry is how to maintain previous production levels and even expand them without exceeding assimilative capacity of the ecosystem. This is where IMTA can become the most innovative solution to the industry.
- Türkiye has ongoing research projects related to the development of IMTA.
- Türkiye has many marine species, including seaweeds with commercial potential and several projects already work on seaweed and IMTA culture, and the potential in Türkiye.
- The country has a total of 24.6 million ha coastal zone, of which 1.5 million ha area, called "economic coastal zone", has a high potential to grow seaweed in ecologically-balanced IMTA systems.
- Türkiye is still in its infancy and its potential in mariculture is far from being fully exploited. From the point of seaweed aquaculture, Türkiye is just using its marine aquaculture potential at minor levels, however it is believed that it will expand undoubtedly in following years by seaweed cultivation in IMTA systems where with 15% dry weight content, 5 ton fresh weight seaweed/ha/year in sea-based IMTA and

110 ton fresh weight seaweed/ha/year in land-based IMTA systems can be cultivated.

- And, producing a ton of dry algal biomass at IMTA system utilizes approximately 360 kg carbon, 63 kg nitrogen and 8.6 kg phosphorus.

- 830 tons of CO_2 can be taken up annually by a 1,000 mt fish-2,000 mt shellfish-500 mt seaweed IMTA farm and 1,230 tons of CO_2 can be taken up annually by a 1,000 mt fish-7,000 mt seaweed IMTA farm.

- Türkiye has potential 289,018.5 tonnes. y^{-1} Carbon sequestration just by potential seaweed production of 963,395 dw seaweed annually, if the country increased its production to match production in China which produces ~116 tons dry seaweed y^{-1} km^{-1}

IMTA provides exciting new opportunities for valuable crops of aquatic species and for Turkish IMTA approaches, the IMTA component may include species of :

- *Gracilaria, Gelidium, Gigartina, Hypnea, Porphyra, Asparagopsis, Juvenile Laminaria, Sargassum, Cystoseira, Dictyopteris, Ulva* and *Caulerpa* (seaweeds).

- *Dysidea avara* and *Chandrosia reniformis* (sponges).

- *Ostrea*, *Crassostrea*, *Pecten*, *Mytilus*, *Tapes*, and *Haliotis*, (molluscs).

- *Paracentrotus*, *Arbacia*, and *Holothuria* (echinoderms).

- *Nereis, Arenicola, Glycera* and *Sabella* (polychaetes).
- *Penaeus* and *Homarus* (crustaceans).
- *Sparus, Dicentrarchus, Oncorhynchus, Salmo, Thunnus, Scophthalmus,* and *Mugil* (fish).

In order to ensure the expansion of IMTA in Türkiye several steps should be taken where appropriate. These include: (1) establishing the economic value of IMTA systems and their co-products, (2) developing bio-economic models for IMTA systems, (3) exploring additional economic value for IMTA co-products, (4) exploring CO_2 utilization against global warming by IMTA coproducts, (5) Selecting the right species and habitats, (6) promoting effective government legislation/regulations and incentives for IMTA developments and the commercialization of IMTA products, (7) recognizing the benefits of IMTA and educating stakeholders about this practice, and (8) establishing the Research & Development & Commercialization for IMTA.

Taking all these factors into account, IMTA can be used as a valuable tool towards building a sustainable aquaculture industry in Türkiye. IMTA systems can be environmentally responsible, profitable and sources of employment in coastal regions for Türkiye that develops them properly, especially when government, industry, academia, communities and non-governmental environmental organizations (ENGOs) work in consultation with each other. It is highly recommended that IMTA systems be utilized wherever possible, and ultimately replace monoculture operations in areas where they can be developed.

IMTA is the best option for a sustainable aquaculture industry in Türkiye. It is environmentally responsible, economically profitable and socially acceptable. The IMTA studies established in Türkiye, have provided some solid examples concerning all these issues (environmental, economical and social) and can be referred to as pioneer models for Türkiye, although much more R&D&C is needed.

The key of IMTA is integration. As pointed out during a workshop on IMTA in Saint John, New Brunswick, Canada, in March 2004 (Robinson and Chopin 2004), a successful IMTA operation must integrate all stakeholders into its development plan. Government, industry, academia, the general public and ENGOs must work together. The role of IMTA in an integrated coastal zone management plan must be clearly defined. Beyond selecting the appropriate species for growth at a particular site, economics and social acceptability must also play a key role. Once these are established, a focused R&D&C programme will ensure efficiency and long-term sustainability for the aquaculture sector.

References

Barrington K, Chopin T, Robinson S (2009). Integrated multi-trophic aquaculture (IMTA) in marine temperate waters. In Soto D (ed), Integrated mariculture: a global review. FAO *Fisheries and Aquaculture Technical Paper*, no 529. Rome, FAO. pp.7-46.

Buschmann AH, Mora OA, Gomez P, Botttger M, Buitano S, Retamales C, Vergara PA, Gutierrez A (1994). *Gracilaria chilensis* outdoor tank cultivation in Chile: use of land-based salmon culture effluents. *Aquaculture Engineering* 13: 283–300.

Buschmann AH, López DA, Medina A (1996a). A review of the environmental effects and alternative production strategies of marine aquaculture in Chile. *Aquacultural Engineering* 15: 397-421.

Buschmann AH, Troell M, Kautsky N, Kautsky L (1996b). Integrated tank cultivation of salmonids and *Gracilaria chilensis* (Gracilariales, Rhodophyta) *Hydrobiologia* 326/327: 75-82.

Buschmann AH, Correa JA, Westermeier R, Paredes MA, Adeo D, Potin P, Aroca G, Beltrán J, Hernández-González MC (2001). Cultivation of *Gigartina skottsbergii* (Gigartinales, Rhodophyta): recent advances and challenges for the future. *Journal of Applied Phycology* 13: 255-266.

Buschmann AH, Hernández-González MC, Astudillo C, de la Fuente L, Gutierrez A, Aroca G (2005). Seaweed cultivation, product development and integrated aquaculture studies in Chile. *World Aquaculture* 36: 51-53.

Buschmann AH, Riquelme VA, Hernández-González MC, Varela D, Jiménez JE, Henríquez LA, Vergara PA, Guíñez R, Filún L (2006). A review of the impacts of salmonid farming on marine coastal ecosystems in the southeast Pacific. *ICES Journal of Marine Science* 63: 1338-1345.

Carmona R, Kraemer GP, Yarish C (2006). Exploring Northeast American and Asian species of *Porphyra* for use in an integrated finfish-algal aquaculture system. *Aquaculture* 252: 54-65.

Chapman FA, Fitz-Coy SA, Thunberg EM, Adams CM (1997). United States of America trade in ornamental fish. *Journal of the World Aquaculture Society* 28: 1-10.

Chopin T (2006). Integrated Multi-Trophic Aquaculture. What it is and why you should care… and don't confuse it with polyculture. *Northern Aquaculture* 12 (4): 4.

Chopin T, Yarish C, Wilkes R, Belyea E, Lu S, Mathieson A (1999). Developing *Porphyra*/salmon integrated aquaculture for bioremediation and diversification of the aquaculture industry. *Journal of Applied Phycology* 11: 463-472.

Chopin T, Buschmann AH, Halling C, Troell M, Kautsky N, Neori A, Kraemer GP, Zertuche-Gonzalez JA, Yarish C, Neefus C (2001). Integrating seaweeds into marine aquaculture systems: a key towards sustainability. *Journal of Phycology* 37: 975-986.

Chopin T, Robinson SMC, Troell M, Neori A, Buschmann AH, Fang J (2008). Multi-trophic integration for sustainable marine aquaculture, pp. 2463-2475. In: Jorgensen, SEJ, Fath, BD (eds.). *The Encyclopedia of Ecology*. *Ecological Engineering* (Vol. 3). Elsevier, Oxford.

Cirik S, Turan G, Ak I, Koru E (2006). *Gracilaria verrucosa* (Rhodophyta) culture in Türkiye. International Conference on

Coastal oceanography and Sustainable Marine Aquaculture: Confluence and Synergy, 2-4 May 2006, Sabah, Malaysia.

Deniz H (2010). Türkiye: Best practices in aquaculture management and sustainable development. In: Andrews-Chouicha E, Franz N, Ravet K, Schmidt CC, Strange T (eds), *Advancing the Aquaculture Agenda: Workshop proceedings*, OECD, 15-16 April 2010, Paris, France, pp. 183-193.

Edwards P (2004). Traditional Chinese aquaculture and its impact outside China. *World Aquaculture*, 35:24–27.

FAO (2006a). State of world aquaculture, 2006. Food and Agriculture Organization of the United Nations, FAO Fisheries Technical Paper 500, Rome.

FAO (2006b). Fisheries Global Information System (FIGIS) website. www.fao.org/figis/servlet/TabLandArea?tb_ds=Aquaculture&tb_mode=TABLE&tb_act=SELECT&tb_

grp=COUNTRY

FAO (2009a). The state of world fisheries and aquaculture 2008, FAO, Rome, www.fao.org/fishery/sofia.en.

FAO (2009b). Yearbook of Fishery Statistics: Summary Tables of Fishery Statistics, FAO, Rome.

Muir JF, Little DC, Young JA, Bostock JC (2010). Growing the wealth of aquaculture. In:

Andrews-Chouicha E, Franz N, Ravet K, Schmidt CC, Strange T (eds), *Advancing the Aquaculture Agenda: Workshop proceedings*, OECD, 15-16 April 2010, Paris, France, pp. 39-107.

Neori A, Chopin T, Troell M, Buschmann AH, Kraemer GP, Halling C, Shpigel M, Yarish C (2004). Integrated aquaculture: rationale, evolution and state of the art emphasizing seaweed biofiltration in modern mariculture. *Aquaculture* 231: 361-391.

Nicosia F, Lavalli K (1999). Homarid lobster hatcheries: their history and role in research, management, and aquaculture. *Marine Fisheries Review* 61(2): 1-57.

Olive PJW (1999). Polychaete aquaculture and polychaete science: a mutual synergism. *Hydrobiologia* 402: 175-183.

Osinga R, Sidri M, Cerig E, Gokalp SZ, Gokalp M (2010). Sponge Aquaculture Trials in the East-Mediterranean Sea: New Approaches to Earlier Ideas, *The Open Marine Biology Journal,4*, 74-81.

Pearce C M, Daggett TL, Robinson SMC (2004). Effect of urchin size and diet on gonad yield and quality in the green sea urchin (*Strongylocentrotus droebachiensis*). *Aquaculture* 233: 337-367.

Phillips BF, Liddy GC (2003). Recent developments in spiny lobster aquaculture. Proceedings of the Third World Fisheries Congress: Feeding the World with Fish in the Next Millenium – the Balance Between Production and Environment. *American Fisheries Society Symposium* 38: 43-57.

Phillips BF, Smith RM, Maguire GB (2004). Western rock lobster: Potential for enhancement and aquaculture. *Journal of Shellfish Research* 23: 307.

Shpigel M, Neori A (1996). The integrated culture of seaweed, abalone, fish, and clams in modular intensive land-based system. I. Proportion of size and projected revenue. *Aquacultural Engineering* 15(5): 313–326.

Turan G (2009). Potential Role of Seaweed Culture in Integrated Multitrophic Aquaculture (IMTA) Systems for Sustainable Marine Aquaculture in Türkiye, *Aquaculture Europe*, Vol 34 (1), March 2009, pp. 5-11.

Turan G, Neori A (2010). Intensive Seaweed Aquaculture: A Potent Solution Against Global Warming. In: Israel A, Einav R, Seckbach J (eds), Seaweeds and Their Role in Globally Changing Environments, Cellular Origin, Life in Extreme Habitats and Astrobiology, Springer, 15, pp. 357-372.

Turan G, Koru E, Tekogul T, Seyhaneyildiz S, Can E, Peker O, Cirik S (2007). Seaweed Aquaculture in Türkiye: Pilot Projects With potential For Integrated Aquaculture Systems, Aquaculture Europe 07 October 24-27, 2007, Istanbul, Türkiye.

Turan, G, Koru E, Tekogul H, Seyhaneyildiz S, Peker O, Cirik S (2007). Seaweed Resources of Türkiye, Aquaculture Europe 07 October 24-27, 2007,Istanbul, Türkiye.

Turan G, Ak I, Cirik S, Koru E, Kaymakci-Basaran A (2006). *Gracilaria verrucosa* (Hudson) Papenfuss Culture in Intensive Fish Farm. Ege University Journal of Fisheries Faculty, Volume: 23 (1/2): 305-309 (In Turkish).

Turan G, Cirik S, Tekogul H, Koru E, Seyhaneyildiz S, Peker O, Can E (2007). Seaweed Cultivation in Integreted Aquaculture Systems. XIV. National Fisheries Symposium, Mugla University, Fisheries Faculty, 4-7 September 2007 Mugla, Türkiye (In Turkish).

Turan G, Cirik S (2008). Culture, mineral-vitamin composition, and thalassotherapy application studies on seaweeds. The 11th International Conference on Applied Phycology, 22-27 June 2008, The National University of Irland, Galway, Irland.

Turan G, Tekogul H, Koru E, Cirik S (2009). Contribution of Seaweed Cultivation IMTA Systems to Shaping Sustainable Aquaculture in Türkiye. European Aquaculture 09, 14-17 August, Trondheim, Norway.

Turan G, Tekogul H, Koru E, Cirik S (2010). Seaweed-based Integrated Multi-Trophic Aquaculture: A potent solution for sustainable aquaculture in Türkiye. Aquaculture 2010, March 1-5, San Diego, California, USA.

Troell M, Halling C, Nilsson A, Buschmann AH, Kautsky N, Kautsky L (1997). Integrated marine cultivation of *Gracilaria chilensis* (Gracilariales, Rhodophyta) and salmon cages for reduced environmental impact and increased economic output. *Aquaculture* 156: 45-61.

Troell M, Halling C, Neori A, Chopin T, Buschmann AH, Kautsky N, Yarish C (2003. Integrated mariculture: asking the right questions. *Aquaculture* 226: 69-90.

Troell M, Robertson-Andersson D, Anderson RJ, Bolton JJ, Maneveldt G, Halling C, Probyn T (2006). Abalone farming in South Africa: an overview with perspectives on kelp resources, abalone feed, potential for on-farm seaweed production and socio-economic importance. *Aquaculture* 257: 266-281.

Whitmarsh DJ, Cook EJ, Black KD (2006). Searching for sustainability in aquaculture: an investigation into the economic prospects for an integrated salmonmussel production system. *Marine Policy* 30: 293-298.

Yang YF, Li CH, Nie XP, Tang DL, Chung, IK (2004). Development of mariculture and its impacts in Chinese coastal waters. Rev Fish Biol Fish 14:1–10.

Yarish, C., and Pereira, R., (2008). Mass Production of Marine Macroalgae. *In*: Ecological Engineering, Sven Erik Jørgensen and Brian D. Fath (Editor-in-Chief), Vol. [3] of Encyclopedia of Ecology, 5 vols., Oxford: Elsevier, pp: 2236-2247

CHAPTER II

Sustainable Practices in Trout Farming

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1. Introduction

Trout farming has become a rapidly growing aquaculture sector in line with the increasing demand for sustainable food sources worldwide (Bartley, 2022). This growth is particularly concentrated on species such as rainbow trout (*Oncorhynchus mykiss*) that are fast-growing, more adaptable to environmental conditions, and have high commercial value. Trout can be grown in a variety of aquaculture systems due to their ability to adapt to both freshwater and marine water conditions (Pillahi & ark., 2020). Türkiye stands out as a major producer on a global scale in this field

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thanks to its geographical advantages in terms of trout farming (Midilli, Küçük & Dinçer, 2012).

Various farming systems are used in trout production. Open-circuit systems include farming in natural flowing waters or lakes, while recirculating aquaculture units are systems where water is recycled. In recent years, recirculating aquaculture systems have been suggested to protect resources and provide sustainable production due to global warming. Such systems have the potential to provide water saving and sustainability, especially in regions where water resources are limited (Ashley, 2007 Subasinghe, Soto & Jia, 2009). However, the initial costs of recirculating aquaculture systems are higher than open systems, and this is an effective factor on production efficiency (Timmons, 2002). Another farming method, cage systems, allows farming in net cages in large water bodies (such as lakes or seas). Although cage systems offer a low-cost option, they bring some risks in terms of water quality and environmental impact (Mavraganis & et al., 2020). Feed waste, post-digestion waste and environmental waste can cause pollution of lake and sea basins. Therefore, care should be taken to keep such wastes to a minimum.

In trout farming, correct feeding strategies are of critical importance in terms of growth performance and health. In order to ensure that protein, fat, vitamins and minerals are balanced in fish feeds, feed rations should be prepared by considering different temperature and oxygen values. Because feeds directly affect the growth and immunity of trout (Jobling, 2012). Especially high costs and environmental effects require the development of more efficient feeding strategies. Automatic feeding systems optimize feed consumption, reduce waste formation and provide cost control (Anyango & et al., 2004). In addition, feed formulations enriched with plant-based proteins stand out as a sustainable option in terms of reducing feed costs and protecting natural resources (Naylor & et al., 2000). However, attention should be paid to the use of highly digestible raw materials, taking into account the feeding habits of the fish.

High stock densities in the aquaculture environment make trout more susceptible to viral, bacterial and parasitic diseases (Murray & Peeler, 2005). Viral diseases such as infectious pancreatic necrosis (IPN) are among the most common diseases, and prevention of these diseases is possible with biosecurity measures (Gentry & et al., 2020). Biosecurity measures include methods such as water disinfection, isolation of sick individuals and sterilization of equipment (Austin & Austin, 2016). In addition to chemical disinfectants (formaldehyde, chloramine T, potassium permanganate), environmentally friendly alternatives such as herbal disinfectants (tea tree oil, peppermint oil, garlic extract) are increasingly preferred (Subasinghe, Soto & Jia, 2009).

In this study, it is aimed to provide guiding information to researchers and breeders in the sector about the techniques and strategies applied in trout farming, and practices that increase consumer confidence by reducing environmental impacts, such as certified production in accordance with sustainability standards.

2. Trout Production and Consumption Quantities in Türkiye and the World

Türkiye has an important place in world trout production. According to 2022 data, Türkiye's trout production is approximately

180 thousand tons. Approximately 120 thousand tons of this production is in portions (250-350 gr) and 60 thousand tons in kilograms (2-3 kg). Türkiye is the largest trout producer in Europe. In recent years, intensive production has been carried out especially in the Black Sea and Eastern Anatolia regions (TÜİK, 2023). A large portion of the trout produced is exported to European countries and many countries of the world. It is aimed to produce over 200 thousand tons of annual production in Türkiye in the next few years.

Trout production worldwide is estimated to be 2.2 million tons by 2022. Other countries that stand out in trout production include the USA, Norway and China. Norway, in particular, stands out with its high-quality salmon production (Bartley, 2022; FAO, 2023). Consumption amounts are increasing worldwide, and fish consumption is expected to increase due to healthy eating trends.

3. Breeding Principles

Trout farming is based on various principles to obtain productive products in a sustainable manner . These principles have been developed for the healthy growth of fish, minimization of environmental impacts and ensuring economic sustainability (Pillay & Kutty, 2005). In this section, the basic principles to be considered in trout farming will be detailed.

3.1. Water Quality Management

Water quality is of vital importance for productivity and fish health in trout farming. Water quality parameters include pH, dissolved oxygen, ammonia and temperature (Chen, Ling, & Blancheton, 2006; Bhatnagar & Devi, 2013; Soler & et al., 2021). For example, the ideal pH range for trout is between 6.5-8.5, and the temperature should be between 8-11 °C in hatcheries and 12-16 °C in grow-out groups (Wedemeyer& Wydoski, 2008; Boyd & Tucker, 2012). Managing water quality prevents the spread of diseases and ensures healthy growth of fish.

3.2. Disease Prevention and Biosecurity

In trout production, diseases are seen depending on seasonal changes in water quality parameters, feeding and feed content, physical practices, environmental factors and can lead to high economic losses. Biosecurity measures are necessary to prevent the spread of diseases. Measures such as isolation of diseased individuals, water disinfection and equipment sterilization reduce the risk of disease (Austin & Austin, 2016; Austin & et al., 2022).

3.3. Economic and Environmental Impacts

The economic and environmental impacts of production techniques are important factors to consider in trout farming. The use of recirculating aquaculture system increases environmental sustainability by reducing water consumption and increases production efficiency. However, the installation and operation of these systems may require high costs. Therefore, the selection of production techniques should be made by considering economic and environmental factors (Wurts, 2000; Naylor & et al., 2000).

3.4. Genetic Selection

Genetic selection is critical for efficiency and a healthy production process in trout farming. Selecting high-yielding and disease-resistant individuals increases the genetic quality of the flock. Genetic selection programs are carried out by crossing individuals with specific characteristics. Among these characteristics, growth rate, meat quality, high yield and disease resistance are important (Gjedrem & Baranski, 2010). Preservation of genetic diversity also plays an important role in reducing the risk of disease spread (Austin, 2023).

3.5. Feeding Management

Feeding management is of vital importance for the healthy growth and high yield of trout (Austin, 2023). Nutritional quality directly affects the growth rate and meat quality of fish. Specially formulated feeds should be used for trout. These feeds should be balanced in terms of protein, fat, vitamins and minerals (Naylor & et al., 2000). Feeding frequency and amount should also be adjusted according to the growth stage of the fish. Generally, young trout should be fed several times a day (3-5%), while larger individuals should be fed once or twice a day (1-2%).

3.6. Breeding Systems

Farming systems refer to the environments in which trout are raised. These systems can take various forms, such as recirculating systems, stream systems, and lake-pond systems. Closed circulation systems use water resources more efficiently and reduce environmental impacts. These systems allow continuous monitoring and control of water quality (Ebeling & Timmos, 2012).

Fluid systems are systems where natural water sources are used and the water is constantly changing. In these systems, the quality of the water must be carefully monitored. Pond systems are generally used to raise fish in a less controlled environment. In such systems, environmental conditions have a great influence and therefore productivity can vary (Beveridge & Brummett, 2015).

3.7. Disease Management

Disease management is an important issue in trout farming. Biosecurity measures should be taken to prevent the spread of diseases. These include sterilization of equipment, water disinfection, and isolation of diseased individuals (Austin, 2011; Austin & et al., 2022; Rathor & Swain, 2024). In addition, vaccination and selection of healthy individuals reduce the risk of disease spread (Austin, 2016). Trout are particularly susceptible to viral diseases, so care should be taken against diseases such as IPN, VHS, and IHN (Alfred & et al., 2020).

3.8. Environmental Sustainability

Trout farming is an important issue in terms of environmental sustainability. Farmers need to develop various strategies to minimize environmental impacts. Factors such as water consumption reduction, waste management and energy efficiency should be taken into account to increase environmental sustainability (Mohan, 2007; Naylor & et al., 2021; Austin, 2023). In addition, it is important to develop fish farming practices by considering the protection of natural habitats and the balance of ecosystems.

3.9. Economic Sustainability

Economic sustainability is one of the key elements of success in trout farming. Farmers need to develop effective management strategies to reduce production costs and increase productivity. Meeting market demands, providing quality products and developing marketing strategies are elements that support economic sustainability (Ferreira & et al., 2021).

Trout farming requires an efficient, healthy and sustainable production process. Consideration of basic principles such as genetic selection, water quality management, feeding management, rearing systems, disease management and environmental sustainability are critical for successful trout farming (Schaltegger, Lüdeke-Freund, & Hansen, 2012; Austin, 2023). The application of these principles ensures healthy fish growth and an economically sustainable production process.

4. Feeding

Feeding is a critical factor in trout farming to achieve healthy growth and high yields (Austin & et al., 2022). Proper feeding of trout directly affects growth rates, meat quality and general health status (Nguyen, Dinh & Davis, 2020). In this section, the basic elements and feeding strategies to be considered in feeding trout will be discussed.

4.1. Nutritional Requirements

In feeding trout, first of all, it is necessary to take into account the nutritional requirements of the species, which vary according to their age and size (Trung & et al., 2022). The protein needs of young trout are higher during their growth period and feeds containing 50-55% protein should generally be preferred. For adult trout, this rate is around 40-45% (Krogdahl & et al., 2023). In addition, the balance of protein, fat, carbohydrates, vitamins and minerals, mostly of animal origin (especially fatty, red meat fish), should be taken into account in the nutritional content. Omega-3 and omega-6 fatty acids are especially important for the healthy growth of trout.

4.2. Types of Feed

Bait used for trout generally falls into two main categories: commercial baits and natural baits:

4.2.1. Commercial Feeds

They are feeds specially formulated for trout and suitable for their nutritional requirements. These feeds are usually in granular, extruder pellet form and their nutritional content varies according to the age and growth stage of the trout, water temperature and oxygen content of the water. For example, small granular feeds are preferred for young trout, while larger feeds are preferred for adults (Torrecillas, & et al., 2021). The formulation should be updated according to seasonal temperature changes. For example; In waters with high temperatures (17 degrees and above), the fat in the feed content should be reduced by 4-5% to facilitate digestion. In sources with low temperatures below 10 degrees, the fat content should be 22-24%. In recent years, the need for sustainable feed sources has increased (Hernández & et al., 2023). While the production of traditional feeds leads to environmental impacts, alternative feed sources have the potential to overcome this problem. Alternative sources such as soy, pea, barley and insect proteins are potential feed raw materials that can be used in the nutrition of trout. The use of such feeds both reduces production costs and environmental impacts (Tacon & Metian, 2009).

4.2.2. Natural Feeds

Since trout are carnivores, natural feed sources that can be used in their nutrition include zooplankton, benthic organisms and other aquatic organisms. Such feeds are suitable for the natural feeding habits of trout and provide healthy development. However, the use of natural feeds may have some difficulties and risks in terms of sustainability (Ringo & et al., 2014). The supply of these zooplankton and other microscopic organisms may not always be possible and may negatively affect fish health by carrying pathogens found in their habitats. Feed production in trout farming is an important issue in terms of environmental sustainability. The supply of raw materials used in the production of feeds from sustainable sources minimizes the negative effects of aquaculture on the ecosystem (Nasopoulou & et al., 2013). In addition, waste management practices help to dispose of waste generated during feed production without harming the environment (Pullin, Froese & Pauly, 2007).

4.2.3. Feeding Strategies

Feeding strategies are important factors affecting the growth rate and feed conversion rate of trout. Feeding frequency, amount and method have a direct effect on the health of fish. Young trout should be fed several times a day, while larger individuals should be fed once or twice a day (Satpathy, Mukherjee & Ray, 2003). During feeding, the feed consumption of the fish should be monitored and the amount of feed should be adjusted accordingly. Feeding may vary depending on seasonal water quality and temperature (Kamalam, Rajesh & Kaushik, 2020). Nowadays, free feeding is mostly done in enterprises. It is fed at the rate that the fish takes the feed with appetite, not the percentage of biomass.

4.2.4. Feed Conversion Ratio

Feed conversion ratio (FCR) is an important productivity indicator in trout farming. This ratio shows the ratio of the amount of feed consumed by trout for their growth to the live weight they gain. A low FCR means a more efficient feeding strategy. The ideal FCR ratio for trout generally varies according to the age of the fish, but it varies between 0.6-0.8 in fingerling groups; 0.9-1.2 in pre-growing and portion groups and 1.4-1.6 in fish weighing more than kg (Dumas, France & Bureau 2010). On the other hand, specific growth rate (SGR) is an important parameter used to evaluate the growth rate of individuals. This ratio helps to follow the growth performance of fish in farming by showing the weight gain over a certain period (Nguyen, Dinh & Davis, 2020). Factors affecting SGR (such as nutrition, environmental conditions, genetic traits, water temperature, and diseases) are continuously being investigated in order to increase efficiency and reduce costs in trout farming (Aas & et al., 2006; Drew & et al., 2007; McLean & et al., 2022). For example, the effect of water temperature on SGR is quite pronounced; higher temperatures generally increase growth rate, while extreme temperatures may negatively affect growth by causing decreased oxygenation, digestive system disruption, and stress (Jobling, 2012; Handeland & et al., 2013). In order to improve feed conversion ratio, it is important to improve feed quality, consider environmental conditions, and optimize feeding strategies.

4.2.5. Nutrition and Health Relationship

The health of trout is closely related to nutrition. Inadequate nutrition can lead to various health problems in fish (Austin, 2007). In particular, vitamin and mineral deficiencies can cause the immune system to weaken. As a result, trout are exposed to more diseases (Kumar & et al., 2022). In addition, the development of nutritional strategies and their integration with disease management support the healthy development of trout.

Feeding trout plays a critical role in achieving healthy growth and productivity. Meeting nutritional requirements, correct selection of feed types and effective implementation of feeding strategies increase the sustainability of trout farming (Huyben & et al., 2019; Kiron & et al., 2022). In addition, the use of alternative feed sources and sustainable feed production practices will determine the direction of future developments in this field.

5. Trout (*Oncorhynchus mykiss*) Production

The production techniques used in trout farming are critical for the healthy rearing, growth and high yield of fish (Torrissen, Shearer & et al., 2013). The basic methods in trout production include natural and artificial production techniques, management of water conditions, breeding processes and genetic management. In this section, special focus will be given to the production of eggs, fingerlings, portions and salmon.

5.1. Natural Production

Natural production refers to the rearing of fish in their natural habitats, in natural water sources such as ponds and rivers (Cascarono & et al., 2021, Ruzzante & et al., 2022). In this method, the natural reproductive cycles of fish are observed and production conditions vary depending on environmental factors. Natural production can be affected by environmental effects and therefore low productivity problems may occur. However, this method offers advantages in terms of fish being able to exhibit their natural behaviors (Beveridge & Brummett, 2015).

5.2. Artificial (Culture) Production

Artificial production techniques allow trout to be raised in a controlled environment. This method generally results in higher productivity and better growth rates (Linder & et al., 2012). The following steps are applied in artificial production:

5.2.1. Egg Collection and Fertilization

Artificial insemination is carried out by taking eggs from female trout and sperm from males. This process increases the fertilization rate of eggs and helps to obtain offspring with the desired genetic characteristics (Eya & et al., 2013). Today, by imitating natural life and reproduction cycles, eggs and sperm can be taken from fish throughout the year outside of the reproduction period, as seen in Figure 1.

Figure 1. Egg and sperm collection from broodstock trout (Original, 2023)

5.2.2. Raising Offspring

After the eggs and sperm from the broodstock trout are collected by milking (massaging the abdominal area of the fish), dry or wet fertilization is performed. The fertilized eggs are incubated in a controlled environment (Collins & et al., 2018; Carter & Codabaccus, 2022; Fujimoto & et al., 2008). After incubation, the baby trout hatch depending on the water temperature. After the eggs have completely hatched, they are kept in incubation cabinets until the food sacs are withdrawn (Johnson & et al., 2019). Then, they are taken to concrete or fiberglass pools called pre-growth tanks, which are 3x1x0.5 m^3 in size, as seen in Figure 2. The fry continue to be fed in these pools until they reach a weight of approximately 2-3 grams. After this period, the fish are gradually taken to larger pools (fattening) depending on their size.

In trout production, parameters such as temperature and oxygen levels must be carefully controlled at all stages of production from egg. 70-75% of fish production costs are feed costs. Therefore, it is very important to increase feed quality and manage and control water quality for fish to be healthy and grow (Becke & et al., 2019).

Figure 2. Incubation cabinet (a), egg pan (b), fiberglass pool (c), concrete pre-growth pool (d), (Original, 2023)

5.2.3. Portion Enlargement

As the young trouts grow, they are taken to portion growth tanks as seen in Figure 3. At this stage, when the trouts reach a certain weight, that is, until they reach portion size (250-350 gr), they are fed and then sold in retail or wholesale. If fish above kilograms are to be produced, growth continues and they can be offered for sale in weights of 1 kg to 3 kg. During this process, the feed dimensions and content are also reformulated according to the size of the fish (Asche, Cojocaru & Roth, 2018). While preparing the feed, the healthy growth of the fish is generally ensured by carefully managing the feed raw matrial quality and water temperature (Naylor & et al., 2021).

Figure 3. Portion trout production pools (beyazgazete.com)

5.2.4. Salmon Production

Salmon (*Salmo salar*) production is similar to the cultivation of trout (*Oncorhynchus mykiss*) over 1 kg, but it has some important differences. Salmon is a species that can switch between freshwater and saltwater (Taranger & et al., 2010; Liu & et al., 2016). In salmon production, juvenile salmon (smolt) must be raised in freshwater before switching to saltwater. This process allows salmon to adapt to the saltwater environment and helps to achieve high yields (Cardinaletti & et al., 2022).

In Türkiye, production is carried out in coastal areas starting from the Sinop coast in the Black Sea region and extending to the Rize coast. The method applied in the production of trout over kg here is; After growing in inland waters (in concrete pools or lakes, ponds or dams) up to 300-500 gr, they are adapted to salt water and grown up to 2-3 kg (Austin & et al. 2022). Figure 4. Approximately 40% of trout production in the Black Sea consists of trout over kg (Black Sea salmon).

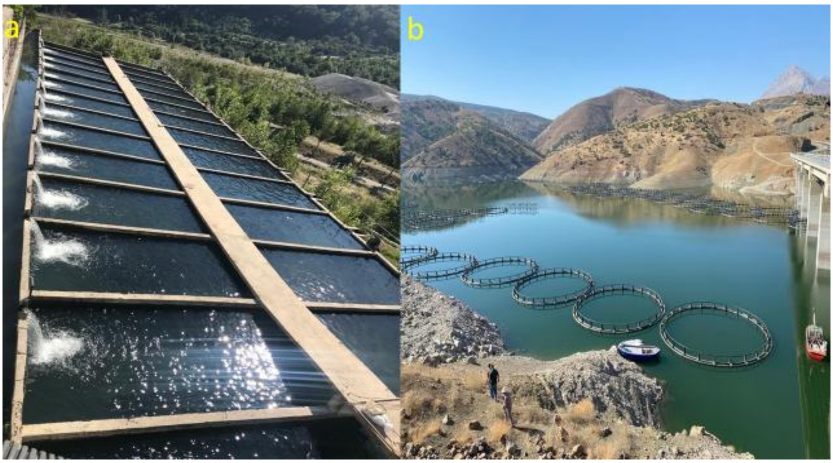

Figure 4. View from fish production facilities above kg in concrete pools (a) and cages (b) (Original, 2022)

6. Diseases and Treatment Methods

Diseases are an important problem in trout farming that can cause production losses (Garver & et al., 2017; Doğan, 2024).

Prevention and management of diseases are critical for healthy fish farming (Dorsan & Torhy, 1993; Bergmann & Fichtner, 2008). In this section, the types of diseases commonly seen in trout, their symptoms, causes and treatment methods will be discussed.

6.1. Diseases Seen in Trout

The most common diseases encountered in trout farming are bacterial, viral, parasitic and fungal diseases. Each of these diseases can negatively affect the health of trout (Rathor & Swain, 2024).

6.1.1.Bacterial Diseases

Infections usually occur due to factors such as stress, poor water quality and nutritional deficiencies. Among the most common bacterial diseases, Columnaris disease caused by *Flavobacterium columnare* is common during periods when water temperatures increase (Buller, 2014). Furunculosis, caused by the bacteria *Aeromonas salmonicida*, can cause high mortality by causing infection in the blood and internal organs of fish (Noga, 2010). Bacterial pathogens such as *Streptococcus iniae* also cause disease by damaging the nervous system and tissues of infected fish and are a type of infection with a high risk of transmission (Roberts, 2012). Vibrio infection caused by species such as *Vibrio anguillarum* causes hemorrhagic septicemia in fish and is particularly severe during the summer months when water temperatures increase (Roberts & et al., 2006). Red mouth disease is an infection caused by the *Yersinia ruckeri* bacterium and manifests itself with symptoms such as redness around the mouth and bleeding in internal organs (Ohtani & et al., 2019).

There are Infectious Hematopoietic Necrosis (IHN), Infectious Pancreatic Necrosis (IPN) and Viral Hemorrhagic

Septicemia (VHS). These diseases can cause sudden death rates and high morbidity (Wright & et al., 2023).

6.1.2. Viral Diseases

Viral diseases can weaken the immune system of trout and lead to death. They are especially effective as a result of deterioration in water quality and cause high rates of loss. The main viral diseases can be listed as Infectious Hematopoietic Necrosis (IHN), Infectious Pancreatic Necrosis (IPN) and Viral Hemorrhagic Septicemia (VHS) (Hedrick & et al., 2003; Meyer, Wright & et al., 2023).

6.1.3. Parasitic Diseases

Parasites are other important factors affecting the health status of trout. External parasites (e.g., protozoa and copepods) and internal parasites (e.g., nematodes and trematodes) can reduce the growth rate and increase mortality rates of trout (Noga, 2010; Roberts, 2012; Faruk, 2018). Among the main parasitic diseases, *Ichthyophthirius multifiliis* (white spot disease), *Gyrodactylus salaris* (monogenic parasite), *Trichodina* spp. species and *Diplostomum spathaceum* (eye parasite), *Lernaea spp.,* also known as "anchor worm" among the public, are species that can cause serious health problems in trout (Woo, 2006; Bakke, Harris & Cable, 2007).

6.1.4. Fungal Diseases

Fungal infections are usually seen in fish that are stressed or have a weak immune system. Especially water pollution and high temperatures can trigger fungal infections (Wagner & et al., 2002). *Saprolegnia spp* . is one of the most common fungal infections in trout. *Saprolegnia* species settle on the skin and gills of fish, forming white cottony structures and can spread rapidly in open wounds. It can also cause serious infections on eggs, which increases egg losses (Willoughby, 1994). *Branchiomyces spp*., known as gill fungus, causes infection in the gill tissue of trout, restricting oxygen intake. In severe infections, fish are at risk of dying by remaining in an anoxic environment (Roberts, 2012). Another fungal infection is *Ichthyophonus hoferi* . This fungal infection is systemic and causes granuloma formation in internal organs. It is usually slow-progressing but can have fatal consequences in infected fish (Bruno, West & Beakes, 2011).

6.2. Symptoms of Diseases

Disease symptoms in trout may vary depending on the type of disease. Commonly observed symptoms include: Difficulty swimming or imbalance, inflammation in the gills and body, loss of appetite or decreased feed intake, sudden death events, skin lesions and color changes (Kumar & et al., 2024). These symptoms are important to evaluate the health status of trout and apply the necessary treatment methods.

6.3. Prevention of Diseases

Disease prevention is one of the most important strategies in trout farming. Providing a healthy rearing environment is necessary to reduce the risk of disease (Can & et al., 2023; Austin, 2023). Preventive measures can be listed as follows:

6.3.1. Water Quality Management

Regular monitoring of water quality and ensuring appropriate conditions are critical to disease prevention. Parameters such as water temperature, pH, dissolved oxygen level and ammonia must be kept under control (Diaz & et al., 2015).

6.3.2. Hygiene and Disinfection

It is important to keep the aquaculture areas in hygienic conditions to prevent the spread of infections. Regular cleaning and disinfection of equipment and tanks is extremely important (Froehlich, Gentry & Halpern, 2017).

6.3.3. Stress Management

First of all, the stress levels of fish need to be reduced and their immune systems strengthened. Factors such as stock density, poor water quality and overfeeding in the aquaculture environment increase stress. Therefore, necessary precautions should be taken to prevent these negative factors (Barton, 2002).

6.4. Treatment Methods

The treatment methods to be applied after the diagnosis of the diseases vary according to the type of disease (Buller, 2014).

6.4.1. Antibiotics

Antibiotics can be used to treat bacterial infections. However, excessive use of antibiotics can lead to increased antibiotic resistance. Therefore, it is important to use antibiotics with caution and in accordance with veterinary advice (Miranda, Godoy & Lee 2018).

6.4.2. Vaccination

Although there is no known treatment method for viral diseases in trout, vaccination plays a major role in their prevention. Vaccines strengthen the immune system of trout and provide resistance against diseases (Zhang, Spanjers & van Lier, 2013; Dey & Thomson, 2023).

6.4.3. Chemical Applications

Chemical treatment methods can be used in the treatment of parasitic infections. Chemicals such as formaldehyde and hydrogen peroxide, Cloramin T can be effective in the treatment of external parasites. However, such treatments must be applied with caution (Noga, 2010).

6.4.4. Alternative Treatment Methods

In recent years, herbal and natural treatment methods have also been used. For example, some herbal extracts, such as garlic extract, thyme oil, and tea tree oil, have been shown to strengthen the immune system of fish and increase resistance to diseases (Sihag & Sharma, 2012; Austin, 2023).

7. Other Sustainable Practices

7. 1. Certified Sustainable Production

Certification demonstrates compliance with sustainability standards in trout farming and increases consumer confidence. Certified Sustainable Production in trout farming is an approach that demonstrates that farms comply with environmental, social and economic sustainability standards (Bush & et al., 2013). In this system, fish farms are inspected by various certification bodies and their compliance with certain criteria is approved. Certified production guarantees that consumers are offered a more responsible and sustainable product (Potts & Haward, 2007; Saha, 2024).

7. 1.1. Types of Certification

The main certification bodies and programs that provide sustainability standards in trout farming are:

7.1.1. a Aquaculture Stewardship Council (ASC) Certificate

ASC is one of the best-known organizations promoting environmental and social sustainability in aquaculture (Alhazzaa, Nichols & Carter, 2019).

Criteria:

Protecting water quality

Conservation of biodiversity

Control of antibiotic and chemical use

Social responsibility (employee rights, engagement with communities)

Traceability of feed and raw material sources

Audits: The certification process is managed by rigorous controls by independent auditors. Farms are inspected at regular intervals to ensure they continue to meet the criteria (Aquaculture Stewardship Council. 2023; Fiorile & et al., 2023).

7.1.1.b GlobalG.AP Certificate (Good Agriculture Practice (GAP))

GlobalG.AP is a global certification standard for agriculture and aquaculture. It monitors farms for compliance with safety, quality and sustainability standards (Hatanaka & Busch, 2008; Saha, 2024).

Criteria:

Food safety and traceability

Environmental sustainability (waste management, water use)

Occupational health and safety

Animal Welfare

Advantages: GlobalG.AP certification increases the competitiveness of products in international markets and expands export opportunities (Dey, 2008; Tacon & Metian, 2015).

7.1.1. c Organic Certification

Organic trout farming covers a farming model where chemical fertilizers, pesticides and synthetic feed additives are not used and natural methods are at the forefront (McEwin & McNally, 2014; Dolores-Salinas & Miret-Pastor, 2024).

Criteria:

Use of natural feeds (Zooplankton, phytoplankton, Crustacea)

Environmentally friendly production methods

Fish health and welfare

Certification Bodies: There are different organic certification bodies based on countries. For example, there is the European Union Organic Certificate, USDA Organic in the USA, and organic certificates approved by the Ministry of Agriculture and Forestry in Türkiye (TÜRKAK, Good Agricultural Practices, MSC) (Hatanaka & Busch, 2008).

7.1.1.d Marine Stewardship Council (MSC) Certificate

MSC certification is generally used for marine fish, but it is a standard that reduces the environmental impact of fish that escape from farms into the wild and encourages practices that protect the environment (Ponte, 2012).

Criteria: Protection of wild species, reduction of impact on the marine ecosystem and sustainable fisheries management.

7.2. Advantages of Certified Sustainable Production

Environmental Impact is Reduced: The criteria determined in the certification process reduce environmental pollution, protect biodiversity and promote the sustainable use of natural resources (Ponte, 2012; Bjørndal & Haugen, 2023).

Consumer Confidence Increases: Certified products are preferred more by consumers because it is guaranteed that these products are produced under reliable and sustainable conditions (Smith, 2023).

Provides Competitive Advantage in the International Market: Especially in the European and North American markets, products with sustainability certification are in greater demand and can be sold at higher prices (Tacon & Metian, 2015).

Traceability is Provided: Certification systems increase traceability by recording every stage of the production chain. In this way, consumers can easily see which farm the product was produced on and under what standards (Hatanaka & Busch, 2008; Gulbrandsen, 2010).

7. 3. Certification Process

For a trout farmer looking to become certified, the process typically consists of the following steps:

7.3.a. Preliminary Preparation: The farm is brought into compliance with the criteria of the relevant certification body. This includes reviewing production methods and making necessary changes.

7.3.b. Application: The farm applies to the certification body of its choice.

7.3.c. Audit: Independent auditors make field visits to the farm, evaluate the production process and check compliance with the criteria.

7.4.d. Reporting: As a result of the inspection, a report is prepared and it is decided whether the farm is suitable for the certificate.

7.4.e. Certification: If the farm meets the required criteria, it is eligible to receive a certificate. The certificate is usually valid for a certain period of time and is updated with periodic audits (Cashore, Auld & Newsom, 2003; Gulbrandsen, 2010) .

7. 4. Difficulties of Certification and Solutions

High Cost: The certification process can be costly, especially for small-scale producers, in which case government incentives and support programs may be available.

Complex Processes: Certification procedures can be complex. Manufacturers can overcome these challenges with the right guidance and training, by receiving expert consulting services throughout the process.

Adapting to Standards: Some farms may need to change their current production methods. In this case, the process can be facilitated with gradual transition and training programs.

Certified sustainable production increases environmental and social responsibility awareness in trout farming, provides economic advantages for businesses in the long term and offers a reliable product to consumers. In this way, it contributes to the increase of sustainability standards both in the aquaculture sector and in food production in general (Cashore, Auld & Newsom, 2003; Grant & Shaw, 2019).

7.5. Energy Efficiency and Renewable Energy Use

Energy efficiency and renewable energy use in trout farming are critical to both reduce production costs and environmental impacts. The limited availability of traditional energy sources and increasing environmental pressures encourage innovative energy-saving solutions and the use of renewable energy in aquaculture (Moller & et al., 2023; Vasilenko & et al., 2020).

7.5.1. Energy Efficiency Applications

Energy efficiency aims to achieve the same efficiency by reducing the amount of energy used or to achieve more efficiency with less energy (Austin & et al. 2022; Scroggins & et al., 2022). The following methods can be used to increase energy efficiency in trout farming:

7.5.1.a Use of Energy Efficient Equipment

Low Energy Consumption Pumps: Water pumps used in trout farms consume a large portion of energy. The use of energy efficient pumps saves energy.

Automatic Control Systems: Water temperature, oxygen levels and other parameters are constantly monitored with sensors and automation systems, and equipment is operated when needed. In this way, unnecessary energy consumption is reduced.

LED Lighting: LED lighting consumes less energy and has a longer lifespan than traditional fluorescent or incandescent lighting.

7.5.1.b. Heat Recovery

Heat recovery systems can be installed to maintain the temperature of the water used in recirculating aquaculture systems (Recirculating Aquaculture Systems, RAS). These systems reduce energy needs by stabilizing the temperature of the water (Ebeling &Timmons, 2012).

Heat Pump Usage: Heat pumps are used to heat water by taking low temperature energy from the surroundings. This consumes less energy than electric heaters.

7.5.1.c. Insulation and Energy Management

Tank Insulation: Keeping trout tanks well insulated saves energy by maintaining the temperature of the water.

Energy Management Systems: Systems that continuously monitor and control energy consumption optimize energy use and prevent unnecessary consumption.

7.5.2. Renewable Energy Use

The use of renewable energy sources in trout farming increases environmental sustainability by reducing fossil fuel consumption and provides cost advantages in the long term (Austin & et al. 2022; Majumdar & et al., 2023; Amusa & et al., 2024). Renewable energy sources that can be used in this context are:

7.5.2.a. Solar Energy

Solar Panels: Solar panels can be installed in trout farms to meet the electricity needs. These panels can provide energy especially for pumps, lighting and automation systems (Ghosh & et al., 2020).

Solar Water Heating: Water can be heated using solar collectors. This method helps keep the water temperature at the ideal level while reducing energy costs (Kumar, Shrivastava & Untawale, 2015).

7.5.2.b. Wind Energy

Wind Turbines: Wind energy can be used to meet the energy needs of trout farms. Wind turbines are especially suitable for energy production in open areas and coastal areas (Maimun, Soufaljen & Adibah, 2020).

Hybrid Systems: By using solar and wind energy together, energy production capacity can be increased and energy supply can be made more reliable (Nguyen, Matsuhashi & Vo, 2021).

7.5.2. c. Biogas and Biomass Energy

Energy Production with Waste Management: Organic wastes (fish feces and feed residues) generated in trout farms can be used for biogas production. Biogas systems produce energy by processing these wastes and meet the energy needs of the farms (Kumar & et al., 2019).

Composting and Biomass Energy: Composting organic waste and using it in biomass energy plants contributes to sustainable energy sources (Prüter & et al., 2020).

7.5.2.d. Hydroelectric Energy

Trout farms are usually located in areas close to water sources. Small-scale hydroelectric systems can be used to obtain energy from the power of water flow. These systems can provide energy for the operation of pumps and oxygen generators (Wang & et al., 2024).

7.5.3. Advantages of Energy Saving and Renewable Energy Use

Cost Reduction: In the long run, energy efficient systems and renewable energy investments reduce operating costs.

Reducing Environmental Impacts: Reducing fossil fuel use reduces carbon footprint and greenhouse gas emissions.

Energy Independence: The use of renewable energy sources ensures that farms are not affected by fluctuations in energy prices and increases security of energy supply.

Sustainability Image: Farms that use renewable energy and increase energy efficiency become more attractive to environmentally conscious consumers and provide a marketing advantage (Austin & et al. 2022).

Energy efficiency and renewable energy use in trout farming not only increases environmental sustainability but also supports economic sustainability by reducing operating costs. Therefore, the adoption of innovative technologies and practices is beneficial from both environmental and economic perspectives and is expected to become a standard for future fish farming projects (Kumar, Shrivastava & Untawale, 2015; Moller & et al., 2023).

7.6 Protection of Natural Populations

Fish that escape from aquaculture can interbreed with natural populations, reducing genetic diversity and threatening native species (Pauly & Zeller, 2016).

Escape Prevention Systems: In trout farms, safety nets or barriers are used to prevent fish from escaping into the natural environment.

Supporting Local Species: Projects are developed to protect and support local species in farming regions.

7.7. Environmental Impact Assessment and Monitoring

Continuous monitoring of environmental impacts is necessary for sustainable fish farming. This is important for both environmental protection and production efficiency (Pimentão & et al., 2024).

Regular Environmental Monitoring: Water quality, sediment accumulation and ecosystem health are regularly monitored and necessary measures are taken.

Impact Assessment Reports: Before the cultivation activity begins, environmental impact assessment (EIA) reports are prepared to identify possible environmental risks and plan precautions.

7.8. Waste Management and Recycling

Trout farms can discharge organic wastes and nutrients into the water, which can degrade water quality and cause environmental problems (Soto & et al., 2007; Sosa-Villalobos & et al., 2016).

Biofiltration: Biological filter systems can be used to filter wastewater. These filters purify the water from organic waste and make it reusable.

Recycling of Waste: Organic waste can be used as agricultural fertilizer. Also, fish waste can be evaluated in the production of fish oil and fish meal.

Composting: Composting of fish feces and feed waste supports the production of organic fertilizer.

8. Conclusion and Recommendation

Trout farming is of great importance both economically and as a source of food. However, various threats such as diseases, environmental factors and nutritional deficiencies jeopardize the sustainability of this sector. In this study, the basic elements in the trout production and farming process were examined and recommendations were made on disease management.

Studies have shown that water quality, hygienic conditions and stress management are critical for the healthy rearing of trout. Water quality is an important factor that directly affects the growth rate and immune system of trout. Regular monitoring of parameters such as water temperature, pH and oxygen levels helps prevent diseases. It has also been observed that excessive stocking density and poor hygienic conditions lead to the spread of diseases.

Bacterial, viral and parasitic diseases cause significant losses in trout farming. Early detection of disease symptoms and rapid intervention are vital to minimizing losses. It is emphasized that antibiotics, vaccination and chemical treatment methods should be used carefully. Vaccination is considered an effective method in preventing viral diseases. In addition, research into alternative treatment methods can improve the health status of trout.

As a result, it is recommended to adopt an integrated approach for sustainable production in trout farming. Regular monitoring of water quality, ensuring hygienic conditions and preventing diseases will increase success in trout farming. In the future, biotechnological developments and research into natural treatment methods, breeding studies in production and obtaining fast-growing generations resistant to diseases may offer new opportunities in disease management in trout farming. In addition, training programs and information sharing for farmers will contribute to increasing awareness in the sector.

References

Aas, T. S., Grisdale-Helland, B., Terjesen, B. F., & Helland, S. J. (2006). Improved growth and nutrient utilisation in Atlantic salmon (Salmo salar) fed diets containing a bacterial protein meal. Aquaculture, 259(1-4), 365-376.

Alfred, O., Shaahu, A., Orban, D. A., & Egwenomhe, M. (2020). An overview on understanding the basic concept of fish diseases in aquaculture. IRE J, 4, 83-91.

Alhazzaa, R., Nichols, P. D., & Carter, C. G. (2019). Sustainable alternatives to dietary fish oil in tropical fish aquaculture. Reviews in Aquaculture, 11(4), 1195-1218.

Amusa, A. A., Johari, A., Jalil, A. A., Abdullah, T. A. T., Adeleke, A. O., Katibi, K. K., ... & Alhassan, M. (2024). Sustainable electricity generation and farm-grid utilization from photovoltaic aquaculture: a bibliometric analysis. International Journal of Environmental Science and Technology, 21(11), 7797-7818.

Anyango, B., Hou, V., Xu, H., Wu, X., Zhang, W., Zhou, L., & Thay, S. Investigating the Resistance of Rice-Field Fisheries to Transition into Rice-Fish Farming and Pond Aquaculture in Cambodia. Available at SSRN 5005875.

Aquaculture Stewardship Council. (2023). ASC trout standard: Version 1.3. Aquaculture Stewardship Council.

Asche, F., Cojocaru, A. L., & Roth, B. (2018). The development of large scale aquaculture production: A comparison of the supply chains for chicken and salmon. Aquaculture, 493, 446-455.

Ashley, P. J. (2007). Fish welfare: current issues in aquaculture. Applied Animal Behaviour Science, 104(3-4), 199-235.

Austin, B. (2007). Bacterial Fish Pathogens: Disease in Farmed and Wild Fish. Springer.

Austin, B. (2011). Taxonomy of bacterial fish pathogens. Veterinary research, 42, 1-13.

Austin, B. (2023). The impact of disease on the sustainability of aquaculture. Sustainable Aquatic Research, 2(1), 74-91.

Austin, B., & Austin, D. A. (2016). Bacterial fish pathogens: disease of farmed and wild fish. Springer.

Austin, B., Lawrence, A., Can, E., Carboni, C., Crockett, J., Demirtas, N., ... & Gier, G. Y. (2022). Selected topics in sustainable aquaculture research: Current and future focus. Sustainable Aquatic Research, 1(2), 74-125.

Bakke, T. A., Harris, P. D., & Cable, J. (2002). Host specificity dynamics: observations on gyrodactylid monogeneans. International journal for parasitology, 32(3), 281-308.

Bartley, D. M. (2022). World Aquaculture 2020–A brief overview.

Barton, B. A. (2002). Stress in fishes: a diversity of responses with particular reference to changes in circulating corticosteroids. Integrative and comparative biology, 42(3), 517-525.

Becke, C., Schumann, M., Steinhagen, D., Rojas-Tirado, P., Geist, J., & Brinker, A. (2019). Effects of unionized ammonia and suspended solids on rainbow trout (Oncorhynchus mykiss) in recirculating aquaculture systems. Aquaculture, 499, 348-357.

Bergmann, S. M., & Fichtner, D. (2008). Diseases caused by virus: Viral Diseases in Salmonids. In Fish Diseases (2 Vols.) (pp. 55-100). CRC Press.

Beveridge, M. C., & Brummett, R. E. (2015). Aquaculture and the environment. Freshwater fisheries ecology, 794-803.

Bhatnagar, A., & Devi, P. (2013). Water quality guidelines for the management of pond fish culture. International journal of environmental sciences, 3(6), 1980-2009.

Bjørhusdal, V., & Haugen, S. (2023). Circular Economy Implications for Sustainable Supply Chain Practices: Comparative case study within the Norwegian fish farming industry (Master's thesis, Høgskolen i Molde-Vitenskapelig høgskole i logistikk).

Boyd, C. E., & Tucker, C. S. (2012). Pond aquaculture water quality management. Springer Science & Business Media.

Bruno, D. W., West, P. V., & Beakes, G. W. (2011). Saprolegnia and other oomycetes. In Fish diseases and disorders. Volume 3: viral, bacterial and fungal infections (pp. 669-720). Wallingford UK: Cabi.

Buller, N. B. (2014). Bacteria and fungi from fish and other aquatic animals: a practical identification manual. Cabi.

Bush, S. R., Belton, B., Hall, D., Vandergeest, P., Murray, F. J., Ponte, S., ... & Kusumawati, R. (2013). Certify sustainable aquaculture?. Science, 341(6150), 1067-1068.

Can, E., Austin, B., Steinberg, C., Carboni, C., Sağlam, N., Thompson, K., ... & Ergün, S. (2023). Best practices for fish biosecurity, well-being and sustainable aquaculture. Sustainable Aquatic Research, 2(3).

Cardinaletti, G., Di Marco, P., Daniso, E., Messina, M., Donadelli, V., Finoia, M. G., ... & Tibaldi, E. (2022). Growth and welfare of rainbow trout (Oncorhynchus mykiss) in response to graded levels of insect and poultry by-product meals in fishmeal-free diets. Animals, 12(13), 1698.

Carter, C. G., & Codabaccus, M. B. (2022). Feeding in hatcheries. In Feed and feeding practices in aquaculture (pp. 355-398). Woodhead Publishing.

Cascarano, M. C., Stavrakidis-Zachou, O., Mladineo, I., Thompson, K. D., Papandroulakis, N., & Katharios, P. (2021). Mediterranean aquaculture in a changing climate: Temperature effects on pathogens and diseases of three farmed fish species. Pathogens, 10(9), 1205.

Cashore, B., Auld, G., & Newsom, D. (2003). The United States' race to certify sustainable forestry: Non-state environmental governance and the competition for policy-making authority. Business and Politics, 5(3), 219-259.

Chen, S., Ling, J., & Blancheton, J. P. (2006). Nitrification kinetics of biofilm as affected by water quality factors. Aquacultural engineering, 34(3), 179-197.

Collins, A. L., Price, J. N., Zhang, Y., Gooday, R., Naden, P. S., & Skirvin, D. (2018). Assessing the potential impacts of a revised set of on-farm nutrient and sediment ‘basic’control measures for reducing agricultural diffuse pollution across England. Science of the Total Environment, 621, 1499-1511.

Dey, A., & Thomson, R. C. (2023). The biomethane generation potential of wastes and wastewaters from the sericulture, fisheries, and agro-industrial sectors in India. Energy for Sustainable Development, 75, 40-59.

Dey, M. M. (2008). Strategies and options for increasing and sustaining fisheries and aquaculture production to benefit poorer households in Asia (Vol. 1823). WorldFish.

Dias, J., Muñoz, J., Huisman, J., & McDonald, J. (2015). Biosecurity monitoring of Harmful Algal Bloom (HAB) species in Western Australian waters: first confirmed record of Alexandrium catenella (Dinophyceae). BioInvasions Records, 4(4), 233-241.

Doğan, M. (2024). Viral Diseases in Trout and Treatment Methods. Cumhuriyet Üniversitesi Sağlık Bilimleri Enstitüsü Dergisi, 9(2), 267-270.

Dolores-Salinas, E., & Miret-Pastor, L. (2024). Environmental certifications in Brazilian aquaculture. Aquaculture International, 1-22.

Dorson, M., & Torhy, C. (1993). Viral haemorrhagic septicaemia virus replication in external tissue excised from rainbow trout, Oncorhynchus mykiss (Walbaum), and hybrids of different susceptibilities. Journal of Fish Diseases, 16(4).

Drew, M. D., Ogunkoya, A. E., Janz, D. M., & Van Kessel, A. G. (2007). Dietary influence of replacing fish meal and oil with canola protein concentrate and vegetable oils on growth performance, fatty acid composition and organochlorine residues in rainbow trout (Oncorhynchus mykiss). Aquaculture, 267(1-4), 260-268.

Dumas, A., France, J., & Bureau, D. (2010). Modelling growth and body composition in fish nutrition: where have we been and where are we going?. Aquaculture Research, 41(2), 161-181.

Ebeling, J. M., & Timmons, M. B. (2012). Recirculating aquaculture systems. Aquaculture production systems, 245-277.

Eya, J. C., Yossa, R., Ashame, M. F., Pomeroy, C. F., & Gannam, A. L. (2013). Effects of dietary lipid levels on growth, feed utilization and mitochondrial function in low-and high-feed efficient families of rainbow trout (Oncorhynchus mykiss). Aquaculture, 416, 119-128.

Faruk, M. A. R. (2018). Fish parasite: infectious diseases associated with fish parasite. In Seafood Safety and Quality (pp. 154-176). CRC Press.

Ferreira, J. G., Taylor, N. G., Cubillo, A., Lencart-Silva, J., Pastres, R., Bergh, Ø., & Guilder, J. (2021). An integrated model for aquaculture production, pathogen interaction, and environmental effects. Aquaculture, 536, 736438.

Fiorile, G., Puleo, S., Colonna, F., Mincione, S., Masi, P., Herranz Solana, N., & Di Monaco, R. (2023). Consumers' awareness of fish traceability and sustainability: an exploratory study in Italy and Spain. Sustainability, 15(19), 14103.

Food and Agriculture Organization (FAO). (2023). The state of world fisheries and aquaculture 2022: Towards blue transformation. Food and Agriculture Organization of the United Nations. https://doi.org/10.4060/cc0461en

Froehlich, H. E., Gentry, R. R., & Halpern, B. S. (2017). Conservation aquaculture: Shifting the narrative and paradigm of aquaculture's role in resource management. Biological conservation, 215, 162-168.

Fujimoto, K., Yamamoto, T., Sudo, M., Haga, Y., Kurata, M., Okada, T., ... & Kumai, H. (2008). Neutral lipid deposition in larval and juvenile Pacific bluefin tuna, Thunnus orientalis, under different rearing temperatures. Aquaculture Science, 56(1), 19-30.

Garver, K., Wade, J., & Canadian Science Advisory Secretariat. (2017). Characterization of infectious hematopoietic necrosis virus (IHNV) (pp. vi+-2032). Canadian Science Advisory Secretariat (CSAS).

Gentry, R. R., Alleway, H. K., Bishop, M. J., Gillies, C. L., Waters, T., & Jones, R. (2020). Exploring the potential for marine aquaculture to contribute to ecosystem services. Reviews in Aquaculture, 12(2), 499-512.

Ghosh, A., Misra, S., Bhattacharyya, R., Sarkar, A., Singh, A. K., Tyagi, V. C., ... & Meena, V. S. (2020). Agriculture, dairy and fishery farming practices and greenhouse gas emission footprint: a strategic appraisal for mitigation. Environmental Science and Pollution Research, 27, 10160-10184.

Gjedrem, T., & Baranski, M. (2010). Selective breeding in aquaculture: an introduction (Vol. 10). Springer Science & Business Media.

Grant, D. B., & Shaw, S. (2019). Environmental or sustainable supply chain performance measurement standards and certifications. In Handbook on the Sustainable Supply Chain (pp. 357-376). Edward Elgar Publishing.

Gulbrandsen, L. H. (2010). Transnational environmental governance: the emergence and effects of the certification of forest and fisheries. Edward Elgar Publishing.

Handeland, S. O., Imsland, A. K., Ebbesson, L. O., Nilsen, T. O., Hosfeld, C. D., Baeverfjord, G., ... & Stefansson, S. O. (2013). Low light intensity can reduce Atlantic salmon smolt quality. Aquaculture, 384, 19-24.

Hatanaka, M., & Busch, L. (2008). Third-party certification in the global agrifood system: an objective or socially mediated governance mechanism?. Sociologia ruralis, 48(1), 73-91.

Hedrick, R. P., Batts, W. N., Yun, S., Traxler, G. S., Kaufman, J., & Winton, J. R. (2003). Host and geographic range extensions of the North American strain of viral hemorrhagic septicemia virus. Diseases of aquatic organisms, 55(3), 211-220.

Hernández-Contreras, Á., Teles, A., Salas-Leiva, J. S., Chaves-Pozo, E., & Tovar-Ramírez, D. (2023). Feed Additives in Aquaculture. In Sustainable Use of Feed Additives in Livestock: Novel Ways for Animal Production (pp. 811-846). Cham: Springer International Publishing.

http://beyazgazete.com/video/webtv/ekonomi-2/muglada-yetistirilen-alabaliga-yabanci-ilgisi-627928.html

Huyben, D., Vidakovic, A., Sundh, H., Sundell, K., Kiessling, A., & Lundh, T. (2019). Haematological and intestinal health parameters of rainbow trout are influenced by dietary live yeast and increased water temperature. Fish & Shellfish Immunology, 89, 525-536.

Jobling, M. (2012). Fish in aquaculture environments. Aquaculture and Behavior, 36-64.

Johnson, M. A., Noakes, D. L., Friesen, T. A., Dittman, A. H., Couture, R. B., Schreck, C. B., ... & Quinn, T. P. (2019). Growth, survivorship, and juvenile physiology of triploid steelhead (Oncorhynchus mykiss). Fisheries Research, 220, 105350.

Kamalam, B. S., Rajesh, M., & Kaushik, S. (2020). Nutrition and Feeding of Rainbow Trout (Oncorhynchusmykiss). In Fish nutrition and its relevance to human health (pp. 299-332). CRC Press.

Kiron, V., Kathiresan, P., Fernandes, J. M., Sørensen, M., Vasanth, G. K., Lin, Q., ... & Trichet, V. V. (2022). Clues from the intestinal mucus proteome of Atlantic salmon to counter inflammation. Journal of Proteomics, 255, 104487.

Krogdahl, Å., Dhanasiri, A. K., Krasnov, A., Aru, V., Chikwati, E. M., Berge, G. M., ... & Kortner, T. M. (2023). Effects of functional ingredients on gut inflammation in Atlantic salmon (Salmo salar L). Fish & Shellfish Immunology, 134, 108618.

Kumar Srivastava, P., Singh, R. K., Tiwari, A., & Tiwari, G. N. (2024). Thermal modeling of greenhouse integrated semi-transparent photovoltaic thermal (GiSPVT) for sustainable aquaculture production: an experimental validation. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, 46(1), 2436-2447.

Kumar, P., Prajapati, S. K., Malik, A., & Vijay, V. K. (2019). Evaluation of biomethane potential of waste algal biomass collected from eutrophied lake: effect of source of inocula, co-substrate, and VS loading. Journal of Applied Phycology, 31, 533-545.

Kumar, V., Roy, S., Behera, B. K., & Das, B. K. (2022). Disease diagnostic tools for health management in Aquaculture. In Advances in Fisheries Biotechnology (pp. 363-382). Singapore: Springer Nature Singapore.

Kumar, V., Shrivastava, R. L., & Untawale, S. P. (2015). Solar energy: review of potential green & clean energy for coastal and offshore applications. Aquatic Procedia, 4, 473-480.

Linder, C. M., Cole, R. A., Hoffnagle, T. L., Persons, B., Choudhury, A., Haro, R., & Sterner, M. (2012). Parasites of fishes in the Colorado River and selected tributaries in Grand Canyon, Arizona. Journal of Parasitology, 98(1), 117-127.

Liu, Y., Rosten, T. W., Henriksen, K., Hognes, E. S., Summerfelt, S., & Vinci, B. (2016). Comparative economic performance and carbon footprint of two farming models for producing Atlantic salmon (Salmo salar): Land-based closed containment system in freshwater and open net pen in seawater. Aquacultural Engineering, 71, 1-12.

Maimun, A., Soufaljen, A. S., & Adibah, A. (2020). Fish farm electrification utilising a hybrid device of low-speed vertical axis turbine and solar panels. In IOP conference series: materials science and engineering (Vol. 884, No. 1, p. 012072). IOP Publishing.

Majumdar, B. C., Ahammad, B., Kabir, I. E., Mollik, J. R., Baidya, A., Hossain, M. F., ... & Paul, S. I. (2023). Sensorial, physicochemical and microbial quality evaluations of sun-dried marine fishes available in the Bay of Bengal of Bangladesh. Applied Food Research, 3(2), 100369.

Mavraganis, T., Constantina, C., Kolygas, M., Vidalis, K., & Nathanailides, C. (2020). Environmental issues of Aquaculture development. Egyptian Journal of Aquatic Biology and Fisheries, 24(2), 441-450.

McEwin, A., & McNally, R. (2014). Organic Shrimp certification and carbon financing: an assessment for the mangroves and markets project in Ca Mau Province, Vietnam. REAP Project. GiZ, SNV. 81pp.

McLean, E., Alfrey, K. B., Gatlin III, D. M., Gaylord, T. G., & Barrows, F. T. (2022). Muscle amino acid profiles of eleven species of aquacultured animals and their potential value in feed formulation. Aquaculture and Fisheries.

Midilli, A., Kucuk, H., & Dincer, I. (2012). Environmental and sustainability aspects of a recirculating aquaculture system. Environmental Progress & Sustainable Energy, 31(4), 604-611.

Miranda, C. D., Godoy, F. A., & Lee, M. R. (2018). Current status of the use of antibiotics and the antimicrobial resistance in the Chilean salmon farms. Frontiers in microbiology, 9, 1284.

Mohan, C. V. (2007). 8.1 Seed quality in freshwater fish production. Assessment of freshwater fish seed resources for sustainable aquaculture, 499.

Moller, K., Eeswaran, R., Nejadhashemi, A. P., & Hernandez-Suarez, J. S. (2023). Livestock and aquaculture farming in Bangladesh: Current and future challenges and opportunities. Cogent Food & Agriculture, 9(1), 2241274.

Murray, A. G., & Peeler, E. J. (2005). A framework for understanding the potential for emerging diseases in aquaculture. Preventive veterinary medicine, 67(2-3), 223-235.

Nasopoulou, C., Gogaki, V., Stamatakis, G., Papaharisis, L., Demopoulos, C. A., & Zabetakis, I. (2013). Evaluation of the in vitro anti-atherogenic properties of lipid fractions of olive pomace, olive pomace enriched fish feed and gilthead sea bream (Sparus aurata) fed with olive pomace enriched fish feed. Marine drugs, 11(10), 3676-3688.

Naylor, R. L., Goldburg, R. J., Primavera, J. H., Kautsky, N., Beveridge, M. C., Clay, J., ... & Troell, M. (2000). Effect of aquaculture on world fish supplies. Nature, 405(6790), 1017-1024.

Naylor, R. L., Hardy, R. W., Buschmann, A. H., Bush, S. R., Cao, L., Klinger, D. H., ... & Troell, M. (2021). A 20-year retrospective review of global aquaculture. Nature, 591(7851), 551-563.

Nguyen, L., Dinh, H., & Davis, D. A. (2020). Efficacy of reduced protein diets and the effects of indispensable amino acid supplements for Nile tilapia Oreochromis niloticus. Animal Feed Science and Technology, 268, 114593.

Nguyen, N. T., Matsuhashi, R., & Vo, T. T. B. C. (2021). A design on sustainable hybrid energy systems by multi-objective optimization for aquaculture industry. Renewable Energy, 163, 1878-1894.

Noga, E. J. (2010). Fish disease: diagnosis and treatment. John Wiley & Sons.

Ohtani, M., Villumsen, K. R., Strøm, H. K., Lauritsen, A. H., Aalbæk, B., Dalsgaard, I., ... & Bojesen, A. M. (2019). Effects of fish size and route of infection on virulence of a Danish Yersinia ruckeri O1 biotype 2 strain in rainbow trout (Oncorhynchus mykiss). Aquaculture, 503, 519-526.

Pauly, D., & Zeller, D. (2016). Catch reconstructions reveal that global marine fisheries catches are higher than reported and declining. Nature communications, 7(1), 10244.

Pillai, B. R., Lalrinsanga, P. L., Ponzoni, R. W., Khaw, H. L., Mahapatra, K. D., Sahu, S., ... & Pradhan, H. (2020). Selective breeding of giant freshwater prawn (Macrobrachium rosenbergii) in India: Response to selection for harvest body weight and on-farm performance evaluation. Aquaculture Research, 51(12), 4874-4880.

Pillay, T. V. R., & Kutty, M. N. (2005). Aquaculture: principles and practices.

Pimentão, A. R., Cuco, A. P., Pascoal, C., Cássio, F., & Castro, B. B. (2024). Current trends and mismatches on fungicide use and assessment of the ecological effects in freshwater ecosystems. Environmental Pollution, 123678.

Ponte, S. (2012). The Marine Stewardship Council (MSC) and the making of a market for 'sustainable fish'. Journal of Agrarian change, 12(2-3), 300-315.

Potts, T., & Haward, M. (2007). International trade, eco-labelling, and sustainable fisheries–recent issues, concepts and practices. Environment, Development and Sustainability, 9(1), 91-106.

Prüter, J., Strauch, S. M., Wenzel, L. C., Klysubun, W., Palm, H. W., & Leinweber, P. (2020). Organic matter composition and phosphorus speciation of solid waste from an African catfish recirculating aquaculture system. Agriculture, 10(10), 466.

Pullin, R. S., Froese, R., & Pauly, D. (2007). Indicators for the sustainability of aquaculture. In Ecological and genetic implications of aquaculture activities (pp. 53-72). Dordrecht: Springer Netherlands.

Rathor, G. S., & Swain, B. (2024). Advancements in Fish Vaccination: Current Innovations and Future Horizons in Aquaculture Health Management. Applied Sciences, 14(13), 5672.

Rathor, G. S., & Swain, B. (2024). Advancements in Fish Vaccination: Current Innovations and Future Horizons in Aquaculture Health Management. Applied Sciences, 14(13), 5672.

Ringø, E., Olsen, R. E., Jensen, I., Romero, J., & Lauzon, H. L. (2014). Application of vaccines and dietary supplements in aquaculture: possibilities and challenges. Reviews in Fish Biology and Fisheries, 24, 1005-1032.

Roberts, R. J. (2012). Fish pathology. John Wiley & Sons.

Roberts, R. J., Frerichs, G. N., Tonguthai, K., & Chinabut, S. (2006). DNA vaccination and prophylactic measures in aquaculture health management. Poor farmers culture tilapia intensively in Philippines, 21.

Ruzzante, D. E., Hansen, M. M., Meldrup, D., & Ebert, K. M. (2004). Stocking impact and migration pattern in an anadromous brown trout (Salmo trutta) complex: where have all the stocked spawning sea trout gone?. Molecular Ecology, 13(6), 1433-1445.

Saha, C. K. (2024). Governing sociocultural sustainability through standards: Evidence from aquaculture eco-certification schemes. Aquaculture, 578, 740011.

Satpathy, B. B., Mukherjee, D., & Ray, A. K. (2003). Effects of dietary protein and lipid levels on growth, feed conversion and body composition in rohu, Labeo rohita (Hamilton), fingerlings. Aquaculture Nutrition, 9(1), 17-24.

Schaltegger, S., Lüdeke-Freund, F., & Hansen, E. G. (2012). Business cases for sustainability: the role of business model innovation for corporate sustainability. International journal of innovation and sustainable development, 6(2), 95-119.

Scroggins, R. E., Fry, J. P., Brown, M. T., Neff, R. A., Asche, F., Anderson, J. L., & Love, D. C. (2022). Renewable energy in fisheries and aquaculture: Case studies from the United States. Journal of Cleaner Production, 376, 134153.

Sihag, R. C., & Sharma, P. (2012). Probiotics: the new ecofriendly alternative measures of disease control for sustainable aquaculture. Journal of Fisheries and Aquatic Science, 7(2), 72-103.

Smith, M. D. (2023). Economics of Aquatic Foods: Combining Bioeconomics and Market Analysis to Inform Regulations That Deliver Value. Marine Resource Economics, 38(4), 305-327.

Soler, P., Faria, M., Barata, C., García-Galea, E., Lorente, B., & Vinyoles, D. (2021). Improving water quality does not guarantee fish health: Effects of ammonia pollution on the behaviour of wild-caught pre-exposed fish. PLoS One, 16(8), e0243404.

Soto, D., Aguilar-Manjarrez, J., Brugère, C., Angel, D., Bailey, C., Black, K., ... & Wainberg, A. (2007). Applying an ecosystem-based approach to aquaculture: principles, scales and some management measures. In Building an ecosystem approach to aquaculture. FAO/Universitat de les Illes Balears Expert Workshop (Vol. 7, p. e11).

Subasinghe, R., Soto, D., & Jia, J. (2009). Global aquaculture and its role in sustainable development. Reviews in aquaculture, 1(1), 2-9.

Tacon, A. G., & Metian, M. (2009). Fishing for feed or fishing for food: increasing global competition for small pelagic forage fish. Ambio, 294-302.

Tacon, A. G., & Metian, M. (2015). Feed matters: satisfying the feed demand of aquaculture. Reviews in Fisheries Science & Aquaculture, 23(1), 1-10.

Taranger, G. L., Carrillo, M., Schulz, R. W., Fontaine, P., Zanuy, S., Felip, A., ... & Hansen, T. (2010). Control of puberty in farmed fish. General and comparative endocrinology, 165(3), 483-515.

Sosa-Villalobos, C., del Refugio Castañeda-Chávez, M., Amaro-Espejo, I. A., Galaviz-Villa, I., & Lango-Reynoso, F. (2016). Diagnosis of the current state of aquaculture production systems with regard to the environment in Mexico. Latin American Journal of Aquatic Research, 44(2), 193-201.

Timmons, M. B. (2002). Recirculating aquaculture systems.

Torrecillas, S., Montero, D., Carvalho, M., Benitez-Santana, T., & Izquierdo, M. (2021). Replacement of fish meal by Antarctic krill meal in diets for European sea bass Dicentrarchus labrax: Growth performance, feed utilization and liver lipid metabolism. Aquaculture, 545, 737166.

Torrissen, O., Jones, S., Asche, F., Guttormsen, A., Skilbrei, O. T., Nilsen, F., ... & Jackson, D. (2013). Salmon lice–impact on wild salmonids and salmon aquaculture. Journal of fish diseases, 36(3), 171-194.

Trung, T. S., Tran, H. V., Le, M. H., Ky, P. X., Brown, P. B., & Van Ngo, M. (2022). Growth performance, haematological parameters and proximate composition of rainbow trout Oncorhynchus mykiss fed varying dietary levels of protein hydrolysate from heads of Penaeus monodon shrimp processing industry. Regional Studies in Marine Science, 55, 102643.

Turkish Statistical Institute (TUIK). (2023). Fisheries, production and consumption report. Turkish Statistical. Institute. https://www.tuik.gov.tr

Vasilenko, V. N., Frolova, L. N., Dragan, I. V., Mihajlova, N. A., & Zhiltsova, S. I. (2020). Development of industrial feed for channel catfish grown in the Central Federal District of the Russian Federation. Вестник Воронежского государственного университета инженерных технологий, 82(4 (86)), 132-136.

Wagner, B. A., Wise, D. J., Khoo, L. H., & Terhune, J. S. (2002). The epidemiology of bacterial diseases in food-size channel catfish. Journal of Aquatic Animal Health, 14(4), 263-272.

Wang, Y., Zhu, Y., Wang, K., Tan, Y., Bing, X., Jiang, J., ... & Liao, H. (2024). Principles and research progress of physical prevention and control technologies for algae in eutrophic water. Iscience.

Wedemeyer, G. A., & Wydoski, R. S. (2008). Physiological response of some economically important freshwater salmonids to catch-and-release fishing. North American Journal of Fisheries Management, 28(5), 1587-1596.

Willoughby, L. G. (1994). Fungi and fish diseases (pp. 57-pp).

Woo, P. T. K. (2006). Vol. 1: Protozoan and metazoan infections. Wallingford [etc.]: CABI.

Wright, A., Li, X., Yang, X., Soto, E., & Gross, J. (2023). Disease prevention and mitigation in US finfish aquaculture: A review of current approaches and new strategies. Reviews in Aquaculture, 15(4), 1638-1653.

Wurts, W. A. (2000). Sustainable aquaculture in the twenty-first century. Reviews in fisheries science, 8(2), 141-150.

Zhang, X., Spanjers, H., & van Lier, J. B. (2013). Potentials and limitations of biomethane and phosphorus recovery from sludges of brackish/marine aquaculture recirculation systems: A review. Journal of environmental management, 131, 44-54.

CHAPTER III

Disinfection of Fish Eggs with Medicinal Aromatic Plants: Present and Future Focus

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1. Introduction

In the field of aquaculture, the health of fish eggs is the basis of successful fish farming. Traditional disinfection methods using chemical agents negatively affect the environment and cause pathogens to develop resistance to drugs (Semple & Dixon, 2020). There are many studies on the use of various aromatic plant extracts in disinfecting fish eggs and preventing the growth of pathogenic

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microorganisms. Medicinal aromatic plants, rich in bioactive compounds, can be considered as a promising alternative with their strong antimicrobial, antifungal and antiparasitic properties (Dawood & et al.,2021).

Fish farming is a rapidly growing sector worldwide, and aquaculture products contribute significantly to people's access to healthy food by increasing supply and demand (FAO, 2018). One of the most important elements of production is the health of fish eggs. Microbial contamination of fish eggs, especially during the incubation period, can cause serious problems. Bacteria and fungi that develop on the surface of fish eggs can negatively affect hatching success and cause hatchling deaths. Egg disinfection has also become mandatory to reduce the transmission of pathogenic microorganisms to other farms via eggs (Can, Saka & Fırat, 2010; Can & et al., 2012). Fungi such as Saprolegnia are among the common pathogens that cause significant losses in fish eggs. Traditional disinfection methods usually include chemicals such as formalin, iodine and hydrogen peroxide; however, these substances can cause environmental damage and human health risks (Pirbalouti & et al., 2009). Therefore, medicinal aromatic plants and essential oils are attracting attention as environmentally friendly disinfectant alternatives (Austin & Austin, 2016; Austin & et al., 2022; Meneses & et al., 2022).

Aromatic plants contain essential oils with antimicrobial, antifungal and antioxidant properties (Can & et al., 2023). These oils are part of the defense mechanisms of plants and are effective against microorganisms. Bioactive compounds such as thymol, carvacrol and eugenol can prevent the growth of many microorganisms. In particular, plants such as thyme (*Origanum vulgare*), tea tree (*Melaleuca alternifolia*), garlic extract (*Allium sativum*) and mint (*Mentha piperita*) stand out with their antimicrobial effects (Amiri & Meshkini, 2019; Fierascu & et al., 2021). Studies in this field show that medicinal aromatic plants and essential oils are effective in the disinfection of fish eggs **(**Khemis & et al., 2016, Doğan, 2024). With a particular focus on the use of medicinal aromatic plants, interest in the research of alternative, environmentally friendly approaches to the preservation of fish eggs is increasing day by day.

The aim of this study was to evaluate the antimicrobial effects of these natural compounds in egg disinfection and to reveal their application potential by reviewing the literature on the use of essential oils of medicinal and aromatic plants in the disinfection of fish eggs.

2. Medicinal plants used in fish egg disinfection

2.1. Hops (*Humulus lupulus*)

Hops (*H. lupulus* L.) is a perennial plant native to temperate climates in the Northern Hemisphere. Although primarily known as one of the four ingredients needed to make beer, hops were originally used as a medicinal plant (Barnes & et al., 2012). Almost all parts of the plant are rich in bioactive compounds. The powerful antimicrobial, antioxidant, and antifungal properties of its bitter acids and flavonoids, combined with the increasing interest in natural health-promoting substances, offer new and intriguing perspectives (Good & et al., 2020).

2.2. Calendula (Calendula officinalis)

Disinfection of fish eggs is important for the prevention of aquatic animal diseases and the healthy development of fry. Different chemical and herbal disinfectants are used to prevent eggs from becoming infected (Syahidah & et al., 2015). Generally, chemicals such as formalin, iodophors and chlorine are widely used to disinfect fish eggs. However, excessive use of these chemicals can have negative effects on aquatic ecosystems. Therefore, natural disinfectants, especially herbal ingredients, come to the fore. Many studies show that Calendula has low toxicity and successfully kills pathogens in fish eggs (Singh, Bhandari & Timalsina, 2021). The use of this plant offers both an environmentally friendly solution and protects egg health without creating harmful effects on fish. These completely natural and easily available plants are recommended for the disinfection of trout eggs (Nazımoğulları & Yanık, 2024).

2.3. Eucalyptus (Eucalyptus globulus)

Eucalyptus oil, known for its antimicrobial properties, has been investigated as a potential disinfectant in aquaculture, including its use in fish farming (Souza & et al., 2019). It has been proposed as an alternative to chemical disinfectants to prevent fungal and bacterial infections, especially in species such as rainbow trout (*Oncorhynchus mykiss)*. Studies have shown that eucalyptus oil can effectively inhibit certain pathogens, but its use should be carefully controlled to avoid toxicity in aquatic environments. Although the oil of this plant has been shown to have promising potential, further research is required to determine optimum dosages and evaluate its long-term effects on fish health (Ghiasi & et al., 2022).

2.4. Laurel (Laurus nobilis)

Laurel (*Laurus nobilis*) plant has been traditionally investigated for use in fish egg disinfection. Extracts obtained from laurel leaves have antifungal and antibacterial properties and can inhibit the growth of pathogenic microorganisms in fish eggs. This plant is among the natural disinfectants recommended especially to prevent fungal infections. Studies show that laurel extracts can support the healthy development of fish eggs and can be used as an alternative to chemical disinfectants (Özdemir, Taştan & Güney, 2022; Swamy & et al., 2023).

2.5. Thyme (Origanum onites)

Origanum onites (thyme) is used as an effective natural disinfectant in fish egg disinfection. The essential oil obtained from this plant has antibacterial, antifungal and antimicrobial properties and is especially useful in preventing fungal infections (Mabrok & Wahdan, 2018: Yılmaz, Taşbozan & Erbaş, 2018). Studies show that *Origanum onites* oil can support the healthy development of fish eggs and can be applied as an alternative to chemical disinfectants. In particular, *Origanum onites* essential oil prevents the growth of pathogens in fish eggs, contributing to higher fertilization rates of eggs (Rashidian & et al., 2021).

2.6. Onion (*Allium cepa*)

Onion (*Allium cepa*) extracts are being investigated as a potential natural alternative for fish egg disinfection. Onion exhibits antibacterial, antifungal and antiviral effects thanks to the sulfur compounds and organosulfides it contains (Reda & et al., 2024). Studies show that onion extracts can inhibit the development of pathogens in fish eggs and support healthy embryo development of eggs. In addition, onion extract promotes sustainable fish farming practices by offering an environmentally friendly alternative to chemical disinfectants (Özçelik & et al., 2020; Zamini & et al., 2023). Therefore, *Allium cepa* can be used as a natural disinfectant and can help avoid the harmful effects of chemical substances, especially in aquatic environments (Elgendy & et al., 2023).

2.7. Yarpa (Achillea officinolis)

Achillea officinalis (Yarpa) is another plant that has the potential to be used as an effective natural disinfectant in fish egg disinfection. *Achillea officinalis* has antibacterial, antifungal and antioxidant properties thanks to the flavonoids, tannins and essential oils it contains (Miliauskas & et al., 2004). Studies show that this plant can help prevent fungal infections and other microbial contamination by inhibiting the growth of pathogenic microorganisms in fish eggs. In addition, the use of *Achillea officinalis* offers an alternative approach for an environmentally friendly and sustainable fish farming practice (Amiri & Meshkini, 2019; Masigol, Mostowfizadeh-Ghalamfarsa & Grossart, 2021).

2.8. Chamomile (Matricaria chamomilla)

Matricaria chamomilla, namely the chamomile plant, is being investigated as an alternative disinfectant in the field of aquaculture. Chamomile is a herbal product that is being studied as an alternative to traditional chemical disinfectants due to its natural antimicrobial properties. The antimicrobial components of extracts obtained from the flowers of *Matricaria chamomilla* offer a potential natural solution for the disinfection of fish eggs (Das & et al., 2019; Larcombe & et al., 2024). Considering the environmental and biological side effects of disinfection with chemicals in particular, the use of herbal disinfectants to ensure biological safety is gaining importance (Salehi, Soltani & Islami, 2015). Studies show that chamomile extract has an effective antimicrobial effect against pathogenic bacteria and can be used as an environmentally friendly method for the protection of eggs. However, further research is required to determine an effective usage dose and to understand the long-term effects of herbal compounds on fish embryos.

2.9. Tea Tree Oil (Melaleuca alternifolia),

Tea tree (*Melaleuca alternifolia*) is a plant native to Australia and is known for its medicinal properties. Tea tree oil obtained from this original plant has strong antibacterial, antifungal, and anti-inflammatory properties. It has been traditionally used for skin diseases, wound care, and fungal treatments. Tea tree oil, which is widely used in cosmetic and pharmaceutical products today, also stands out as a natural disinfectant (Carson, Hammer & Riley, 2006; Brun & et al., 2019). In recent studies, herbal disinfectants have shown promising anthelmintic activity against monogenean infections in fish (Doan & et al., 2020; Zhang & et al., 2022).

2.10. Garlic extracts (*Allium sativum*)

It is known for its antifungal properties. Garlic contains a compound called allicin, which has an inhibitory effect on the growth of fungal pathogens (Baylan & et al., 2018). Garlic extracts are distinguished by their low toxicity to fish. However, determining the correct concentrations and continuous monitoring are necessary to ensure effective disinfection (Al-Janae'e, Ali & Al-Edany, 2017). It has been shown to be effective against fungal pathogens, especially Saprolegnia in various studies (Özçelik & et al., 2020).

These herbal disinfectants have significant potential to both reduce environmental impacts and support sustainable aquaculture practices. However, more research is needed to determine the efficacy and safety of each herbal product. Optimizing the application conditions and dosages of these products will help increase their effectiveness at water temperatures above 7-12 °C and minimize their possible side effects (Valenzuela-Gutiérrez & et al., 2021).

3. Application Doses

Fish egg disinfection using medicinal and aromatic plants attracts attention as environmentally friendly and sustainable products instead of traditional chemical disinfectants (Özçelik & et al., 2020). Various medicinal plants known for their antimicrobial properties are being tested for their effectiveness in preventing microbial contamination in fish eggs. Application concentrations of plant extracts can vary significantly depending on the fish species, the type of plant used, the part of the plant (seed, leaf, stem, shoot, etc.) and the amount of metabolites contained in the plant.

In current research, the most commonly used herbs for fish roe disinfection include *Thymus vulgaris* (thyme), *Origanum vulgare* (oregano), *Lavandula angustifolia* (lavender), and *Rosmarinus officinalis* (rosemary), all of which contain essential oils with strong antibacterial and antifungal properties. Recommended application dosages for these herbs generally range from 1% to 5% concentration of the plant extract, although some studies have investigated higher concentrations of up to 10% for more severe contaminations (Doan & et al., 2020).

For example, a study using *Thymus vulgaris* essential oil found that a 2% concentration was effective for disinfection without significantly damaging eggs. However, the exact dosage should be adjusted according to the specific characteristics of the fish species and the pathogen in question, as higher concentrations could potentially cause toxicity or damage to developing embryos (Turan, Gürağaç & Sayın, 2012; Çalışıcı-Narin, 2019).

4. Application Periods

Application time is one of the critical factors affecting disinfection effectiveness and survival rates of fish eggs. Typically, the exposure time to the plant extract varies from 10 minutes to 60 minutes, depending on the type of plant extract used and the severity of contamination (Doğan, 2024).

Shorter exposure times, usually around 10-20 minutes, are usually sufficient for disinfection with essential oils such as thyme or marjoram. However, in some cases where there is heavy contamination or more persistent pathogens, longer exposure times (30 to 60 minutes) may be required. It is important to time the exposure correctly, as prolonged contact with plant extracts can have adverse effects on egg viability, including low hatching rates or delayed development.

Studies have shown that immersion in a 2% oregano oil solution for 30 minutes can effectively reduce the bacterial load in fish eggs and maintain a high hatching rate (Can & Kaşıkçı, 2018). For example, Atlantic salmon (*Salmo salar*) eggs showed effective disinfection results when exposed to rosemary extract for 30 minutes, indicating a potentially ideal exposure time for this species.

In disinfection, as in fish anesthesia applications (Can & Sümer, 2019), contact with the least damaging substance in the shortest time can be considered as the most important factor to prevent work and time loss. Disinfection applications exceeding 30 minutes may pose a risk as they may also lead to water quality changes during application. Controllability decreases for disinfection personnel, therefore, the selection of the best disinfecting plant materials in the shortest time is important. In light of the studies conducted, it is revealed that future studies should focus on increasing the efficiency of disinfection and the survival rates of embryos. In this context, it is essential to conduct comparative trials on different species on concentration and duration.

5. Effect on Survival Rate

Medicinal and aromatic plants for disinfection is the potential impact on the survival rate (hatching rate) of fish eggs. The aim is to effectively disinfect the eggs without harming the developing embryos.

Several studies have shown that medicinal plant extracts, when used at optimum concentrations and exposure times, can effectively disinfect fish eggs without significantly affecting their viability. For example, in a study using *Thymus vulgaris* essential oil, the hatching rate of fish eggs remained high (approximately 85–90%) when eggs were disinfected at a 2% concentration for 20 min. Similarly, lavender extract has been shown to have antimicrobial effects on *Oncorhynchus mykiss* (rainbow trout) eggs and has minimal effects on survival rates (Turan, Gürağaç & Sayın, 2012; Çalışıcı-Narin, 2019; Pirinççioğlu, 2022).

However, excessive or prolonged exposure to plant extracts may lead to a decrease in hatching success. For example, higher essential oil concentrations or prolonged exposure times have been associated with lower survival rates due to the toxicity of some compounds to developing embryos (Conti & et al., 2014; Ferraz & et al., 2022). Therefore, careful optimization of dosage and exposure time is crucial to maintain high survival rates while effectively controlling microbial contamination.

6. Techniques Used in Impact Assessment

Medicinal and aromatic plants on fish eggs involves a variety of techniques, ranging from microbiological analysis to embryo development assessments (Lindholm-Lehto & Pylkkö, 2024). Commonly used methods to evaluate disinfection effectiveness are:

Microbial Load Analysis: One of the primary techniques used to assess the antimicrobial effect of medicinal plant extracts on fish eggs is the microbial load test. This involves culturing microbial samples from eggs to measure bacterial and fungal populations. The reduction in microbial load indicates the effectiveness of the disinfection procedure. Standard methods such as the plate count technique are often used to measure bacterial growth on selective agar media.

Hatching and Survival Rate Analyses: The ultimate measure of the effectiveness of a disinfection protocol is the survival rate of fish eggs and the percentage of successful hatching. Hatching analyses involve monitoring the number of eggs that hatch successfully after disinfection compared to controls. Survival rates are usually assessed by counting the number of live embryos after treatment and comparing them to untreated controls.

Histological Examination: Histological techniques can also be used to evaluate the effect of plant extracts on the morphology and development of eggs. These techniques provide the demonstration of possible toxicity at the cellular level that may occur with the use of plant products. It allows the evaluation of possible damage to the egg membrane or embryo before and after treatment.

concentration of active compounds in plant extracts. These analyses help researchers identify and quantify specific bioactive compounds responsible for antimicrobial activity, thus facilitating the finding of the most suitable formulation for egg disinfection.

Microscopic Observation: Microscopic methods can be used to observe the physical and chemical changes in the egg membrane after treatment. This is important to understand whether the plant extracts cause any damage to the eggs or embryos, which in turn affects the hatching rate.

7. Efficiency

Disinfection of fish eggs with medicinal and aromatic plants is preferred over chemical disinfectants due to both antimicrobial efficacy and minimal toxicity to developing embryos.

Application dosages, exposure times, survival rates, and evaluation techniques are critical factors that need to be optimized for each fish species and plant extract used. Future research will likely focus on improving these parameters, developing standard protocols, and exploring synergies between different plant species for more effective and sustainable fish egg disinfection strategies (Kumar & Bossier, 2018; Brun & et al., 2019).

Below are tables containing optimum hatching rates and microbial findings obtained from studies conducted on the disinfection of fish eggs. These tables include fish egg type, application type, duration, plant material used, optimum hatching rate, microbial load at optimum dose, and bibliography information. Studies are listed in the table as in vivo (Table 1) and in vitro (Table 2).

Table 1. *Optimum hatching rates and microbial findings obtained from some studies conducted on fish eggs (in ivo)*

Fish Species	Herbal Plants	Studied Pathogen	Application Method	Exposure Time (Min)	Optimal Application Dose	Total Pathogen Load (CFU/ml)	Hatching efficiency (%)	Survival rate (%)	References
Rainbow trout (*Oncorhynchus mykiss*)	Hops (*Humulus lupulus*)	Saprolegnia	Bath Treatment	20	1 mg	NM	90,33%	90,11%	Nazımoğulları, M. U., & Yanık, T. (2024)
Rainbow trout (*Oncorhynchus mykiss*)	Calendula (*Calendula officinalis*)	Saprolegnia	Bath Treatment	20	1 mg	NM	% 89.00	% 89.33	Nazımoğulları, M. U., & Yanık, T. (2024)
Persian sturgeon (*Acipenser persicus Borodin*)	*Eucalyptus globulus*	Overall fungal and bacterial loads	Short-term bath	30	100 mg/L	Bacterial count: 5.92 log CFU/g. Fungal count: 10 CFU/g.	62.66±2.51	3133.33 healthy larvae	Zamini et al., 2023
Persian sturgeon (*Acipenser persicus Borodin*)	*Allium sativum* (garlic)	Overall fungal and bacterial loads	Short-term bath	30	100 mg/L	Bacterial count: 6.26 log CFU/g Fungal count: 16 CFU/g	55.33±1.52	2766.66 healthy larvae	Zamini et al., 2023
Rainbow trout (*Oncorhynchus mykiss*)	*Oregano (Origanum onites)*	*Saprolegnia* infections	daily drip application	5	500 ppm	NM (Complete inhibition of fungal growth)	82.11%,	81.39%	Özdemir et al., 2022
Rainbow trout (*Oncorhynchus mykiss*)	Laurel *(Laurus nobilis)*	*Saprolegnia* infections	daily drip application	5	500 ppm	NM (Complete inhibition of fungal growth)	79.87%	NM	Özdemir et al., 2022
Angelfish (*Pterophyllum scalare*)	*Terminalia catappa* (Indian almond leaf) aqueous extract	*Saprolegnia parasitica*	The eggs were placed in water containing the extract (hot extract)	72 hours	50 mg/L and 100 mg/L	NM	Egg hatching ↑	Survival rate of larvae↑	Meneses et al., 2021
Rainbow trout (*Oncorhynchus mykiss*)	Wastes of onion (*Allium cepa*) and garlic (*Allium sativum*) methanolic extracts	*Saprolegnia parasitica*	Bath Treatment	10	0,4 g/L (only garlic skin extract) 0,8 and 1,6 g/L (both Garlic skin and Garlic stem) Onion extract ↔	NM	Dead eggs compared to control with: Using Garlic Skin Extract ↓ Garlic Stem Extract ↓ Onion extract ↔	Garlic Skin Extract: 0,4, 0,8 and 1,6 g/L ↑ Garlic Stem Extract: 0,8 and 1,6 g/L ↑ Onion extract ↔	Özçelik et al., 2020
Rainbow trout (*Oncorhynchus mykiss*)	*Achillea officinalis*	*Saprolegnia parasitica*	*Constant Flow*	60	150 and 200 mg/mL	NM	71.28±0.30	Mortality 28.6±0.05	Amiri and Meshkini, 2019
Rainbow trout (*Oncorhynchus mykiss*)	*Matricaria chamomilla*	*Saprolegnia parasitica*	*Constant Flow*	60	100 and 150 mg/mL	NM	75.90±0.26	Mortality 23.67±0.76	Amiri and Meshkini, 2019
Rainbow trout (*Oncorhynchus mykiss*)	*Daenensis thyme(T.daenensis) and Mentha (M.longifolia)*	*Saprolegniasis*	Constant flow treatment method	30	Daenensisthyme at20 mgL-1 Mentha 10 mgL-1	NM	Hatching success ↑	Mortality ↓	Salehi et al.,2016

NM: This information has non-mentioned in referenced article, ↑ : Effective, increasing; ↔ : No significant differences; ↓ : Reducing

Table 2: *Results of some studies on plant-based products and their effective values applied to fish pathogens (in vitro)*

Fish Species	Herbal Plants	Studied Pathogen	Application Method	Exposure temperature and time	MIC	MLC	Results and Effective consantrations	Reference
Rainbow trout (*Oncorhynchus mykiss*)	*Oregano (Origanum onites)*and *Laurel (Laurus nobilis)*	*Saprolegnia* infections	Conducted in petri dishcontaining Potato dextrose agar (PDA)	20°C 96 hr	250 ppm	500 ppm	Growth of the fungus was 100% inhibited for 500 ppm both herbals.	Özdemir et al., 2022
Angelfish (*Pterophyllum scalare*)	Terminalia catappa (Indian almond)	Saprolegnia parasitica	Conducted in solid (potato dextrose agar) and liquid (potato dextrose broth) mediums	25°C 96 hours	NM	NM	5 g/L and 10 g/L hot extracts : inhibited mycelial growth and showed fungisidal effect	Meneses et al., 2021
Rainbow trout (*Oncorhynchus mykiss*)	*Eucalyptus globulus*, *Myrtus communis* (Myrtle), *Thymus daenensis* (Thyme), *Matricaria recutita* (Chamomile), *Satureja bachtiarica* (Savory), *Mentha longifolia* (Pennyroyal)	*Saprolegnia parasitica and Aspergillus species*	Incubation	25°C 24 hours	Myrtus communis and Mentha longifolia (Yarpuz): (Mersin): 10 µL mL⁻¹	Study look for MFC and it is Same as MIC.	For Saprolegnia parasitica: Pennyroyal 5 µL mL⁻¹↑ Thyme and Myrtle 10 µL mL⁻¹↑ For Aspergillus species: 10-20 µL mL⁻¹ ↑	Salehi ve ark., 2015
Rainbow trout (*Oncorhynchus mykiss*)	Essentialoils: Thymus daenensis, Thymus khuzestanicum Ethanol extracts: Mentha longifolia, Satureja bachtiarica, Tanacetumparthenium, Myrtus communis	*Saprolegnia parasitica*	Inkubation	18°C 7 days	Thymus daenensis and Thymus khuzestanicum: 0.63 µL mL⁻¹ Tanacetum parthenium: 31.25 µg mL⁻ Mentha longifolia: 62.5 µg mL⁻¹ Satureja bachtiarica: 125 µg mL⁻¹	Thymus daenensis, Thymus khuzestanicum: 22 µL mL⁻¹ Tanacetum parthenium:600 µg mL⁻¹ Mentha longifolia: 550 µg mL⁻¹ Satureja bachtiarica: 750 µg mL⁻¹	Thymus daenensis Thymu khuzestanicum Mentha longifolia↑	Pirbalouti ve ark., 2009

NM: This information has non-mentioned in referenced article, ↑ : Effective, increasing; ↔ : No significant differences; ↓ : Reducing

8. Advantages and Disadvantages of Herbal Disinfectants

8.1. Advantages

Herbal disinfectants used in fish and fish egg disinfection have many advantages over traditional chemical disinfectants in aquaculture (Can & et al., 2023). First of all, natural extracts obtained from plants such as garlic, chamomile, and thyme contain biodegradable components that do not harm the environment and aquatic organisms. Unlike chemical substances, these herbal disinfectants reduce environmental pollution and contribute to the protection of water resources. These herbal extracts, which have antimicrobial and antifungal properties, prevent the proliferation of pathogens and support the healthy development of eggs (Nazımoğulları & Yanık, 2024). The non-toxic effects of natural plant extracts on fish embryos provide important protection in terms of egg and offspring health. While chemical disinfectants have the risk of causing resistance development, the use of herbal disinfectants also minimizes the risk of developing resistance. In addition, essential oils decompose rapidly in nature and the risk of leaving residue is low. With these properties, herbal disinfectants stand out as a sustainable and ecologically appropriate disinfection method (Salehi, Soltani & Hosseini-Shekarabi, 2016; Austin & et al., 2022).

8.2. Disadvantages

There are also some disadvantages of herbal disinfectants in fish and fish eggs disinfection. First of all, the effectiveness of herbal essential oils may be lower than chemical disinfectants and may not be sufficient to completely eliminate pathogens. Since the mechanisms of action of herbal disinfectants are complex, the effectiveness of different plants against different pathogen types may vary. Therefore, stable and reliable results may not be obtained when these herbal products are used. In addition, some of the components contained in natural extracts may have toxic effects on fish embryos if the appropriate dose is exceeded. Furthermore, the specific antimicrobial compounds in many plant extracts are not well understood, and isolating pure compounds from them poses a significant challenge. (Li & et al., 2024) The lack of standardized formulations of herbal disinfectants may lead to difficulties in determining the dosage, and it may be difficult to achieve the same effect every time. Another important challenge is that the application time and form of herbal disinfectants may differ from each other.

In order for herbal disinfectants to be effective, they sometimes require long-term contact and this can slow down the cultivation process. For these reasons, more research is needed to use herbal disinfectants safely and effectively (Nazımoğulları & Yanık, 2024).

Medicinal aromatic plants in fish egg disinfection is attracting attention as an environmentally friendly and sustainable alternative. The use of herbal products instead of traditional chemical disinfectants is increasing, which offers the opportunity to both protect the environment and increase biodiversity in fish species. However, there are several important focal points for further development of this field.

9.Future focuses

9.1. In-Depth Study of Plant Extracts and Active Compounds

Efficiency of medicinal and aromatic plants depends on the type and concentration of active plants they contain. The effects they show against these genetic microorganisms need to be better understood. In particular, the study on the effectiveness of plants with antibacterial, antifungal and antiviral products should be deepened. In addition, the effects of these relationships on fish eggs (possible harmful difficulty, negative effects on egg development, etc.) should be examined in detail and optimal doses should be determined. In the future, these studies will enable the development of more sensitive formulations that will minimize potential damage to direct microbial control and other embryos (Austin & et al., 2022).

9.2. Development of Standardized Application Protocols

Determining appropriate disinfection protocols for different fish species is of great importance for increasing treatment processes. In the future, more standardized application dosages and durations will need to be determined for disinfection processes with medicinal aromatic plants (Varlı, Hancı & Kalafat, 2020; Rhodes & et al., 2023). These protocols should not harm the egg development of different fish species and provide effective protection against microorganisms. This is especially important for ensuring the widespread use of fish products.

9.3. Use of Multiple Herb Mixtures

Herbal extracts used alone may not be effective in all cases. In this way, traditional combined use should be investigated further. By taking advantage of different spectrum synergistic effects, more powerful and broad-spectrum disinfection solutions can be developed. For example, the combined use of lavender, rosemary, and thyme is not only suitable for families, but also effective against fungal and viral diseases (Aydın, 2022). Thus, it is possible to protect fish eggs by taking advantage of multiple mechanisms of action.

9.4. Biotechnological and Nanotechnological Approaches

In the future, there are biotechnological and nanotechnological applications to increase the amount of herbal extracts (Jeyavani & et al., 2022). For example, combining herbal extracts with nanoparticles, providing more effective disinfection. Nanotechnology allows active systems to reach the egg faster and more effectively, allowing higher efficacy to be achieved with lower doses (Austin & et al., 2022; Adetuyi & et al., 2024). However, research on nanotechnology and biological safety also needs to be deepened.

9.5. Integrated Solutions for Sustainable and Ecological Cultivation

Focus should be placed on developing integrated solutions for fish egg disinfection for sustainable and ecological aquaculture (Ahmed, Thompson & Glaser, 2019). Adopting herbal alternatives instead of chemical disinfectants can protect aquatic ecosystems as well as protecting biodiversity (Arthur & et al., 2008). In addition, the use of such biological disinfection methods will contribute to healthier and more efficient production by reducing the destruction of water used in fish resources (Özçelik & et al., 2020).

The use of native plant species in fish egg disinfection can be encouraged in the future. This can both increase biodiversity by preserving native plant diversity and provide new perspectives for research. Using them for this purpose can provide a more economical disinfection solution by reducing transportation costs.

9.6. Assessment of Environmental and Economic Impacts

It is possible to evaluate the economics and effects of disinfection with medicinal plants in detail. The extent to which it is economically suitable for medical production services, fish production, and the level of symptoms (e.g. effects on biodiversity) should be one of the most important research focuses in this field (Atique, 2023). In addition, herbal disinfectants should be comprehensively presented in terms of sustainability compared to chemical alternatives (Can & et al., 2023).

Thus, the use of environmentally friendly methods in the fish products sector will become widespread and replace traditional chemical disinfectants.

10. Conclusion and Recommendations

Plant-based disinfectants have been gaining more attention in recent years as an environmentally friendly alternative for fish and fish eggs disinfection. Medicinal aromatic plants and essential oils are attracting attention as promising natural alternatives for fish egg disinfection. International studies show that these compounds can be used effectively in eggs of different fish species. However, the most important factors to be considered during application are appropriate concentration and effective application time. Since there may be a risk of toxic effects at high concentrations, it is necessary to determine safe ranges. Therefore, it is very important to conduct toxicity tests and economic analyses of plants in order to increase the use of medicinal aromatic plants in fish egg disinfection. By focusing future studies on this area, practical and safe uses of natural products will be determined and their commercial use will increase.

Medicinal aromatic products is a method that is compatible with ecological systems, environmentally friendly, does not leave residue, and is economical and practical. It ensures that similar studies in the future will make this field more efficient, safe and sustainable.

As a result, further research is required to investigate the effectiveness and toxicity of herbal disinfectants, to eliminate the deficiencies encountered in their standardization, and to determine their practical use.

References

Adetuyi, B. O., Olajide, P. A., Omowumi, O. S., & Adetunji, C. O. (2024). Application of Plant-Based Nanobiopesticides as Disinfectant. Handbook of Agricultural Biotechnology, Volume 1: Nanopesticides, 63.

Ahmed, N., Thompson, S., & Glaser, M. (2019). Global aquaculture productivity, environmental sustainability, and climate change adaptability. Environmental management, 63, 159-172.

Al-Janae'e, A. M., Ali, A.H., & Al-Edany, T.Y. (2017). Efficacy of some aromatic plant extracts on treating the eggs of the common carp (*Cyprinus carpio* L.) against fungal infection in comparison with traditional fungicide malachite green. Basrah Journal of Agricultural Sciences, 30(2), 59-71.

Amiri, H., & Meshkini, S. (2019). Antifungal effects of *Achillea officinolis* and *Matricaria chamomilla* plant extracts on control infection of rainbow trout eggs by Saprolegnia parasitica. Veterinary Research, 15(1), 97–107. https://doi.org/10.21270/archi.v8i12.4654.

Arthur, J. R., Baldock, C. F., Bondad-Reantaso, M. G., Perera, Ramesh, Ponia, B., & Rodgers, C. J. (2008). Pathogen risk analysis for biosecurity and the management of live aquatic animal movements. Diseases in Asian Aquaculture, 6, 21-52.

Atique, F. (2023). The effect of plants on microbes, water quality, and fish performance in an aquaponic system. JYU Dissertations.

Austin, B., & Austin, D. A. (2016). Bacterial Fish Pathogens: Disease of Farmed and Wild Fish (6th ed.). Springer.

Austin, B., Lawrence, A., Can, E., Carboni, C., Crockett, J., Demirtas, N., ... & Gier, G. Y. (2022). Selected topics in sustainable aquaculture research: Current and future focus. Sustainable Aquatic Research, 1(2), 74-125.

Aydin, HB (2022). Investigation of Antimicrobial Activity of Nettle (Urtica Dioica L.) Extract on Foodborne Campylobacter Jejuni (Master's thesis, Marmara University (Turkey)).

Barnes, J. M., Dupont, T. R., Barnes, M. E., Durben, D. J., & Dixson, J. A. (2012). Initial investigations of hops as a salmonid egg fungicide. North American Journal of Aquaculture, 74(3), 310-313.

Baylan, M., Akpınar, GC, Canogullari, SD, & Ayasan, T. (2018). The effects of using garlic extract for quail hatching egg disinfection on hatching results and performance. Brazilian Journal of Poultry Science, 20, 343-350.

Brun, P., Bernabè, G., Filippini, R., & Piovan, A. (2019). In vitro antimicrobial activities of commercially available tea tree (*Melaleuca alternifolia*) essential oils. Current microbiology, 76, 108-116.

Can, E., Austin, B., Steinberg, CE., Carboni, C., Sağlam, N., Thompson, K., Yiğit, M., Seyhaneyildiz Can, S., & Ergün, S. (2023). Best practices for fish biosecurity, well-being and sustainable aquaculture. Sustainable Aquatic Research, 2(3), 221–267. https://doi.org/10.5281/zenodo.10444855

Can, E., Karacalar, U., Saka, S., & Firat, K. (2012). Ozone disinfection of eggs from gilthead seabream Sparus aurata, sea bass Dicentrarchus labrax, red porgy, and common dentex *Dentex dentex*. Journal of Aquatic Animal Health, 24(2), 129-133.

Can, E., Saka, Ş., & Firat, K. (2010). Disinfection of gilthead sea bream (*Sparus aurata*), red porgy (*Pagrus pagrus*), and common dentex (*Dentex dentex*) eggs from sparidae with different disinfectants. Kafkas University Faculty of Veterinary Medicine Journal, 16(2).

Can, P. Ö., & Kaşıkçı, G. (2018). Effect of rosemary and thyme oil addition on the refrigerated storage of marinated rainbow trout (*Oncorhynchus mykiss* Walbaum 1972). Turkish Journal of Agriculture-Food Science and Technology, 6(12), 1701-1707.

Can, E., & Sümer, E. (2019). Anesthetic and sedative efficacy of peppermint (*Mentha piperita*) and lavender (*Lavandula angustifolia*) essential oils in blue dolphin cichlid (*Cyrtocara moorii*). *Turkish Journal of Veterinary & Animal Sciences*, *43* (3), 334-341.

Carson, C. F., Hammer, K. A., & Riley, T. V. (2006). *Melaleuca alternifolia* (tea tree) oil: a review ofantimicrobial and other medicinal properties. Clinical microbiology reviews, 19(1), 50-62.

Conti, B., Flamini, G., Cioni, P. L., Ceccarini, L., Macchia, M., & Benelli, G. (2014). Mosquitocidal essential oils: are they safe against non-target aquatic organisms? Parasitology research, 113, 251-259.

Çalışıcı-Narin, Ö. (2019). The effect of thyme (Thymus vulgaris) oil added to the feed at different rates on the growth of carp (*Cyprinus carpio* L.) fry (Master's thesis, İskenderun Technical University/Institute of Engineering and Science/Department of Fisheries).

Das, S., Horváth, B., Šafranko, S., Jokić, S., Széchenyi, A., & Kőszegi, T. (2019). Antimicrobial activity of chamomile essential oil: Effect of different formulations. Molecules, 24(23), 4321.

Dawood, M. A., El Basuini, M.F., Zaineldin, A.I., Yilmaz, S., Hasan, M.T., Ahmadifar, E., ... & Sewilam, H. (2021). Antiparasitic and antibacterial functionality of essential oils: An alternative approach for sustainable aquaculture. Pathogens, 10(2), 185.

Doan, H. V., Soltani, E., Ingelbrecht, J., & Soltani, M. (2020). Medicinal herbs and plants: Potential treatment of monogenean infections in fish. Reviews in Fisheries Science & Aquaculture, 28(2), 260-282.

Doğan, M. 2024. Chemicals and Amounts Used Against Fungal Infections During Trout (Onchorynchus mykiss) Egg Incubation Period. Journal of Limnology and Freshwater Fisheries Research x(x): xxx-xxx

Elgendy, M. Y., Ali, S. E., Abdelsalam, M., Abd El-Aziz, T. H., Abo-Aziza, F., Osman, HA, ... & Abbas, W. T. (2023). Onion (*Allium cepa*) improves Nile tilapia (*Oreochromis niloticus*) resistance to saprolegniasis (*Saprolegnia parasitica*) and reduces immunosuppressive effects of cadmium. Aquaculture International, 31(3), 1457-1481.

FAO (2018). The State of World Fisheries and Aquaculture. Food and Agriculture Organization of the United Nations.

Ferraz, C. A., Pastorinho, M. R., Palmeira-de-Oliveira, A., & Sousa, A. C. (2022). Ecotoxicity of plant extracts and essential oils: A review. Environmental Pollution, 292, 118319.

Fierascu, R. C., Fierascu, I., Baroi, A. M., & Ortan, A. (2021). Selected aspects related to medicinal and aromatic plants as alternative sources of bioactive compounds. International Journal of Molecular Sciences, 22(4), 1521.

Ghiasi, M., Binaii, M., Ghaednia, B., Farabi, SMV, & Alavi, E. S. (2022). Evaluation of Eucalyptus (*Eucalyptus globulus*) essential oil on growth performance, hemato-immunological parameters and resistance against *Aeromonas hydrophila* in common carp (Cyprinus carpio). Journal of Aquaculture Development, 16(2), 119-131.

Good, C., Davidson, J., Straus, D. L., Harper, S., Marancik, D., Welch, T., ... & Summerfelt, S. (2020). Assessing peracetic acid for controlling post-vaccination Saprolegnia spp.-associated mortality in juvenile Atlantic salmon *Salmo salar* in freshwater recirculation aquaculture systems. Aquaculture Research, 51(6), 2624-2627.

Jeyavani, J., Sibiya, A., Sivakamavalli, J., Divya, M., Preetham, E., Vaseeharan, B., & Faggio, C. (2022). Phytotherapy and combined nanoformulations as a promising disease management in aquaculture: A review. Aquaculture International, 30(2), 1071-1086.

Khemis, I. B., Aridh, N. B., Hamza, N., M'Hetli, M., & Sadok, S. (2016). Antifungal efficacy of the cactaceae *Opuntia stricta* (Haworth) prickly pear ethanolic extract in controlling pikeperch Sander lucioperca (Linnaeus) egg saprolegniasis. Journal of Fish Diseases, 39, 377–383. https://doi.org/10.1111/jfd.12356 .

Kumar, V., & Bossier, P. (2018). Importance of plant-derived compounds and/or natural products in aquaculture. Aquafeed, 10, 28-31.

Larcombe, E., Alexander, M. E., Snellgrove, D., Henriquez, F. L., & Sloman, K. A. (2024). Current disease treatments for the ornamental pet fish trade and their associated problems. Reviews in Aquaculture.

Li, S., Jiang, S., Jia, W., Guo, T., Wang, F., Li, J., & Yao, Z. (2024). Natural antimicrobials from plants: Recent advances and future prospects. *Food Chemistry*, *432*, 137231.

Lindholm-Lehto, P. C., & Pylkkö, P. (2024). Saprolegniosis in aquaculture and how to control it? Aquaculture, Fish and Fisheries, 4(4), e2200.

Mabrok, M.A. E., & Wahdan, A. (2018). The immune modulatory effect of oregano (*Origanum vulgare* L.) essential oil on Tilapia zillii following intraperitoneal infection with Vibrio anguillarum. Aquaculture International, 26, 1147-1160.

Masigol, H., Mostowfizadeh-Ghalamfarsa, R., & Grossart, H. P. (2021). The current status of Saprolegniales in Iran: Calling mycologists for better taxonomic and ecological resolutions. Mycologia Iranica, 8(2), 1-13.

Meneses, J. O., da Silva, I. C. A., da Cunha, A. F. S., dos Santos Cunha, F., Dias, J. A. R., Abe, H. A., & Fujimoto, R. Y. (2022). Protective effect of Terminalia catappa leaf extracts against Saprolegniosis on angelfish eggs. Aquaculture Research, 53(2), 377-387.

Miliauskas, G., Venskutonis, P.R., & Van Beek, T.A. (2004). Screening of radical scavenging activity of some medicinal and aromatic plant extracts. Food chemistry, 85(2), 231-237.

Nazımoğulları, M. U., & Yanık, T. (2024). Investigation of the use of hops (*Humulus lupulus*) and calendula (*Calendula officinalis*) as disinfectants on the hatching efficiency of rainbow trout (*Oncorhynchus mykiss*). Marine Science and Technology Bulletin, 13(4), 296-303. https://doi.org/10.33714/masteb.1540047

Özçelik, H., Taştan, Y., Terzi, E., & Sönmez, AY (2020). Use of onion (*Allium cepa*) and garlic (*Allium sativum*) wastes for the prevention of fungal disease (*Saprolegnia parasitica*) on eggs of rainbow trout (*Oncorhynchus mykiss*). Journal of Fish Diseases, 43(10), 1325-1330.

Özdemir, R. C., Taştan, Y., & Güney, K. (2022). Prevention of Saprolegniasis in rainbow trout (Oncorhynchus mykiss) eggs using oregano (*Origanum onites*) and laurel (*Laurus nobilis*) essential oils. Journal of Fish Diseases, 45(1), 51-58.

Pirbalouti, A. G., Taheri, M., Raisee, M., Bahrami, H. R., & Abdizadeh, R. (2009). In vitro antifungal activity of plant extracts on *Saprolegnia parasitica* from cutaneous lesions of rainbow trout (Oncorhynchus mykiss) eggs. J Food Agric Environ, 7, 94-6.

Pirinççioğlu, S.R. (2022). Determination of antimicrobial activities of essential oils of different thymes grown in Çanakkale conditions (Master's thesis, Çanakkale Onsekiz Mart University, Institute of Graduate Education).

Rashidian, G., Boldaji, J. T., Rainis, S., Prokić, M. D., & Faggio, C. (2021). Oregano (Origanum vulgare) extract enhances zebrafish (Danio rerio) growth performance, serum and mucus innate immune responses and resistance against *Aeromonas hydrophila* challenge. Animals, 11(2), 299.

Reda, R., Khalil, A.A., Elhady, M., Tayel, S.I., & Ramadan, E.A. (2024). Anti-parasitic activity of garlic (*Allium sativum*) and onion (*Allium cepa*) extracts against Dactylogyrus spp.(Monogenean) in Nile tilapia (*Oreochromis niloticus*): Hematology, immune response, histopathological investigation, and inflammatory cytokine genes of gills. BMC Veterinary Research, 20(1), 334.

Rhodes, L. D., Parrish, K. L., & Willis, M. L. (2023). Review of Best Practices for Biosecurity and Disease Management for Marine Aquaculture in US Waters.

Salehi, M., Soltani, M., & Hosseini-Shekarabi, S. P. (2016). Effects of antifungal activity of Daenensis thyme (Thymus daenensis) and Mentha (Mentha longifolia) essential oils on rainbow trout (*Oncorhynchus mykiss*) eggs hatchability. Sustainable Aquaculture and Health Management Journal, 2(2), 97-107.

Salehi, M., Soltani, M., & Islami, H. R. (2015). In vitro antifungal activity of some essential oils against some filamentous fungi of rainbow trout (*Oncorhynchus mykiss*) eggs. Aquaculture, Aquarium, Conservation & Legislation, 8(3), 367-380.

Semple SL, Dixon B. Salmonid Antibacterial Immunity: An Aquaculture Perspective. Biology (Basel). 2020 Oct 11;9(10):331. doi: 10.3390/biology9100331. PMID: 33050557; PMCID: PMC7599743.

Singh, S. K., Bhandari, M. P., & Timalsina, P. (2021). Effect of dietary supplementation of carotenoids on growth performance of rainbow trout (*Oncorhynchus mykiss,* Walbaum) in Rasuwa, Nepal.

Souza, C. D. F., Baldissera, M. D., Baldisserotto, B., Heinzmann, B. M., Martos-Sitcha, J. A., & Mancera, J. M. (2019). Essential oils as stress-reducing agents for fish aquaculture: a review. Frontiers in physiology, 10, 785.

Swamy, J. M., Patil, A., Biradar, P., Yadav, S.R., Bhosle, R., & Tipale, J. (2023). Exploring the Therapeutic and Nutritional Significance of Bay Laurel (*Laurus nobilis*) as a Feed Additive in Aquaculture. International Journal of Environment and Climate Change, 13(12), 192-197.

Syahidah, A., Saad, C.R., Daud, H.M., & Abdelhadi, Y.M. (2015). Status and potential of herbal applications in aquaculture: A review. Iranian Journal of Fisheries Sciences, 14(1), 27-44.

Turan, F., Gürağaç, R., & Sayın, S. (2012). Essential oils in aquaculture. Turkish Journal of Scientific Reviews, (1), 35-40.

Valenzuela-Gutiérrez, R., Lago-Lestón, A., Vargas-Albores, F., Cicala, F., & Martínez-Porchas, M. (2021). Exploring the garlic (*Allium sativum*) properties for fish aquaculture. Fish Physiology and Biochemistry, 47(4), 1179-1198.

Varlı, M., Hancı, H., & Kalafat, G. (2020). Production potential and bioavailability of medicinal and aromatic plants. Research Journal of Biomedical and Biotechnology, 1(1), 24-32.

Yılmaz, E., Taşbozan, O., & Erbaş, C. (2018). Potential of medical herbal products to be used in aquaculture. Eastern Anatolian Journal of Science, 4(2), 16-23.

Zamini, A. Taati, R., Rezaeiardeh, M. R., & Najafikhah, A. (2023). Comparative performance of Eucalyptus globulus Labill. and Allium sativum Linn. extracts in reducing the fungal and bacterial load of Persian sturgeon (*Acipenser persicus* Borodin) eggs during the incubation period. Iranian Journal of Medicinal and Aromatic Plants Research, 39(3), 433-444.

Zhang, W., Zhao, J., Ma, Y., Li, J., & Chen, X. (2022). The effective components of herbal medicines used for prevention and control of fish diseases. Fish & shellfish immunology, 126, 73-83.

CHAPTER IV

Sustainable Developments in Offshore Aquaculture

Volkan KIZAK[1]

1. Introduction

Aquaculture, which can be considered young among production systems, has a great potential for the future of humanity. Aquaculture provides nutritious food to a growing world population and reduces the need for fishing. Therefore it contributes to the conservation of natural fish stocks. Aquaculture products also has lower carbon footprint than other types of farming.

It is a known fact that seafood has more potential benefits than other protein sources. The majority of seafood comes from aquaculture. Aquaculture is the fastest growing food sector, with more than a third of protein production expected to come from aquaculture by 2050 (Froehlich et al., 2018). Ocean resources are being depleted rapidly, so the role of aquaculture in food security is

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becoming even more critical (Lu et al., 2022). Sustainable food production at sea is becoming increasingly important as the growing global human population will require more food. Aquaculture production is increasingly threatened by pollution and user conflicts, presenting an opportunity for offshore mariculture (Lovatelli et al., 2013). As freshwater resources become even scarcer, offshore aquaculture will inevitably become one of the most used production procedures in many parts of the world in the coming decades (Soto & Wurmann, 2018). The world population is expected to reach 10 billion by 2050 and the demand for food will increase significantly accordingly. Offshore aquaculture emerges as a fundamental solution in line with this need (Nguyen & Wang, 2024). Offshore aquaculture is one of the new frontiers for mariculture production that can meet the growing demand. Aquaculture is being pushed to offshore or land-based locations due to competition for coastal water use, high coastal land values, human activities on land, poor water quality in many coastal areas (Cicin-Sain et al., 2005).

The spread of mariculture to offshore is a challenge in terms of technological, environmental and spatial perspectives as well as legal situations. As the distance of mariculture activity from the coast in deeper waters increases, more exposed to weather conditions will happen, and more capital investment and more technological complexity will be required. Additionally, operating costs may increase (Lovatelli et al., 2013). On the other hand, offshore aquaculture can provide wide area and a large environmental carrying capacity, as well as reducing competition with other users of marine space. Better environmental conditions can effectively reduce the risk of diseases and parasites in aquaculture, thereby producing high-quality seafood (Long et al., 2024). The water quality of the deep sea is good, the soil pollution and disease rate are low, and it is convenient for offshore aquaculture (Feng et al., 2018). One of the potential benefits of offshore aquaculture is controlling of the fish parasites. Locating cages away from existing cages and in more open and dispersed environments cause reducing parasite pressure (Morro et al., 2022). Nowadays, culture of marine organisms in deep marine waters has now become technically possible, as demonstrated by dozens of commercial facilities using offshore aquaculture technologies around the world. In this chapter, information is given about the latest developments in offshore aquaculture. We hope to provide useful information to those involved in this sector.

2. Mariculture and Offshore

Mariculture is considered offshore when it is carried out more than 2 km from the coast, in water depths greater than 50 m, in wave heights of 5 m or more, in areas exposed to ocean waves, variable winds and strong ocean currents, where remote operations, automatic feeding are required (Lovatelli et al., 2013). Increasing conflicts in nearshore areas have led to the search for new areas where aquaculture operations can expand. For decades, there have been active scientific and political efforts to move marine aquaculture from nearshore habitats to more open and remote ocean areas. Efforts have not always been successful because of the unique geographic, topographic, physical, geological, chemical, biological, and oceanographic characteristics of each site. To date, almost all marine aquaculture activities has been concentrated in protected nearshore areas. Conducting aquaculture operations in such areas is attractive because it requires less investment in robust technology and worker safety, generates lower insurance costs, and is easier to manage logistically (Buck et al., 2024). However, as aquaculture expands worldwide, the raising of fish in the open seas is also increasing. Although there are many technological and economic challenges to farming in more open environments, there are also many potential benefits, such as more space, less conflict with other uses of the marine environment, and less impact on the sea (Knapp, 2013). In recent years, offshore aquaculture has gained momentum, so the production of an increasing number of marine fish species is being moved to the open seas (Morro et al., 2022). Offshore aquaculture holds promise as a source of new economic development and increased seafood supply (Gentry et al., 2017).

Although calm waters and easy access make coastal marine culture attractive, some environmental impacts and conflicts with other uses are becoming more apparent in increasingly crowded coastal areas (Gentry et al., 2017). Mariculture has relatively limited space for development in most of the world's coastal waters, so there is an increasing interest in moving mariculture further offshore where there are larger and potential areas with little conflicts. Expansion of the mariculture sector could help meet the growing demand for seafood that cannot be met by fishing alone (Lovatelli et al., 2013). Mariculture is expanding into deeper offshore environments in response to improved technology and limited fishery potential. Sustainable development of aquaculture in this area depends on quantifying and minimizing its impacts on other ocean-based activities (Gentry et al., 2017).

3. Offshore Aquaculture

Offshore aquaculture involves raising marine species in the open ocean, away from traditional coastal mariculture areas. This new approach offers ample spaces with less competition from other coastal developments, such as shipping, tourism, recreation, and conservation. Additionally, these open areas provide improved water quality that are crucial for producing good quality seafood. Strong waves and currents in these areas help disperse aquaculture waste, reduce biofouling, and prevent marine ecosystem degradation often associated with intensive aquaculture activities near shore (Nguyen & Wang, 2024).

Offshore and open ocean terms have been used to describe aquaculture sites which are further from the shore, and related terms use in various combinations (Buck et al., 2024). Originally, the term offshore referred to activities located in open waters far from shore, i.e. open ocean aquaculture. Subsequently, offshore aquaculture term has also been used in other cases (Morro et al., 2022).

Mariculture operations are categorized based on site location then describes according to the distance from the coast, water depth, exposure status, access to the site and the operational requirements (Lovatelli et al., 2013). Coastal mariculture is typically done in shallow and sheltered waters. Off-the-cost mariculture differs from coastal mariculture mainly in terms of distance from the shore and degree of exposure. This mariculture occurs 0.5–3 km from the shore in water depths of 10 to 50 m. The sites may be partially sheltered, but currents are stronger, and wind and waves affect facilities more severely than coastal mariculture areas. Offshore mariculture is under the influence of powerful ocean waves, swells, currents and harsh winds. Open ocean mariculture term can comprise both off-the-coast and offshore mariculture (Lovatelli et al., 2013). There is also another term called deeper offshore aquaculture that refers to mariculture activities located in open offshore areas. In this type of offshore aquaculture system storm resistant infrastructures, closed containments and automatic feeding systems are used. Deeper offshore aquaculture has the potential to operate in deeper offshore areas or open seas (Dong et al., 2023a).

Deeper offshore aquaculture or offshore aquaculture are systems with steel frames and automatic feeding equipment that can withstand or avoid strong typhoons. Considering the coexistence of nearshore aquaculture, offshore aquaculture and deeper offshore aquaculture, deeper offshore aquaculture can be profitable by farming higher quality marine organisms that are difficult to cultivate or species that can generate additional income through deeper offshore aquaculture (Dong et al., 2023b).

3.1. Offshore Aquaculture Types

Soto & Wurmann (2018) stated that most current offshore aquaculture systems are submergible devices. Underwater aquaculture devices such as cages and longlines can perform better even strong force, category 4 hurricanes. Many different offshore cages have been devised, built, tested and some of them being commercialized. Offshore aquaculture requires more sophisticated technologies. A very wide range of designs have been promoted for mariculture (Beveridge, 2004). These include bottom supported platforms, such as Texas towers, jack-up rigs and monopods, floating and semi-submersible platforms, containing modified ships, as well as net pens supported between moored spar buoys (Lovatelli et al., 2013).

According to Long et al. (2024), the types of aquaculture facilities are categorized into four groups: semi-submersible cage, bottom-sitting cage, submerged cage and vessel. However, large aquaculture facilities can be categorized into open and closed modes depending on their water exchange modes. Open large scale aquaculture facilities mostly occur in the form of cages, which are fixed. Closed large scale aquaculture facilities are represented by special closed aquaculture ships that can sail to different sea areas and thus maintain a suitable water temperature. On the other hand, there are high construction costs and technical challenges in addition to high energy consumption (Xu et al., 2021; Long et al., 2024).

Dong et al. (2023a) categorized the types of deeper offshore aquaculture into six groups;

- Offshore pens such as Lanzuan 1 that utilize rigid steel, concrete structures, or copper alloy nets.
- Stabilized cages such as Genghai 1 has steel frame cages stabilized in the waters by pile legs.
- Floating cages such as Dehai 1 which relies on the buoyancy provided by a floating platform.
- Submersible cages such as Deep Blue 1.
- Semi-submersible cages such as Ningde 1, are designed to have small water plan areas.
- Closed containments such as Guoxin 1, include aquaculture vessels and sea-based aquaculture tanks.

The first example of the mobile aquaculture vessel that is called Floating Fish Farming Unit (3FU) (Picture 1,2,3,4), has been constructed and taken off into Black Sea in Türkiye (Bilen et al., 2013).

Picture 1. 3FU platform (Original).

Picture 2. Converted fish tanks from ship holds (Original).

Picture 3. Fish tank (Original).

Picture 4. Rainbow trouts adapted to sea water in tanks (Original).

The mobile aquaculture vessel is a sustainable way due to its mobility, production rates and eco-friendly feature (Li et al., 2022a). Offshore areas can be used for fish farming by ship aquaculture platforms which are expected to become a way to expand offshore aquaculture (Yu et al., 2023). The sailing performance of closed aquaculture vessels can meet the needs of more marine fish farming. In order to ensure the optimum growth status of cultured fish and shorten the farming cycle, seawater with suitable temperature and salinity can be obtained by using deep water intake device for aquaculture (Long et al., 2024). Aquaculture vessels are in rapid development and large aquaculture vessels are already in use in China (Tao et al., 2023). Guoxin 1 is the world's first smart fishery large scale aquaculture vessel (Long et al., 2024).

4. Opportunities and Challenges of Offshore Aquaculture

4.1. Opportunities

The image of aquaculture is often negative across countries and regions. Moving aquaculture offshore would likely reduce many environmental and food security risks (Lovatelli et al., 2013). Increasing pressure on coastal use from factors such as tourism and urban development is providing a strong impetus for the relocation of mariculture activities to offshore waters. In many countries with well-developed mariculture industries, there is an increasing concern about waste issues, disease outbreaks and escapes of farmed fish (Tacon & Halwart, 2007). There is an increasing level of interaction between mariculture activities and other users of coastal waters, which has at times led to serious conflicts between key stakeholders. Well-organized civil society organizations have also been successful in influencing public opinion against the expansion of mariculture activities in coastal waters in many parts of the world, calling for production to be moved further away from the coast (Lovatelli et al., 2013).

In many countries, it cannot be said that the development of the nearshore mariculture industry is viewed positively. It is certain that in the coming decades, many marine aquaculture activities will need to be relocated to open ocean areas (Soto & Wurmann, 2018). The reasons for this are as follows;

- Conflicts for coastal areas.
- Sanitary and environmental degradation, financial loss and instability.
- Deteriorating of coastal water quality.
- The cost of coastal marine areas.
- Negative perspective of coastal residents on aquaculture (Soto & Wurmann, 2018).

All food production activities have environmental impacts and aquaculture has much lower impacts than other terrestrial protein sources. This could be seen as an opportunity for the expansion of the aquaculture. The expansion of mariculture into open waters may reduce the negative sensitives about aquaculture due to the greater capacity of such waters to dilute wastes (Lovatelli et al., 2013).

In a situation where attempts are being made to restrict nearshore aquaculture, pushing the sector towards open sea aquaculture and even encouraging it should be seen as an opportunity for offshore aquaculture. In addition, the rapid developments in aquaculture and ship industry technology in recent years have increased the potential for offshore aquaculture and made it possible to realize it.

4.2. Challenges

In general, there are several main difficulties for offshore aquaculture systems. Investment and operating costs are quite high. It operates in the open sea under much more difficult conditions than coastal aquaculture systems. Due to such huge challenges, although offshore aquaculture is not widespread in the world at this stage, this sector has a high potential to make a leap forward with the impact of technological developments in the coming years.

There are some important operational aspects that are challenges for offshore aquaculture. Juvenile supply, feeding, grading, harvesting, cleaning, monitoring, waste management, keeping fish healthy, predators and vandalism prevention, biosecurity and well-trained personnel. All of which have to be carried out under difficult and dangerous conditions (Lovatelli et al., 2013).

4.2.1. High investment and management costs

Offshore aquaculture has so far been very limited. Many industry players are not keen to take the lead, probably due to the large initial investments, extra costs and more complex logistics involved in offshore transportation. Offshore aquaculture systems will require more investment than conventional aquaculture systems (Soto & Wurmann, 2018). Investment and all operational costs will increase. More expensive and special materials will be required for structures that will be exposed to more difficult conditions. These will require more frequent replacement compared to aquaculture farms closer to the coast (Morro et al., 2022). Coastal net cage operations are mostly based on systems made of high-density polyethylene pipes or galvanized steel frames supported by plastic floating boxes. However, significant changes and innovations in infrastructure are required for offshore fish farming. High infrastructure costs are one of the biggest challenges (Nguyen & Wang, 2024). Offshore aquaculture has high investment, high profit thresholds and many difficulties. Since it requires more investment in equipment construction, production and management costs are also high (Long et al., 2024). Economic viability of a commercial offshore aquaculture facility can only be achieved with a huge production (Lovatelli et al., 2013).

4.2.2. Site selection

Operating offshore aquaculture incurs additional transportation and operating costs. There is uncertainty about site selection, how structures designed for nearshore farms will be used offshore, and the response of each fish species to harsh conditions. In order to maximize fish welfare and minimize economic losses related to damage to structures, the selection of potential aquaculture sites must be done correctly and must be feasible in terms of legal permits and licenses (Morro et al., 2022). Correct site selection is very important in aquaculture to improve the economy and competitiveness of aquaculture. Different production models and strategies can be developed for each depth (Long et al., 2024).

4.2.3. Species selection

The tolerance of the aquaculture species to be raised in the harsh conditions of the offshore environment should be determined and the site selection should be determined accordingly (Morro et al., 2022). The selection of species should be made by considering the species features, market, environment, aquaculture technology and equipment (Long et al., 2024). It is necessary to produce high value-added seafood to cover high investment and operating costs (Dong et al., 2023b). Recently, some studies focused on fish species that might be suitable for offshore aquaculture. Yu et al. (2023) indicated that the growth performance and nutritional composition of the large yellow croaker reared in offshore vessel were better than in the cage.

4.2.4. Fish health and welfare

The offshore environment will affect aquaculture species both directly and indirectly. Strong currents and storms can alter fish behavior and produce benefits or detriments in terms of health and welfare (Morro et al., 2022).

4.2.5. Feeding

Storms and high winds in the open ocean make regular feeding and monitoring of fish quite challenging. Developing remote-controlled systems for precise feeding in an unstable environment is a priority (Lovatelli et al., 2013). In addition, suitable fish feeds for offshore aquaculture should be developed (Long et al., 2024).

4.2.6. Maintenance systems

Maintenance of marine fish farming is much more difficult to sustain in open sea environment than in sheltered sea (Lovatelli et al., 2013). Offshore aquaculture farming devices will be more expensive to operate and maintain. More sophisticated and expensive equipment and procedures are required highly trained personnel (Soto & Wurmann, 2018). To give an example for maintenance, when the net is submerged for a long time, biofouling organisms attach to it. In this case, net cleaning equipment will become an important device (Long et al., 2024).

4.2.7. Monitoring

Remote monitoring is well established in coastal and off-the-coast mariculture. Offshore aquaculture facilities will require more automation and remote control. Remote systems are ultimately to be a key part of offshore operations (Lovatelli et al., 2013).

4.2.8. Breeding

Advanced studies in breeding technology suitable for offshore aquaculture environmental conditions are needed (Long et al., 2024).

4.2.8. Harvesting

Manual method, crane and fish pumps are used in offshore fish farming for harvesting (Long et al., 2024).

4.2.9. Equipments

The existing equipment currently used in the industry has some disadvantages such as large size, high energy consumption, low efficiency and poor reliability (Long et al., 2024).

4.2.10. Facility Design

Aquaculture vessel is one of the offshore aquaculture production systems and it has great application potential in the field of aquaculture. On the other hand, there are some handicaps such as hull motion response and tank sloshing, which are impact the fish growth (Li et al., 2022b). Sloshing in a fish tank may alter the flow patterns and affect the welfare of fish (Li et al., 2022a). The response of the vessel to waves and sloshing in the tank can affect the aquaculture operations. Therefore, the hydrodynamic structure of the aquaculture vessel is important (Tao et al., 2023). Since the hull form design of the offshore aquaculture platform is complex, it is difficult to determine a globally optimum hull form (Feng et al., 2018).

5. Environmental Considerations of Offshore Aquaculture

The relationship between the development of offshore aquaculture and ecological conservation should be carried out in coordination (Long et al., 2024). Mariculture introduces high densities of additional life into the ocean, affecting the natural environment in diverse and complex ways. The magnitude of these effects varies depending on the characteristics of the operational activities. Location also plays an important role (Gentry et al., 2017).

The environmental risks associated with offshore aquaculture may be less than those associated with nearshore aquaculture. In deeper areas with high currents, organic matter is unlikely to significantly impact the seabed, cause local eutrophication, or cause other cumulative effects. However, offshore aquaculture operations may increase the risk of creating local conditions that could trigger phytoplankton blooms or lead to jellyfish outbreaks (Soto & Wurmann, 2018). It should not be overlooked that other environmental interactions, such as visual pollution, unpleasant odors, and excessive noise that may be important in nearshore mariculture activities may be of less concern in offshore aquaculture (Lovatelli et al., 2013). On the other hand, Soto & Wurmann (2018) reported that fish cages will be relatively far from the shore, some species such as salmon or mussels may have a low chance of interacting with local biodiversity or establishing a population.

6. Conclusion

Expansion of mariculture from coastal to offshore areas is an important strategy for aquaculture (Lovatelli et al., 2013). Offshore aquaculture is still in its infancy and more research is needed to learn more about this farming system and understand its interactions with its environment (Gentry et al., 2017). It should be aimed to strengthen ecological and environmental monitoring management in offshore aquaculture areas (Long et al., 2024). Engagements with authorities, local communities and other ocean users will be required for offshore aquaculture to become acceptable (Soto & Wurmann, 2018).

Consequently, it is a fact that fish perform much better in offshore locations where the water exchange is invariably greater. In addition, the problems faced by the mariculture sector in coastal areas are also well known. That's why most of the aquaculture operations around the world may need to be moved away from shore, especially to deeper offshore.

References

Beveridge, M.C.M. (2004). Cage Aquaculture. Oxford, UK, Blackwell Publishing.

Bilen S., Kızak V. & Gezen A.M. (2013). Floating fish farm unit (3FU). Is it an appropriate method for salmonid production? *Marine Science and Technology Bulletin*, 1(2), 9-13.

Buck B.H., Bjelland H.V., Bockus A., Chambers M., Costa-Pierce B.A., Dewhurst T., Ferreira J.G., Føre H.M., Fredriksson D.W., Goseberg N., Holmyard J., Isbert W., Krause G., Markus T., Papandroulakis N., Sclodnick T., Silkes B., Strand Å., Troell M., Wieczorek D., van den Burg S.W.K. & Heasman K.G. (2024). Resolving the term “offshore aquaculture” by decoupling “exposed” and “distance from the coast”. *Frontiers in Aquaculture*, 3, 1428056.

Cicin-Sain B., Bunsick S.M., Corbin J., DeVoe M.R., Eichenberg T., Ewart J., Firestone J., Fletcher K., Halvorson H., T. MacDonald T., Rayburn R. Rheault R. Thorne-Miller B., Didden J. & Blaydes M. (2005). Recommendations for an Operational Framework for Offshore Aquaculture in U.S. Federal Waters. Technical Report. Gerard J. Mangone Center for Marine Policy, University of Delaware.

Dong S.L., Dong Y.W., Huang L.Y., Zhou Y.G., Cao L., Tian X.L., Han L.M. & Li D.H. (2023a). Advancements and hurdles of deeper-offshore aquaculture in China. *Reviews in Aquaculture*, 16, 644–655.

Dong S., Dong Y., Huang L., Tian X., Han L., Li D. & Cao L. (2023b). Toward offshore aquaculture in China: opportunities, challenges and development strategies. *Journal of fisheries of China*, 47(3), 039601.

Feng Y., Chen Z., Dai Y., Wang F., Cai J. & Shen Z. (2018). Multidisciplinary optimization of an offshore aquaculture vessel hull form based on the support vector regression surrogate model. *Ocean Engineering*, 166, 145-158.

Froehlich H. E., Runge C.A., Gentry R.R., Gaines S.D. & Halpern B.S. (2018). Comparative terrestrial feed and land use of an aquaculture-dominant world. PNAS, vol. 115, no. 20, 5295–5300.

Gentry R.R., Lester S.E., Kappel C.V., White C., Bell T.W., Stevens J. & Gaines S.D. (2017). Offshore aquaculture: Spatial planning principles for sustainable development. *Ecology and Evolution*, 7, 733–743.

Knapp, G. 2013. The development of offshore aquaculture: an economic perspective. In A. Lovatelli, J. Aguilar-Manjarrez & D. Soto, eds. Expanding mariculture farther offshore: technical, environmental, spatial and governance challenges. FAO Technical Workshop, 22–25 March 2010, Orbetello, Italy. FAO Fisheries and Aquaculture Proceedings No. 24. Rome, FAO. pp. 201–244.

Li Z., Guo X. & Cui M. (2022a). Numerical investigation of flow characteristics in a rearing tank aboard an aquaculture vessel. *Aquacultural Engineering*, 98, 102272.

Li H., Sun Z., Han B., Shao Y. & Deng B. (2022b). Research on the motion response of aquaculture ship and tank sloshing under rolling resonance. *Brodogradnja*, 73, 2.

Long L., Liu H., Cui M., Zhang C. & Liu C. (2024). Offshore aquaculture in China. *Reviews in Aquaculture*, 16, 254–270.

Lovatelli, A., Aguilar-Manjarrez, J. & Soto, D. eds. (2013). Expanding mariculture farther offshore: technical, environmental, spatial and governance challenges. FAO Technical Workshop, 22–25 March 2010, Orbetello, Italy. FAO Fisheries and Aquaculture Proceedings No. 24. Rome, FAO. 73 pp.

Lu, H.Y., Cheng, C.Y., Cheng, S.C., Cheng, Y.H., Lo, W.C., Jiang, W.L., Nan, F.H., Chang, S.H. & Ubina, N.A. (2022). A Low-Cost AI Buoy System for Monitoring Water Quality at Offshore Aquaculture Cages. *Sensors*, 22, 4078.

Morro B., Davidson K., Adams T.P., Falconer L., Holloway M., Dale A., Aleynik D., Thies P.R., Khalid F., Hardwick J., Smith H., Gillibrand P.A. & Planellas S.R. (2022). Offshore aquaculture of finfish: Big expectations at sea. *Reviews in Aquaculture*, 14, 791–815.

Nguyen, H.P. & Wang, C.M. (2024). Advances in Offshore Aquaculture and Renewable Energy Production. Journal of Marine Science and Engineering, 12, 1679.

Soto D. & Wurmann C. (2018). Offshore Aquaculture: A Needed New Frontier for Farmed Fish at Sea. 379-384. The future of ocean governance and capacity development : essays in honor of Elisabeth Mann Borgese (1918–2002) / edited by the International Ocean Institute-Canada, Dirk Werle, Paul R. Boudreau, Mary R. Brooks, Michael J.A. Butler, Anthony Charles, Scott Coffen-Smout, David Griffiths, Ian McAllister, Moira L. McConnell, Ian Porter, Susan J. Rolston, and Peter G. Wells.

Tacon, A.G.J. & Halwart, M. (2007). Cage aquaculture: a global overview. In M. Halwart, D. Soto & J.R Arthur, eds. Cage aquaculture – regional reviews and global overview, pp. 1–16. Fisheries Technical Paper No. 498. Rome, FAO. 241 pp.

Tao Y., Zhu R., Gu J., Li Z., Zhang Z. & Xu X. (2023). Experimental and numerical investigation of the hydrodynamic response of an aquaculture vessel. *Ocean Engineering*, 279, 114505.

Xu Y.F., Xu H., Liu H., Chen Z.X. & Cui M.C. (2021). Research on the development way of deepsea mariculture in China. *Fish Modern*, 48(1), 9-15.

Yu, Y., Huang, W., Yin, F., Liu, H. & Cui, M. (2023). Aquaculture in an Offshore Ship: An On-Site Test of Large Yellow Croaker (*Larimichthys crocea*). *Journal of Marine Science and Engineering*, 11, 101.

CHAPTER V

Nanotechnology and Blue Crabs: Carbon Quantum Dots in Marine Conservation

Övgü GENCER[1]

1. Introduction

The blue crab (Callinectes sapidus) is an ecologically and economically significant marine species native to the western Atlantic Ocean, spanning regions from Nova Scotia to Argentina (Tanveer et al., 2023). Its introduction to other regions, such as the Mediterranean and the Black Sea, has further underscored its adaptability and ecological importance (Glandon & Miller, 2017).

Blue crabs play an integral role in marine ecosystems due to their omnivorous diet, feeding on algae, detritus, mollusks, and smaller fish, while also serving as prey for larger species, such as birds, fish, and marine mammals (Hines, 2007).

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Their habitats include estuaries, coastal lagoons, and salt marshes, where they exhibit remarkable resilience to fluctuating environmental conditions, including changes in salinity, temperature, and oxygen levels (Yesildemir & Celik, 2024). However, these same habitats are under constant pressure from anthropogenic activities such as pollution, overfishing, and habitat modification. Blue crabs are particularly vulnerable to pollutants like heavy metals, pesticides, and microplastics, which can accumulate in their bodies and impact their health, behavior, and reproductive success (Thompson et al., 2009).

Economically, blue crabs are a cornerstone of coastal fisheries, providing significant revenue through commercial and recreational fishing industries (Schiemer et al., 2024). The species is harvested for its meat and byproducts like chitin, which has industrial applications (Henry & Cameron, 1982). Despite its ecological and economic significance, the sustainability of blue crab populations is under threat due to environmental stressors, highlighting the need for innovative conservation and monitoring strategies.

CQDs represent an emerging class of nanomaterials that have garnered attention for their unique properties and versatility (Forward & Cohen, 2014). Typically synthesized from carbon precursors through chemical or green synthesis methods, CQDs are characterized by their small size (<10 nm), photoluminescent properties, chemical stability, and biocompatibility. These features make CQDs highly suitable for applications across biomedical, environmental, and biological research fields.

Fluorescence and Detection Abilities: CQDs exhibit strong fluorescence, which can be tuned across a range of wavelengths by altering their size or surface chemistry. This property is particularly useful in detecting and visualizing contaminants such as heavy metals and pesticides in marine environments (Thompson et al., 2009).

Biocompatibility and Low Toxicity: Unlike many traditional nanomaterials, CQDs are non-toxic and environmentally friendly, allowing their use in biological systems without adverse effects (Ries et al., 2009). Their application in marine studies minimizes ecological disturbance while providing precise data.

Customizable Functional Groups: CQDs' surfaces can be functionalized to interact with specific biological molecules or contaminants, making them highly adaptable for tracking pollutants or studying physiological processes in marine organisms (Ries et al., 2009).

Cost-Effectiveness and Scalability: Compared to other advanced materials, CQDs are relatively inexpensive to produce, especially using green synthesis methods. This scalability makes them an accessible option for widespread use in environmental monitoring (Boicourt & Johnson, 2011).

The integration of CQDs into marine biology research offers a transformative approach to studying blue crab populations and addressing the challenges posed by environmental stressors. This chapter explores the following key areas:

Monitoring Environmental Stressors: CQDs can be used as biosensors to detect the presence of heavy metals, pesticides, and microplastics in the habitats of blue crabs. Their fluorescence-based detection systems allow for real-time, sensitive analysis of pollutant concentrations (Thompson et al., 2009).

Studying Physiological Responses: By incorporating CQDs into research, scientists can trace metabolic and biochemical processes in blue crabs, providing insights into their physiological adaptations to stressors like temperature changes, salinity shifts, and pollution (Forward & Cohen, 2014).

Improving Conservation Strategies: The data collected using CQD-based technologies can inform better management practices, such as identifying critical habitats for protection or evaluating the effectiveness of pollution mitigation efforts (Schiemer et al., 2024).

Bridging Nanotechnology and Marine Conservation: This chapter aims to illustrate how the synergy between nanotechnology and marine ecology can address pressing conservation challenges. The unique properties of CQDs make them a powerful tool for ensuring the sustainability of blue crab populations and the ecosystems they inhabit (Doughtie & Rao, 1983).

2. The Ecological Significance of Blue Crabs

Blue crabs (*Callinectes sapidus*) play a dual role in marine ecosystems as both predators and prey, making them integral to maintaining biodiversity and ensuring energy flow across trophic levels. As predators, blue crabs exhibit omnivorous feeding habits, consuming a wide variety of prey, including bivalves, smaller crustaceans, fish, detritus, and plant material. This diverse diet allows them to regulate populations of other species, thereby influencing community structure and maintaining the balance of the ecosystem.

As prey, blue crabs serve as a critical food source for a variety of larger predators such as fish (e.g., striped bass and red drum), birds (e.g., herons and egrets), and marine mammals. This trophic connection ensures the transfer of energy and nutrients from lower levels of the food web to higher levels. Juvenile and soft-shelled blue crabs, particularly after molting, are especially vulnerable to predation, making them an essential link in the energy dynamics of estuarine and coastal ecosystems.

By fulfilling these dual ecological roles, blue crabs contribute to the overall health and resilience of their habitats. Their presence promotes species interactions that sustain ecosystem functionality, while their feeding and burrowing behaviors aid in nutrient cycling, sediment mixing, and habitat formation for other marine organisms.

The Importance of Blue Crabs in Commercial Fisheries, Local Economies, and as a Source of Protein

Blue crabs (*Callinectes sapidus*) play a vital role in commercial fisheries and local economies while serving as an essential source of protein. In regions such as the Gulf Coast of the United States and the Mediterranean, blue crabs are heavily harvested for their meat, making them one of the most economically valuable marine species (Tanveer et al., 2023). Their commercial and recreational fisheries collectively contribute billions of dollars annually to coastal economies through direct harvesting, processing, and associated industries (Schiemer et al., 2024).

Soft-shell crabs, which are harvested immediately after molting, are especially prized for their culinary value. The demand for blue crab meat supports various economic activities, including fishing, packaging, transportation, and retail, providing employment and economic stability in coastal communities (Henry & Cameron, 1982).

Nutritionally, blue crabs are a rich source of protein, omega-3 fatty acids, and essential micronutrients, making them an important dietary component in seafood-dependent regions (Hines, 2007). Their accessibility and affordability ensure that they contribute to food security in many coastal areas where protein sources are limited.

Also, the industrial use of blue crab byproducts, such as chitin and chitosan derived from their shells, has expanded their value beyond fisheries. These biopolymers are widely used in biotechnology, pharmaceuticals, and environmental remediation, underscoring the multifaceted economic significance of blue crabs (Ries et al., 2009).

Maintaining the sustainability of blue crab populations is crucial for preserving their contributions to local economies and food security. Effective management strategies and conservation measures are needed to mitigate the impacts of overfishing, habitat loss, and environmental stressors, ensuring that blue crabs continue to support human societies (Glandon & Miller, 2017).

2.1. Adaptability to Environmental Changes

Blue crabs (*Callinectes sapidus*) are renowned for their resilience and adaptability, thriving in diverse and dynamic environments such as estuaries, coastal lagoons, and salt marshes. Their ability to tolerate wide salinity ranges and fluctuating temperatures is attributed to advanced physiological mechanisms like osmoregulation and metabolic plasticity (Henry & Cameron, 1982). These adaptations allow them to colonize various habitats and maintain robust populations in the face of natural environmental changes.

However, despite their adaptability, blue crabs are highly vulnerable to anthropogenic stressors, including pollutants, climate change, and habitat disruption. Pollution from industrial, agricultural, and urban runoff introduces heavy metals, pesticides, and microplastics into their habitats. These contaminants accumulate in the blue crab's tissues, leading to oxidative stress, impaired metabolic functions, and reduced reproductive success (Thompson et al., 2009). For example, heavy metal toxicity can disrupt the nervous and immune systems, while microplastics can cause physical damage to their digestive tracts and interfere with nutrient absorption Yesildemir, O., & Celik, M. N. (2024). Climate change further exacerbates these challenges. Rising sea temperatures can accelerate their metabolic rates, increasing energy demands while reducing growth and reproductive capacities (Schneider et al., 2023). Additionally, ocean acidification, driven by increased CO_2 levels, weakens the calcium carbonate composition of their exoskeletons, leaving them more susceptible to predation and physical damage (Ries et al., 2009).

Habitat loss, often caused by coastal development, dredging, and erosion, further threatens blue crab populations by reducing the availability of critical nursery and breeding grounds. Estuarine degradation, combined with overfishing during breeding seasons, puts additional pressure on their already vulnerable populations (Glandon & Miller, 2017).

Despite these vulnerabilities, the blue crab's ecological importance as both predator and prey makes its conservation essential for maintaining marine biodiversity and ecosystem balance. Understanding the interplay between their adaptability and the stressors they face is critical for developing effective management and conservation strategies.

3. Environmental Stressors Affecting Blue Crab Populations

3.1. *Pollution and Contaminants: Impacts on Blue Crabs*

The habitats of blue crabs (*Callinectes sapidus*), such as estuaries and coastal lagoons, are increasingly threatened by pollution from industrial, agricultural, and urban sources. These contaminants, including heavy metals, pesticides, and other chemicals, pose significant risks to the health, behavior, and reproductive success of blue crab populations.

3.1.1.Heavy Metals

Heavy metals such as cadmium, lead, and mercury are common pollutants in coastal habitats, often introduced through industrial discharge and urban runoff. These metals bioaccumulate in the tissues of blue crabs, causing severe physiological disruptions. Heavy metal exposure can impair nervous system function, leading to reduced motor skills and slower reflexes, which diminish the crab's ability to evade predators or catch prey (Doughtie & Rao, 1983). Also, oxidative stress caused by heavy metals disrupts antioxidant defense systems, damaging proteins, lipids, and DNA, which can result in developmental and reproductive failures (Ries et al., 2009).

3.1.2.Pesticides

Agricultural runoff introduces a variety of pesticides into aquatic ecosystems, many of which have endocrine-disrupting properties. These chemicals interfere with hormonal pathways, leading to abnormalities in growth and reproduction. For example, studies have shown that pesticide exposure can suppress egg production in female blue crabs and reduce larval survival rates (Fisher & Foss, 1993). Pesticides also affect the nervous system, causing behavioral changes such as reduced foraging efficiency and altered migration patterns, which further impact survival and reproduction.

3.1.3. Microplastics and Associated Chemicals

Microplastics, often accompanied by chemical additives and adsorbed pollutants, are another significant contaminant in blue crab habitats. Blue crabs can ingest microplastics either directly or through their prey, leading to physical blockages in the digestive tract and reduced nutrient absorption (Thompson et al., 2009). The chemical additives in microplastics, such as phthalates and bisphenols, act as endocrine disruptors, negatively affecting growth, metabolism, and reproduction.

3.1.4. Combined Effects

The synergistic effects of these contaminants amplify their impact on blue crab populations. For example, heavy metals combined with hypoxic conditions in polluted estuaries can exacerbate stress responses, leading to higher mortality rates (Glandon & Miller, 2017). Similarly, pesticide exposure alongside habitat degradation further reduces reproductive success and larval recruitment, threatening population sustainability.

3.1.5. Reproductive Success

The reproductive cycle of blue crabs is particularly sensitive to contaminants. Heavy metals and pesticides have been linked to decreased fecundity and egg viability, while microplastic ingestion affects energy allocation, reducing the resources available for reproduction (Ries et al., 2009).

Larval stages are especially vulnerable, as pollutants can impair developmental processes and increase susceptibility to predation and disease.

By compromising health, altering behavior, and suppressing reproductive capabilities, these pollutants pose a severe threat to the sustainability of blue crab populations. Addressing these issues requires a combination of pollution control, habitat restoration, and targeted conservation efforts to mitigate the impacts of contaminants.

3.2. Climate Change Impacts on Blue Crabs

Climate change presents a complex set of challenges for blue crabs (*Callinectes sapidus*), impacting their physiology, habitat range, and overall population dynamics. Rising ocean temperatures, acidification, and salinity fluctuations are among the most significant stressors driven by climate change, with cascading effects on blue crab survival and ecological roles.

3.2.1. Rising Ocean Temperatures

Increased sea surface temperatures accelerate the metabolism of blue crabs, raising their energy demands (Schneider et al., 2023).

While this metabolic increase can enhance growth rates in moderate conditions, prolonged exposure to elevated temperatures leads to energy deficits, physiological stress, and reduced reproductive success. For example, female blue crabs experience declines in egg production under heat stress, while larval development rates are impaired, decreasing survival (Forward et al., 2024). Higher temperatures also increase susceptibility to disease and predation, particularly in juvenile and molting individuals.

Additionally, the thermal tolerance of blue crabs influences their geographic distribution. Warmer temperatures have enabled the expansion of blue crab populations into previously unsuitable northern waters, such as areas along the northeastern United States and parts of Europe (Boicourt & Johnson, 2011).

However, this range expansion may disrupt local ecosystems and lead to increased competition with native species.

3.2.2. Ocean Acidification

Ocean acidification, caused by rising atmospheric CO_2 levels, directly impacts blue crab physiology by altering the availability of carbonate ions needed for shell formation. Lower pH levels weaken the calcium carbonate structure of blue crab exoskeletons, reducing their defense against predators and environmental stressors (Ries et al., 2009). Acidified waters also interfere with the molting process (ecdysis), causing delays in shell hardening and increasing vulnerability during this critical period (Ries et al., 2009).

Additionally, acidification affects internal processes such as respiration and ion regulation. Hemolymph pH levels in blue crabs are sensitive to external acidification, requiring additional energy to maintain homeostasis. This increased energy expenditure reduces resources available for growth, reproduction, and immune functions (Yesildemir & Celik, 2024).

3.2.3. Changes in Salinity

Fluctuations in salinity caused by climate change-driven alterations in rainfall, storm patterns, and sea level rise also present significant challenges. Blue crabs are euryhaline, capable of tolerating a wide range of salinity levels, but extreme or rapid changes can disrupt osmoregulation. Sudden decreases in salinity due to freshwater influx from heavy rainfall or storms can dilute hemolymph, impairing physiological functions (Marci, 2023). Conversely, higher salinity levels from reduced freshwater input can create hyperosmotic stress, affecting metabolic efficiency and increasing mortality rates.

Salinity changes also influence habitat suitability and reproduction. For example, spawning females prefer brackish waters with stable salinity levels for optimal larval development. Alterations in salinity gradients can disrupt these preferences, leading to reduced larval survival and population declines in affected regions (Hines, 2007).

3.2.4. Cumulative Impacts and Adaptation

The combined effects of rising temperatures, acidification, and salinity changes amplify the stress on blue crabs. These stressors interact in complex ways, such as higher temperatures exacerbating the physiological effects of low pH or salinity fluctuations compounding the energetic costs of homeostasis. While blue crabs have demonstrated remarkable adaptability to environmental changes, the pace and magnitude of climate change may exceed their adaptive capacity.

Populations in areas like the Gulf of Mexico and Chesapeake Bay are particularly vulnerable due to the compounded effects of warming, acidification, and habitat loss. Targeted conservation strategies, such as habitat restoration and adaptive fisheries management, are essential to mitigate these impacts and ensure the sustainability of blue crab populations (Glandon & Miller, 2017).

3.2.5. Habitat Degradation and Its Impact on Blue Crab Populations

3.2.5.1. Loss of Crucial Habitats

Blue crabs (*Callinectes sapidus*) rely heavily on estuaries and coastal wetlands for critical life stages such as reproduction, feeding, and larval development. These habitats provide shelter from predators and serve as nutrient-rich areas that are vital for sustaining healthy populations. However, ongoing habitat degradation poses a severe threat to the survival and population dynamics of this species.

3.2.5.2. Coastal Development

Rapid urbanization and industrial expansion along coastlines lead to habitat loss through land reclamation, dredging, and the construction of infrastructure. Estuaries and wetlands, being transitional zones between land and sea, are particularly vulnerable. The removal of these habitats disrupts the delicate balance of the ecosystem, depriving blue crabs of breeding grounds and food sources (Glandon & Miller, 2017).

3.2.5.3. Overfishing

While blue crabs are a commercially important species, excessive fishing pressure can inadvertently damage their habitats. Fishing practices, such as trawling, disturb seabed ecosystems and degrade the structural integrity of the habitats. Overharvesting also disrupts population dynamics, particularly when mature, reproductive individuals are removed before they can contribute to the population's renewal (Schiemer et al., 2024).

3.2.5.4. Pollution

Pollution from agricultural runoff, urban waste, and industrial discharge introduces harmful substances such as heavy metals, pesticides, and microplastics into blue crab habitats. These contaminants not only affect the water quality but also degrade the physical and biological characteristics of estuarine environments, making them less habitable for blue crabs. For example, hypoxic (low oxygen) zones caused by nutrient overloading severely limit the availability of viable habitats for larval and juvenile development (Yesildemir & Celik, 2024).

3.2.5.5. Effects on Population Dynamics

Habitat degradation has cascading effects on blue crab population dynamics. The loss of breeding grounds reduces reproductive success, leading to lower recruitment of juveniles into the population. In addition, compromised habitats fail to provide adequate protection and food, resulting in increased predation and competition among individuals. These stressors cumulatively lead to population declines and threaten the species' long-term sustainability.

For example, studies have shown that blue crabs in degraded estuarine environments exhibit reduced growth rates, weakened immune systems, and higher mortality due to increased exposure to predators and adverse environmental conditions (Ries et al., 2009). The diminished carrying capacity of these habitats further exacerbates the impact, as they can no longer support the same population densities as before.

3.2.5.6. Conservation Implications

Addressing habitat degradation is critical for the conservation of blue crabs. Efforts such as habitat restoration, pollution control, and the establishment of marine protected areas (MPAs) can help mitigate the negative effects of habitat loss. Restored wetlands and estuaries not only benefit blue crabs but also enhance overall ecosystem health, supporting a diversity of species that depend on these habitats.

4. Overview of CQDs and Their Properties

4.1. Definition and Composition of CQDs

CQDs are nanoscale carbon-based particles with diameters typically less than 10 nanometers. They possess a unique sp^2/sp^3 carbon structure and functional groups on their surface, which contribute to their remarkable properties, including high fluorescence, excellent photostability, and tunable optical characteristics (Hines, 2007). CQDs are derived from organic or carbon-rich precursors through methods like pyrolysis, hydrothermal processing, or chemical oxidation. Their biocompatibility and low toxicity make them particularly appealing for biological and environmental applications, distinguishing them from other quantum dots based on heavy metals.

4.2. Applications in Marine Science

CQDs have emerged as a transformative tool in marine science due to their multifunctionality and adaptability. Their ability to fluoresce under ultraviolet or visible light has facilitated their use in biological imaging to study the physiology and behavior of marine organisms. For example, CQDs can be conjugated with specific biomolecules to track cellular processes or to identify pollutant-induced stress in marine species like blue crabs (Callinectes sapidus) (Carré et al., 2017).

In environmental monitoring, CQDs have demonstrated remarkable efficacy in detecting pollutants such as heavy metals, pesticides, and organic contaminants in marine ecosystems. Functionalized CQDs can serve as sensors that bind selectively to target molecules, enabling real-time and precise detection of environmental pollutants (Henry & Cameron, 1982). Their sensitivity and rapid response times make them invaluable for monitoring water quality in estuarine and coastal habitats.

Additionally, CQDs are used in pollutant remediation research. Their ability to interact with contaminants through adsorption or photocatalysis allows for potential applications in mitigating marine pollution, which directly benefits species like blue crabs that inhabit vulnerable estuarine environments (Gao & Wang, 2023).

4.3. Advantages Over Traditional Methods

Compared to traditional nanomaterials like metal-based quantum dots, CQDs offer several advantages in marine research:

Safety and Biocompatibility: Unlike heavy-metal quantum dots, CQDs exhibit negligible toxicity, minimizing harm to marine organisms and ecosystems during studies (Hines, 2007).

Stability and Versatility: CQDs are resistant to photobleaching and can be modified with diverse surface chemistries, enabling tailored applications across various environmental and biological contexts (Carré et al., 2017).

Cost-effectiveness and Sustainability: CQDs can be synthesized from renewable and inexpensive precursors, making them a sustainable choice for large-scale environmental monitoring and research (Gao & Wang, 2023).

These properties position CQDs as a safer and more efficient alternative for studying marine organisms and ecosystems. By offering insights into the interactions between species like blue crabs and their environment, CQDs contribute significantly to advancing marine science and conservation efforts.

5. Innovative Uses of CQDs in Blue Crab Research

5.1. Pollution Monitoring and Detection

CQDs are gaining prominence as efficient, low-cost sensors for pollution monitoring in aquatic environments, particularly in sensitive estuarine and coastal ecosystems inhabited by blue crabs (Callinectes sapidus). The inherent fluorescence of CQDs, combined with their functionalizable surface chemistry, allows them to act as molecular probes that detect and quantify contaminants with exceptional sensitivity.

Detection of Heavy Metals**:** Heavy metals like mercury, cadmium, and lead are highly toxic pollutants in blue crab habitats, often stemming from industrial runoff or urban wastewater. CQDs functionalized with thiol or amine groups bind selectively to metal ions, altering their fluorescence intensity or emission wavelength. This property has been harnessed to develop portable water-testing kits capable of detecting trace concentrations of heavy metals in real time (Henry & Cameron, 1982). The early detection of such contaminants allows researchers and policymakers to identify polluted zones and implement immediate conservation measures.

Pesticide Monitoring**:** CQDs are also being utilized to detect organophosphates and other agricultural pesticides that leach into blue crab habitats. Modified CQDs can form complexes with pesticide molecules, triggering fluorescence changes. This capability offers an eco-friendly alternative to traditional chemical assays, which often involve hazardous reagents and are less sensitive to low-level contamination (Thompson et al., 2009).

Multifunctional Environmental Sensors**:** Advanced CQD-based devices integrate pollutant detection with environmental parameter monitoring, such as pH and salinity levels. This holistic approach helps assess multiple stress factors affecting blue crab populations, providing a more comprehensive understanding of their habitat conditions (Hines, 2007).

5.2. Studying Physiological Responses in Blue Crabs

The unique fluorescence and biocompatibility of CQDs make them ideal tools for studying how blue crabs physiologically respond to environmental stressors such as pollution, temperature fluctuations, and hypoxia.

Tracking Metabolic Changes: CQDs conjugated with metabolic markers or reactive oxygen species (ROS) probes can reveal how blue crabs manage oxidative stress when exposed to contaminants or fluctuating temperatures. For example, ROS-sensitive CQDs can fluoresce in the presence of oxidative molecules, enabling researchers to quantify stress-induced cellular damage in real time (Carré et al., 2017). This application is critical for understanding how stress impacts key organs like the hepatopancreas, which regulates digestion and detoxification in blue crabs. Imaging of Tissue Responses: CQDs can penetrate biological tissues without disrupting cellular functions, allowing for in vivo imaging of stress responses. For example, they can visualize changes in hemolymph oxygenation during hypoxic events, helping researchers study how crabs adapt to oxygen-depleted environments. This insight can inform conservation strategies by identifying physiological thresholds beyond which blue crab populations cannot survive (Gao & Wang, 2023).

Enzyme Activity Monitoring**:** CQDs have been employed to track changes in enzymatic activities related to stress adaptation, such as esterases involved in detoxification processes. By conjugating CQDs with enzyme-specific substrates, researchers can monitor enzymatic kinetics and infer the health status of blue crabs in polluted waters (Marci, 2023).

5.3. Tracking Environmental Exposure

CQDs are increasingly being used as biomarkers to trace the pathways and accumulation of pollutants within blue crab tissues, offering precise insights into how contaminants affect these organisms.

Bioaccumulation Studies**:** When introduced into blue crab habitats, CQDs can bind to contaminants such as hydrocarbons, pesticides, or heavy metals. Once ingested or absorbed by the crabs, CQDs fluoresce under specific wavelengths, enabling researchers to map the distribution of pollutants within the crabs' tissues. This approach provides valuable data on the bioaccumulation of toxic substances and their physiological impacts (Glandon & Miller, 2017).

Pollutant Pathway Analysis**:** By tagging CQDs with fluorescent dyes, researchers can track the movement of pollutants through the blue crab’s digestive system, hemolymph, and exoskeleton. This technique helps identify the specific organs and processes most affected by exposure, such as disruptions in nutrient absorption or hormonal regulation.

Population-Level Exposure Monitoring**:** CQDs can also be used to study environmental exposure across entire populations. For example, deploying CQDs in heavily polluted regions and observing their uptake in sampled crabs provides a population-wide assessment of contaminant levels, enabling the identification of high-risk areas (Ries et al., 2009).

5.4. Benefits of CQDs in Blue Crab Research

The use of CQDs in blue crab research offers several advantages:

Precision and Sensitivity**:** CQDs allow researchers to detect and monitor low concentrations of contaminants and subtle physiological changes with high precision.

Non-Invasive Applications**:** CQDs enable in vivo studies without harming the organisms, preserving their natural behavior and health.

Cost-Effectiveness**:** CQDs are relatively inexpensive to synthesize and apply, making them accessible for widespread environmental monitoring.

Eco-Friendly Alternatives**:** Unlike traditional methods, CQDs minimize environmental harm by avoiding the use of toxic reagents.

By integrating CQDs into blue crab research, scientists can deepen their understanding of the species' responses to environmental changes and enhance conservation efforts.

6. Conservation and Management Strategies Enhanced by CQDs

6.1. Real-Time Environmental Monitoring

CQDs have the potential to revolutionize environmental monitoring in blue crab (Callinectes sapidus) habitats by enabling real-time, portable, and highly sensitive water quality assessments. By incorporating CQDs into handheld or automated sensors, researchers and conservationists can rapidly detect pollutants such as heavy metals, pesticides, and other toxic substances. These devices can provide immediate feedback on the presence and concentration of contaminants, allowing for swift intervention to mitigate environmental damage (Henry & Cameron, 1982).

For example, CQD-based sensors deployed in estuarine and coastal regions can track pollution levels over time, helping to identify pollution sources and patterns. The portability and affordability of these devices also make them accessible for use by local communities and small-scale fishers, fostering participatory conservation efforts. By providing accurate and timely data, these monitoring systems ensure that habitat disruptions are detected early, minimizing the risk of long-term damage to blue crab populations (Carré et al., 2017).

6.2. Sustainable Fisheries and Aquaculture Practices

CQDs offer innovative solutions for promoting sustainable blue crab fisheries and aquaculture practices. In aquaculture, water quality directly impacts the health and productivity of farmed blue crabs. CQDs can be used to continuously monitor critical parameters such as pH, dissolved oxygen, and pollutant levels, ensuring that farming environments remain optimal for crab growth and reproduction (Thompson et al., 2009).

Additionally, CQDs can be applied to detect early signs of disease or stress in aquaculture systems. For example, fluorescent CQDs can be conjugated with biomarkers to identify physiological changes in crabs due to environmental stress or pathogen exposure. These diagnostic tools enable early interventions, reducing mortality rates and ensuring the sustainability of aquaculture operations.

Sustainable practices supported by CQD technology can also extend to wild fisheries. By monitoring the health of natural habitats and the stress levels of wild crab populations, CQDs help maintain ecological balance and prevent overexploitation. This approach aligns with global efforts to ensure that blue crab fisheries contribute to food security and economic growth without compromising long-term environmental stability (Marci, 2023).

6.3. Improved Data for Policy Making

The integration of CQD-based tools in blue crab research provides reliable, high-resolution data that can inform evidence-based policymaking. By offering precise measurements of pollutant concentrations, habitat conditions, and crab health metrics, CQDs enhance the accuracy of ecological assessments, enabling policymakers to make informed decisions about marine conservation and management.

Pollution Control Policies: Data gathered using CQDs can guide regulations to reduce industrial and agricultural runoff, mitigating the impact of pollutants on blue crab habitats. For example, identifying hotspots of heavy metal contamination can help target specific industries for stricter waste management protocols (Ries et al., 2009).

Marine Protected Areas (MPAs)**:** CQD applications can aid in determining critical habitats for blue crab reproduction and growth, supporting the designation and management of MPAs. By monitoring water quality and crab health within these areas, CQDs ensure that conservation efforts remain effective and adaptive to changing environmental conditions.

Climate Change Adaptation Strategies**:** CQD-based tracking of environmental stressors, such as temperature fluctuations and acidification, can provide crucial insights into the impacts of climate change on blue crab populations. This information enables the development of targeted strategies to enhance resilience and mitigate climate-induced habitat loss (Glandon & Miller, 2017).

7. Future Directions and Potential Research Areas

7.1. Future Directions in CQD Applications for Blue Crab Conservation

Further Development of CQD Sensors and Markers

The continued evolution of Carbon Quantum Dot (CQD) sensors and markers is essential to address the growing challenges in marine biology and ecological research. Advanced CQD-based tools can be tailored to detect specific environmental stressors in blue crab habitats, such as complex chemical mixtures or minute variations in water parameters like salinity and temperature.

Enhanced Specificity and Sensitivity**:** Future CQD sensors should focus on improving the selectivity of pollutant detection, such as differentiating between various heavy metals or pesticide residues. These advancements could lead to real-time, highly localized data, which is crucial for identifying specific threats to blue crab populations (Henry & Cameron, 1982).

Multi-Functional Sensors**:** Developing multi-analyte CQD sensors that can simultaneously detect multiple contaminants and environmental conditions (e.g., pH, oxygen levels) would provide a comprehensive view of habitat health. This functionality would enhance conservationists' ability to respond to complex, multifactorial stressors in marine ecosystems (Carré et al., 2017).

Long-Term Monitoring Tools**:** CQDs with improved photostability and environmental durability could be used in long-term deployment scenarios, such as autonomous underwater monitoring systems. These systems would continuously gather critical data on blue crab habitats, enabling proactive management strategies (Hines, 2007).

7.2. Ecological Modeling with CQDs

Integrating data derived from CQD applications into ecological models can transform our understanding of how environmental stressors impact blue crab populations and their ecosystems.

Predictive Modeling of Climate Change Effects**:** CQD-derived data on temperature tolerance, salinity changes, and acidification impacts can be used to simulate future scenarios for blue crab populations. These models would help predict distribution shifts, reproduction success rates, and population dynamics under various climate change projections (Glandon & Miller, 2017).

Ecosystem Interactions and Stressor Mapping**:** By incorporating CQD-based pollutant tracking and physiological response data, ecological models can map stressor interactions at a systems level. This approach could reveal cascading effects of pollution and habitat degradation on blue crabs and associated species, aiding in ecosystem-level conservation efforts (Gao & Wang, 2023).

Risk Assessment and Habitat Management**:** Modeling can also help prioritize high-risk areas for intervention, guiding resource allocation for habitat restoration and pollution mitigation efforts. Using CQDs to validate model predictions would improve their accuracy and reliability, making them valuable tools for long-term conservation planning.

7.3. Exploring Synergies with Other Nanotechnologies

CQDs have significant potential to complement other emerging nanotechnologies, creating synergies that could enhance research capabilities and ecological understanding of marine species like blue crabs.

Nanomaterial Composites**:** Combining CQDs with nanomaterials such as metal-organic frameworks (MOFs) or graphene derivatives could yield composite materials with enhanced pollutant detection, adsorption, or imaging properties. These composites could be employed in advanced research to tackle complex environmental challenges (Thompson et al., 2009).

Bio-Nanotechnology Integration: CQDs can be coupled with biomimetic structures or enzymes to study intricate physiological and behavioral responses in blue crabs. For example, integrating CQDs with protein-based sensors could provide deeper insights into metabolic pathways affected by environmental stressors (Marci, 2023).

Sustainable Remediation Techniques**:** **S**ynergizing CQDs with other nanotechnologies may also support the development of eco-friendly remediation approaches. For example, using CQDs in tandem with photocatalytic nanomaterials could improve the efficiency of removing pollutants from blue crab habitats, directly benefiting their survival and reproduction (Ries et al., 2009).

8. Conclusion

Blue crabs (*Callinectes sapidus*) are an ecologically and economically critical species, serving as a key component in marine food webs and a valuable resource in global fisheries. This chapter explored their roles as both predators and prey, their adaptability to diverse marine environments, and their vulnerability to anthropogenic stressors such as pollution, climate change, and habitat degradation. Environmental challenges, including heavy metal contamination, ocean acidification, and rising temperatures, threaten the health and sustainability of blue crab populations.

The introduction of CQDs was presented as a novel approach to addressing these challenges. Their unique properties, including fluorescence, biocompatibility, and sensitivity to environmental changes, allow for groundbreaking applications in marine research. CQDs offer innovative methods for monitoring pollutants, visualizing physiological responses, and tracking environmental stressors. This integration provides critical insights into the health and dynamics of blue crab populations, enhancing the ability to protect these species amid global environmental shifts.

8.1. Significance of CQD Integration in Marine Conservation

CQDs mark a paradigm shift in the tools available for marine conservation. Their application extends beyond traditional pollutant detection, providing real-time, dynamic data that can shape proactive conservation strategies. Key advantages include:

Enhanced Monitoring Capabilities**:** CQDs enable continuous and highly accurate assessments of water quality in habitats critical to blue crabs. This helps identify emerging threats early, preventing large-scale habitat degradation and population declines.

Precision in Physiological Studies**:** CQDs facilitate a deeper understanding of how environmental stressors affect blue crabs on a cellular and systemic level. This data can inform targeted conservation interventions, such as habitat restoration or pollution reduction.

Sustainability and Scalability**:** As eco-friendly and cost-effective tools, CQDs are suitable for widespread use, supporting conservation efforts in resource-limited regions where blue crabs are vital to local economies.

Their use bridges gaps between scientific research and practical conservation, offering a scalable solution to mitigate the adverse impacts of human activity and climate change on marine ecosystems.

8.2. Call for Multidisciplinary Research

To fully realize the potential of CQDs in marine conservation, it is imperative to foster collaboration across disciplines. The following avenues highlight the need for interdisciplinary efforts:

Refinement of CQD-Based Tools**:** Continued advancements in CQD synthesis and functionalization are required to enhance their specificity and sensitivity for various applications. Tailoring CQDs for specific pollutants or stress markers in blue crabs will improve their effectiveness in monitoring and diagnostic tasks (Henry & Cameron, 1982).

Integration with Ecological Modeling**:** Data gathered through CQD applications can be incorporated into predictive models, helping researchers understand the long-term impacts of stressors on blue crab populations. This modeling can simulate future scenarios under different climate change and pollution conditions, guiding conservation policies and habitat management (Glandon & Miller, 2017).

Exploration of Synergistic Technologies**:** Combining CQDs with other emerging technologies, such as artificial intelligence (AI) for data analysis or metal-organic frameworks (MOFs) for pollutant remediation, can create comprehensive solutions for marine ecosystem challenges. These synergies can expand the scope of CQDs in marine biology and conservation (Hines, 2007).

Strengthening Stakeholder Engagement**:** Collaboration with policymakers, conservation organizations, and local communities is essential for translating CQD research into actionable strategies. Multidisciplinary teams can bridge the gap between scientific findings and practical implementation, ensuring that the benefits of CQDs reach conservation efforts on the ground.

8.3. The Path Forward

Looking ahead, CQDs offer an exciting opportunity to redefine how we approach marine conservation. Their ability to provide accurate, real-time data empowers scientists and policymakers to tackle some of the most pressing challenges in marine ecosystems. However, the realization of their full potential depends on:

Increased investment in CQD research and technology development,

Collaborative efforts to standardize their applications in marine contexts,

Policies that integrate these advanced tools into conservation frameworks.

The resilience of blue crabs and their vital role in marine ecosystems make them a compelling case study for the integration of CQDs in conservation science. As a promising convergence of nanotechnology and marine biology, CQDs offer a hopeful avenue for protecting not just blue crabs but the broader biodiversity of marine ecosystems.

References

Boicourt, K., & Johnson, Z. (2011). Comprehensive strategy for reducing Maryland's vulnerability to climate change: Phase II: Building societal, economic, and ecological resilience. *Maryland Department of Natural Resources*.

Carré, J., Gatimel, N., Moreau, J., Parinaud, J., & Léandri, R. (2017). Does air pollution play a role in infertility?: A systematic review. *Environmental Health*, 16(1), 82.

Doughtie, D. G., & Rao, K. R. (1983). Ultrastructural and histochemical study of the hepatopancreas of the blue crab, *Callinectes sapidus*. *Journal of Morphology*, 178(1), 1–22.

Fisher, W. S., & Foss, S. S. (1993). A simple test for effects of environmental pollutants on bivalve and crustacean immune functions. *Aquatic Toxicology*, 26(1-2), 1–14.

Forward, R. B., & Cohen, J. H. (2014). The effect of environmental factors on the larval release rhythms of estuarine crabs. *Integrative and Comparative Biology*, 54(2), 199–211.

Gao, F., & Wang, X. (2023). Photocatalytic degradation of marine pollutants using carbon-based nanomaterials: A review. *Journal of Environmental Chemical Engineering*, 11(1), 109–118.

Glandon, H. L., & Miller, T. J. (2017). No effect of low pH on juvenile blue crab *Callinectes sapidus* metabolism in the presence of a predator cue. *Journal of Experimental Marine Biology and Ecology*, 489, 32–37.

Henry, R. P., & Cameron, J. N. (1982). The distribution and partial characterization of carbonic anhydrase in selected aquatic and terrestrial decapod crustaceans. *The Biological Bulletin*, 163(1), 45–57.

Hines, A. H. (2007). Ecology of juvenile and adult blue crabs. In *The Blue Crab: Callinectes sapidus* (pp. 565–654). Maryland Sea Grant College.

Marci, R. (Ed.). (2023). *Environment impact on reproductive health: A translational approach*. Springer.

Ries, J. B., Cohen, A. L., & McCorkle, D. C. (2009). Marine calcifiers exhibit mixed responses to CO_2-induced ocean acidification. *Geology*, 37(12), 1131–1134.

Schiemer, F., Simon, D., & Amarasinghe, U. S. (2024). Sustainable aquatic resource management and inland fisheries in tropical Asia: Lessons learned. *Ambio*, 53(4), 605–617.

Schneider, A. K., Fabrizio, M. C., & Lipcius, R. N. (2023). Reproductive phenology of the Chesapeake Bay blue crab population in a changing climate. *Frontiers in Ecology and Evolution*, 11, 1304021.

Tanveer, M., Mansha, N., Khawar, M. B., Afzal, A., & Shahzaman, S. (2023). Microplastics: Unraveling the signaling pathways involved in reproductive health. *Environmental Science and Pollution Research*, 30(50), 95077–95085.

Thompson, R. C., Moore, C. J., vom Saal, F. S., & Swan, S. H. (2009). Plastics, the environment and human health: Current consensus and future trends. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 364(1526), 2153–2166.

Yesildemir, O., & Celik, M. N. (2024). The effect of various environmental pollutants on the reproductive health in children: A brief review of the literature. *Current Nutrition Reports*, 13(3), 382–392.

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