WANTOFISH

E-BOOK

developing a digital-based curriculum of WAter footprINT awareness in mediterranean FISHeries for sustainable resources in europe

Project No.: 2024-1-TR01-KA220-HED-000247730

2026



TÜRKİYE ULUSAL AJANSI
TURKISH NATIONAL AGENCY

Co-funded by the Erasmus+ Programme of the European Union

BİDGE Yayınları

WANTOFISH - DEVELOPING A DIGITAL-BASED CURRICULUM OF WATER FOOTPRINT AWARENESS IN MEDITERRANEAN FISHERIES FOR SUSTAINABLE RESOURCES IN EUROPE

Editors: Prof. Dr. İlker AYDIN & Prof. Dr. Özgür ALTAN

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ABOUT THE PROJECT

WANTOFISH is an Erasmus+ Cooperation Partnership in Higher Education that promotes awareness and understanding of the water footprint associated with fisheries, aquaculture and fish-processing activities.

Bringing together partner organisations from Türkiye, Spain, Croatia, Greece and Italy, the project combines scientific knowledge, educational experience and digital learning to support more sustainable practices in the Mediterranean fisheries and aquaculture sectors.

Through its educational resources, WANTOFISH aims to help students, educators, researchers and professionals better understand water use, assess its environmental implications and explore practical approaches to protecting aquatic resources.

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PREFACE

In an era where the delicate equilibrium of our global aquatic systems stands at a critical environmental crossroads, it is a profound privilege and an immense source of pride to present this definitive scientific compendium. As the coordinator of the WANTOFISH project, this initiative represents a crowning achievement for both Türkiye and Ege University. Notably, it marks our second consecutive large-scale project secured under the prestigious Erasmus+ KA220 category, solidifying our institution's leadership in international academic collaboration and sustainable aquatic research.

This project owes its success to the dedication of outstanding, elite researchers and experts from five different countries. Through their cross-border collaboration and tireless commitment, every complex milestone of the project has been successfully realized. This e-book serves as one of the primary, comprehensive scientific outputs of that global synergy, translating rigorous multi-disciplinary research into an accessible educational instrument for the future.

At the core of this scientific output lie specialized modules that meticulously explore innovative water management, sustainable aquaculture, and cleaner processing technologies. More importantly, the content places a pivotal emphasis on the strategic management and holistic sustainability of commercial fisheries. By integrating data-driven water footprint metrics into policy frameworks, these modules provide the essential tools required to

curb overexploitation, mitigate climate risks, and secure a resilient blue economy. Ultimately, this comprehensive curriculum is designed to transform contemporary fishing practices, ensuring that the precious bounty of our seas is not just managed for today, but preserved as a thriving, sustainable heritage for future generations.

On a personal note, this work is deeply intertwined with my lifelong passion. My affection for nature, my profound love for the sea, and my lifelong dedication to fisheries are not merely components of my career they are the very core of my identity. I am profoundly in love with my profession. Witnessing the escalating environmental challenges and severe water scarcity across our blue planet has only strengthened my resolve. We no longer have the luxury of indifference; it is an absolute necessity and our ultimate responsibility to fulfill our duties to protect our aquatic resources for the global future.

It is my ultimate hope that this scientific volume inspires researchers, students, and professionals to embrace water stewardship in fisheries and aquaculture, ensuring that our oceans and freshwaters thrive for generations to come.

Prof. Dr. İlker AYDIN
Project Coordinator, Ege University

2026

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MODULE 1. INTRODUCTION TO WATER FOOTPRINT IN FISHERIES AND AQUACULTURE



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Co-funded by the
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INTRODUCTION TO WATER FOOTPRINT IN FISHERIES AND AQUACULTURE

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1. INTRODUCTION

Water constitutes one of the most fundamental elements required for the survival of all living organisms. From the smallest microorganisms to the largest species, biological life is entirely dependent on this resource. It is widely acknowledged that approximately 70% of the Earth's surface is covered by water, which often creates the initial impression of abundance. However, a closer examination reveals that only three parts per thousand of this vast reserve are accessible and suitable for human consumption, thereby underscoring the urgent need to conserve and manage freshwater resources effectively.

Currently, more than 80 countries are experiencing varying degrees of water scarcity, primarily driven by the rapid global population. Although the total volume of water on Earth is estimated

at 150 billion cubic meters, approximately 98% of this is contained within oceans and other saline water bodies, rendering it unsuitable for direct agricultural or industrial utilization. Of the remaining freshwater resources—amounting to less than 4.5 billion cubic meters—around 87% is locked within glaciers, soil, the atmosphere, or underground aquifers. Accessing these reserves frequently requires costly technological interventions, which significantly increases the economic burden of freshwater usage.

Within this context, fisheries and aquaculture represent sectors of critical importance. Both wild-capture and farmed fish production depend upon freshwater resources, collectively forming what is described as the "water footprint" of fisheries.[1] These activities contribute substantially to global food security, with an annual production of approximately 180 million tons. The water footprint of fisheries can be categorized into three dimensions: direct use, indirect use, and virtual use. While international organizations such as the Food and Agriculture Organization of the United Nations (FAO) underline the essential role of fisheries and aquaculture in meeting nutritional needs, it is equally important to recognize the sector's reliance on freshwater resources, which are becoming increasingly scarce due to climate change.

Although considerable progress has been achieved in the study of water footprints across various industrial sectors, research specifically addressing fisheries remains limited. Against this backdrop, the present project seeks to evaluate and present the water footprint portfolio of fisheries, with a particular focus on the

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[1]This outcome was prepared within the WANTOFISH project (Developing a digital-based curriculum of WAter footprint awareness in Mediterranean FISHeries for sustainable resources in Europe), Erasmus+ Key Action 2, project no. 2024-1-TR01-KA220-HED-000247730.

implications of climate-driven freshwater depletion. The project's target audience includes academics, undergraduate and postgraduate students, and professionals engaged in the field. By providing scientific insights and specialized training, the initiative aims to enhance awareness regarding the freshwater dependency of fisheries, while also promoting the implementation of precautionary measures necessary to mitigate environmental impacts and ensure the sustainability of water resources.

As illustrated in Figure 1, the water dependency and stress profile of fisheries and aquaculture activities differs markedly from that of other production systems, such as beef production and rain-fed agriculture, underlining the need for sector-specific water footprint assessment.

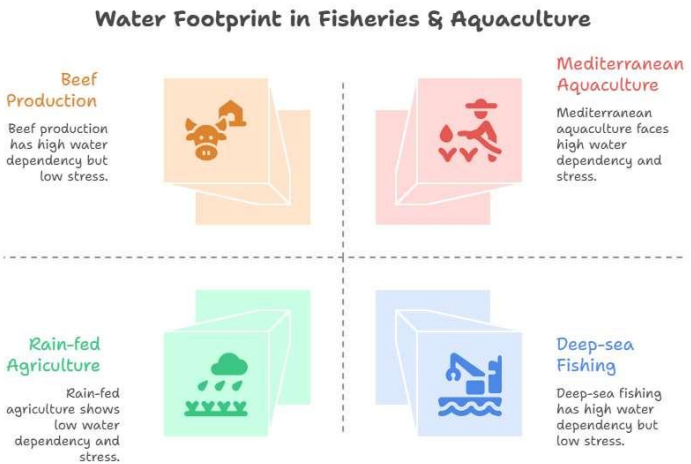


Figure 1. Water footprint comparison across production sectors (visual created via Napkin AI using original text provided by the authors).

Table 1 summarizes the main components of the ecological footprint, situating the water footprint among the other footprint categories—carbon, food, energy, and forest—that together describe the environmental pressure exerted by human activities.

Table 1. Components of the Ecological Footprint

Type of Footprint	Definition	Examples
Carbon Footprint	The amount of land required for nature to absorb greenhouse gas emissions resulting from fossil fuel use.	Transportation, electricity consumption, heating, industrial activities
Water Footprint	The total amount of freshwater used in the production of goods and services consumed by an individual or society.	Agricultural irrigation, food production, textile industry, domestic water use
Food Footprint	The impact of food production and consumption on nature (land, water, energy, and carbon use).	Meat and dairy consumption, packaged foods, imported products
Energy Footprint	The environmental pressure caused by energy consumption.	Electricity use, transportation, fossil fuel consumption
Forest Footprint	The forest area is used for paper, timber, furniture, and the capacity of forests as carbon sinks.	Paper consumption, deforestation, furniture production

Figure 2 provides a visual synthesis of these five footprint categories, as compiled by the authors.

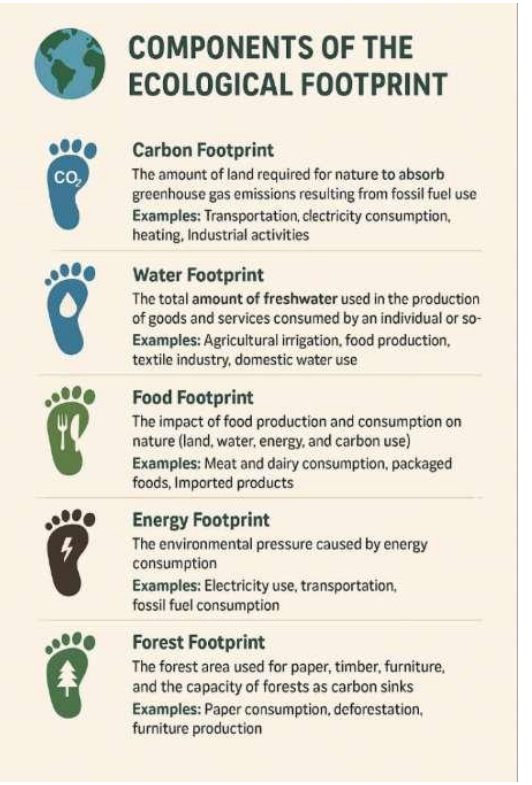


Figure 2. Components of the ecological footprint. Source: Authors.

2. WHAT IS THE WATER FOOTPRINT?

The water footprint refers to the total amount of freshwater used in the production and consumption processes of an individual, society, or product. It includes not only the water we directly use (from the tap) but also the virtual (indirect) water embedded in the goods and services we consume. For example, one cup of coffee corresponds to about 140 liters of water when accounting for the

growing, processing, and transporting of the beans; one kilogram of beef corresponds to about 15,000 liters of water; and one pair of jeans corresponds to about 10,000 liters of water.

3. TYPES OF WATER FOOTPRINT

The water footprint consists of three components. The blue water footprint refers to fresh surface and groundwater (rivers, lakes, reservoirs, aquifers) used in production, for example in irrigation and industrial production. The green water footprint refers to rainwater stored in the soil and used by plants, as in crop production relying on rainfall. The grey water footprint refers to the amount of freshwater required to dilute pollutants generated during production and consumption, such as the water needed to absorb fertilizers and chemicals from agriculture and industry.

4. IMPORTANCE

Freshwater resources are limited and are under pressure from population growth, climate change, industry, and agriculture. Reducing the water footprint is possible through sustainable agriculture, smart water management, recycling, and conscious consumption.

Globally, increasing population, urbanization, and changing consumption habits place significant pressure on natural resources. Among these pressures, the use of limited freshwater resources stands out. Today, nearly 70% of freshwater resources are consumed in agricultural production, making agriculture the sector with the highest water use. Therefore, understanding, monitoring, and managing water consumption in agricultural activities is of critical importance for sustainable resource management.

In this context, the water footprint concept is an important indicator as it reveals not only direct water use but also the total "virtual water" consumed throughout production processes. The water footprint of agricultural products is evaluated through three components: blue water (surface and groundwater), green water (rainwater), and grey water (the amount of water required to dilute pollution). Particularly, water-intensive crops (e.g., cotton, rice, maize, coffee, and livestock products) have significant implications for the sustainability of water resources at both local and global scales.

Studies in the literature highlight that the water footprint of agricultural products is directly related to regional climate conditions, production techniques, irrigation methods, and agricultural productivity levels. Thus, water footprint analyses in agriculture are considered a strategic tool for developing water management policies, improving production processes, and raising consumer awareness.

The concept of the water footprint was first introduced by Hoekstra (2002) and has since become an important tool for evaluating resource management, particularly in the agricultural sector. A comprehensive global analysis by Hoekstra and Mekonnen (2012) emphasized that agriculture accounts for about 90% of the total water footprint, with crops such as cotton, rice, maize, and wheat having the largest share.

Chapagain and Hoekstra (2004) investigated the water footprint of cotton production and showed that both blue and green water consumption are high in its production processes. Similarly, Mekonnen and Hoekstra (2011) demonstrated that the water footprint of livestock products such as meat and dairy is significantly higher compared to plant-based products.

Studies specific to Turkey also highlight the importance of the agricultural water footprint. Research conducted in the Konya Basin (Aldaya & Hoekstra, 2010) revealed that irrigation-intensive agricultural activities exert significant pressure on groundwater reserves. Likewise, Eroğlu et al. (2017) evaluated the water footprint of cotton production in Turkey, noting that water consumption varies depending on production efficiency.

Recent research further suggests that the water footprint should not only be considered as a measurement tool but also as a decision-support mechanism for developing sustainable production policies (Ridoutt & Pfister, 2010). In this regard, integrating water footprint analyses into agricultural planning is of critical importance for both food security and ecosystem conservation.

4.1. MEDITERRANEAN-SPECIFIC STUDIES

In Mediterranean countries, where water scarcity is a critical issue, several studies have highlighted the importance of incorporating the water footprint approach into agriculture and aquaculture. Research on dietary patterns across Mediterranean populations shows that food consumption accounts for a much higher share of the water footprint compared to direct household use, with values ranging between 3,277 and 5,789 liters per capita per day (Science of Food Consumption, 2016). Comparative analyses further demonstrate that adopting the EAT-Lancet diet model could reduce the dietary water footprint by 17%–48%, while the traditional Mediterranean diet achieves more moderate reductions of 4%–35% (Resources, Conservation & Recycling, 2021; JRC, 2021). Beyond consumption, water footprint assessments in the Mediterranean agricultural sector reveal that farming activities account for approximately 64% of total water use in the region, highlighting the necessity of using the water footprint as a decision-support tool for

sustainable management (Fresenius Environmental Bulletin, 2014). These findings collectively underscore the central role of water footprint analysis in guiding both dietary choices and agricultural strategies in Mediterranean countries, where pressures on freshwater resources are particularly acute.

Over the past three decades, research on the evolution of fisheries and aquaculture in the European Union (EU) has significantly advanced, in parallel with global developments. Compared to other agricultural fields such as plant production and animal husbandry, this sector has progressed rapidly and has now reached an almost industrial stage (FAO, 1997; Guillen et al., 2019). The primary goal of commercial aquaculture and capture fisheries remains maximizing yield per unit area, while production costs and sustainability concerns increasingly shape decision-making processes. However, despite the economic benefits and technological progress, natural resources have often been exploited in an uncontrolled manner.

Climate change has further exacerbated this challenge, disturbing natural balances and leading to frequent extreme events such as heavy precipitation and prolonged drought. These events have had major implications for commercial industries, including fisheries and aquaculture, particularly in regions highly vulnerable to environmental changes such as the Mediterranean basin (Gephart et al., 2017; FAO, 2020). While the sector alone cannot be blamed for the deteriorating global equilibrium, its intensive use of water resources highlights the urgent need for more sustainable practices.

This project proposal aims to raise awareness about the significance of water, one of the two essential elements of life, and to provide knowledge on sector-specific water resource protection strategies, including the calculation and reduction of the water

footprint (WF) of fisheries and aquaculture operations (Hoekstra, 2017; Symeonidou et al., 2024). The project targets a wide audience—academics, middle and senior managers, graduate, postgraduate, and doctoral students, as well as professionals in the fisheries sector—who are interested in understanding and applying water footprint methodology in order to minimize production-related impacts. By advancing knowledge dissemination and demonstrating sector-specific applications, the project will contribute to the adoption of environmentally friendly fisheries and aquaculture practices, safeguarding the water-based foundation of the industry.

5. PROPOSED CASE STUDIES FOR THE MEDITERRANEAN BASIN

5.1. SEA BASS AND SEA BREAM FARMING IN TURKEY (AEGEAN REGION)

Turkey is one of the largest producers of sea bass and sea bream in the Mediterranean. Intensive cage farming in coastal areas relies heavily on water quality and circulation. A case study can be developed to calculate the water footprint of these farms, including both direct water use (net cleaning, water renewal) and indirect use (feed production). Potential reduction strategies could include optimizing feed conversion ratios and incorporating alternative protein sources with lower water footprints, as illustrated in Figures 3 and 4.



Figure 3. Sea bass and sea bream catch prepared for processing. Source: Authors.



Figure 4. Net handling during sea bass and sea bream harvesting. Source: Authors.

5.2. SHELLFISH AQUACULTURE IN SPAIN (GALICIA AND MEDITERRANEAN COAST)

Mussel and oyster farming in Mediterranean coastal lagoons presents a unique opportunity to study water footprint, as bivalves filter nutrients directly from the water and may contribute to ecosystem services. A case study could compare the water footprint of bivalve aquaculture to that of finfish farming, highlighting the role of low-input systems in sustainable aquaculture (Figure 5).



Figure 5. Land-based aquaculture rearing tanks. Source: Authors.

5.3. TILAPIA AND CARP FARMING IN EGYPT (NILE DELTA)

Egypt is the largest aquaculture producer in Africa, with freshwater systems concentrated in the Nile Delta. However, water scarcity, salinization, and pollution from agricultural runoff pose severe threats. A case study could examine water footprint accounting in semi-intensive tilapia and carp ponds, identifying both direct consumption and grey water components related to nutrient

discharges. The findings would be directly relevant to the management of water-limited environments in the Mediterranean basin.

5.4. INTEGRATED MULTI-TROPHIC AQUACULTURE (IMTA) IN GREECE

Greece has been a pioneer in aquaculture innovation in the Mediterranean, particularly in integrating fish, algae, and invertebrates within the same system.[2] A case study could assess how IMTA reduces the water footprint compared to conventional monoculture systems, as depicted in Figure 6. This would demonstrate the role of circular approaches in enhancing sustainability and reducing environmental impacts.

[2]IMTA systems combine species from different trophic levels (e.g., fed fish, extractive shellfish, and algae) so that the by-products of one species serve as inputs for another, reducing overall resource use.

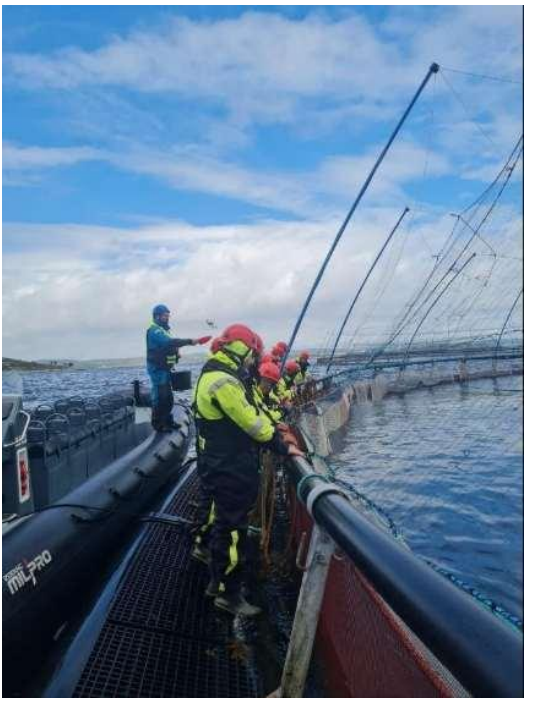


Figure 6. Net inspection at an integrated multi-trophic aquaculture site. Source: Authors.

5.5. SMALL-SCALE ARTISANAL AQUACULTURE IN ITALY (SOUTHERN MEDITERRANEAN LAGOONS)

In regions such as Sicily and Sardinia, artisanal aquaculture systems are deeply embedded in local traditions and ecosystems. A case study could focus on the balance between cultural heritage, economic livelihoods, and water footprint management. Emphasis would be placed on demonstrating how small-scale operations can achieve low water footprints through adaptive management practices.

By combining scientific analyses with these Mediterranean case studies, the project will produce an applied framework that

connects theoretical knowledge to practice. It will also support the adoption of best practices across different scales of aquaculture, from large commercial operations to artisanal systems, thereby strengthening the resilience of the sector against climate change impacts, as exemplified by post-harvest handling practices such as the one shown in Figure 7.



Figure 7. Post-harvest fish processing on a production line. Source: Authors.

6. EXPECTED ECOLOGICAL AND ECONOMIC IMPACTS

As summarized in Figure 8, implementing sustainable water management practices in fisheries is expected to reduce freshwater pressure, mitigate nutrient pollution, enhance climate adaptation, lower operational costs, and improve market value, ultimately contributing to a more sustainable fisheries industry.



Figure 8. Sustainable water management in fisheries (visual created via Napkin AI using original text provided by the authors).

6.1. ECOLOGICAL IMPACTS

Reduced freshwater pressure and ecosystem conservation: by quantifying water use across the aquaculture supply chain, producers can identify hotspots of overconsumption and implement water-saving strategies, reducing stress on already scarce freshwater sources in the Mediterranean (Ridoutt & Pfister, 2010).

Lower nutrient pollution and eutrophication risks: considering the grey water footprint highlights nitrogen and phosphorus discharges, enabling better management of feed and effluents to prevent eutrophication in lagoons and semi-enclosed coastal systems (Mungkung et al., 2013).

Climate adaptation through efficient water use: water footprint monitoring supports resilience against climate-induced droughts and heatwaves, maintaining ecological services and production sustainability (Gephart et al., 2017), as symbolized in Figure 9.



Figure 9. Conceptual link between fisheries, water, and the economy. Source: AI

7. REFERENCES

Aldaya, M. M., & Hoekstra, A. Y. (2010). *The water needed to have Italians eat pasta and pizza.* Agricultural Systems, 103(6), 351–360.

Bohnes, F. A., Hauschild, M. Z., & Schluep, M. (2019). Life cycle assessment of aquaculture systems: A critical review. *Reviews in Aquaculture,* 11(4), 1061–1079.

Chapagain, A. K., & Hoekstra, A. Y. (2004). *Water footprints of nations.* UNESCO-IHE Institute for Water Education.

Eroğlu, E., Çakmak, B., & Gökalp, Z. (2017). Water footprint analysis of cotton production in Turkey. *Journal of Agricultural Sciences,* 23(2), 145–156.

European Commission (2021). *A new approach for a sustainable blue economy in the EU: Transforming the EU's Blue Economy for a Sustainable Future.* Brussels.

FAO (1997). *Aquaculture Development Trends in Europe.* FAO Fisheries Circular No. 886. Rome: Food and Agriculture Organization of the United Nations.

FAO (2020). *The State of World Fisheries and Aquaculture 2020. Sustainability in Action.* Rome: FAO.

Gephart, J. A., Henriksson, P. J. G., Parker, R. W. R., Shepon, A., Gorospe, K. D., Bergman, K., ... & Troell, M. (2017). Environmental performance of blue foods. *Nature,* 597, 360–365.

Guillen, J. (2025). What is happening to the European Union aquaculture. *Aquaculture,* 616, 746–758.

Guillen, J., Natale, F., Carvalho, N., Casey, J., Hofherr, J., Druon, J. N., ... & Fiore, G. (2019). Aquaculture subsidies in the

European Union: Evolution, impact and future potential for growth. *Marine Policy,* 104, 19–28.

Gyalog, G., Sipos, D., & Zseni, A. (2022). Comparative development of freshwater aquaculture in the European Union and Latin America. *Sustainability,* 14(11), 6443.

Hoekstra, A. Y. (2002). *Virtual water trade: Proceedings of the International Expert Meeting on Virtual Water Trade.* UNESCO-IHE.

Hoekstra, A. Y. (2017). Water footprint assessment: Evolvement of a new research field. *Water Resources Management,* 31(10), 3061–3081.

Hoekstra, A. Y., & Mekonnen, M. M. (2012). *The water footprint of humanity.* Proceedings of the National Academy of Sciences, 109(9), 3232–3237.

Mekonnen, M. M., & Hoekstra, A. Y. (2011). *The green, blue and grey water footprint of crops and derived crop products.* Hydrology and Earth System Sciences, 15(5), 1577–1600.

Mungkung, R., Aubin, J., Prihadi, T. H., Slembrouck, J., van der Werf, H. M. G., & Legendre, M. (2013). Life cycle assessment for environmentally sustainable aquaculture management: A case study of combined aquaculture systems for carp and tilapia. *Journal of Cleaner Production,* 57, 249–256.

Pahlow, M., van Oel, P. R., Mekonnen, M. M., & Hoekstra, A. Y. (2015). Increasing pressure on freshwater resources due to terrestrial feed ingredients for aquaculture production. *Science of the Total Environment,* 536, 847–857.

Ridoutt, B. G., & Pfister, S. (2010). A revised approach to water footprinting to make transparent the impacts of consumption

and production on global freshwater scarcity. *Global Environmental Change,* 20(1), 113–120.

Symeonidou, S., Pitta, E., Papandroulakis, N., & Karakassis, I. (2024). Water consumption and the water footprint in aquaculture: A review. *Water,* 16(23), 3376.



MODULE 2. WATER FOOTPRINT IN COMMERCIAL FISHERIES

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WATER FOOTPRINT IN THE COMMERCIAL FISHERY

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1. INTRODUCTION

Commercial fishing is a cornerstone of the Mediterranean economy and cultural heritage, as summarised in Figure 1. It employs over 180,000 people and generates around 4.6 billion euros annually (WWF, 2023). Almost 80% of the region's fleet of about 80,000 vessels consist of small-scale operations that provide food security and livelihoods for rural populations in Southern Europe, North Africa and the Middle East (Figure 2) (FAO, 2023).



Figure 1. Commercial fishing in the Mediterranean: a critical introduction (visual created via Napkin AI using the original text provided by the authors).

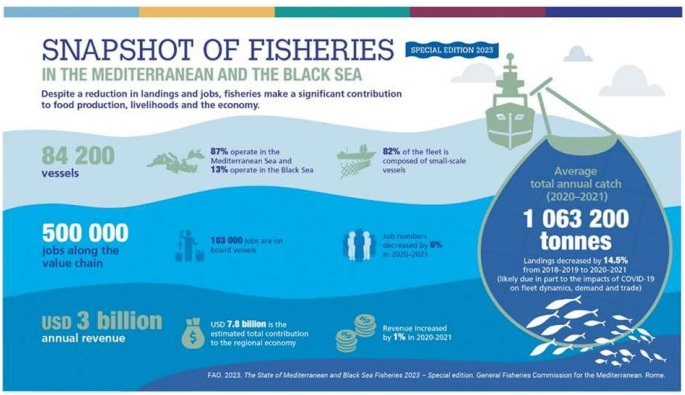


Figure 2. Snapshot of fisheries in the Mediterranean and the Black Sea (FAO, 2023).

Over the last fifty years, fish stocks in the Mediterranean have declined by more than a third, and almost 58% of stocks remain overexploited. Although overfishing has fallen by about 15% in recent years, today's fishing pressure is still nearly twice the level compatible with sustainability. This is driven by illegal, unreported and unregulated (IUU) practices, the uncontrolled expansion of the fleet, and climate change, which intensifies overexploitation by

reducing productivity, shifting species' ranges and stressing habitats, thereby amplifying risks for Mediterranean fisheries (FAO, 2023; WWF, 2023; European Commission, 2024).

In this context, the water footprint of fisheries has become a crucial dimension of environmental impact assessment. By capturing total freshwater consumption - both directly for vessel operation and processing and indirectly for gear manufacturing, embedded feed and fuel production - water footprint analysis reveals hidden dependencies on scarce water resources (Hoekstra et al., 2011). In the Mediterranean region, where river flows are already burdened by drought and overfishing, these hidden water costs have tangible economic consequences. A recent study by the Joint Research Centre estimates that a reduction in water quantity in the Italian River Po alone could lead to a 6 percent decrease in fish biomass and annual losses of up to €4.7 billion if water management and fisheries management measures are not coordinated (JRC, 2025).

Integrating water resource management into fisheries regulation requires ecosystem-based management and cross-sectoral coordination. The FAO Code of Conduct for Responsible Fisheries and the GFCM Regional Action Plan for Small-Scale Fisheries both emphasise the importance of participatory co-management, ecological river flow allocations and science-based catch limits (FAO, 2022; GFCM, 2021). Marine protected areas, fishing bans, mesh size regulations and vessel monitoring systems can curb overfishing while protecting critical habitats and non-target species.

Evidence from co-managed bays in Greece, permanently protected fishing areas in Catalonia, and co-management fishing projects in the Spanish Mediterranean area shows that when local communities share responsibility for decision-making and revenue sharing, fish stocks recover and incomes stabilise.

Changing dietary habits is another effective way to reduce both overfishing and demand for freshwater. Modelling of consumption patterns in the Mediterranean region shows that following the EAT-Lancet Commission's healthy and sustainable diet could reduce regional water use by up to 48% while lowering pressure on wild stocks (Springmann et al., 2018). Combining such demand-side strategies with robust supply-side reforms - improving gear selectivity, traceability systems and market incentives such as eco-labelling - creates a pathway to a genuinely resilient and resource-efficient fisheries sector.

Protecting the unique marine ecosystems of the Mediterranean, and the communities that depend on them, requires coordinated action at local, regional, national and international levels. Integrating water footprint metrics into fisheries policy, strengthening co-management frameworks and promoting more responsible diets can collectively guide the sector back within planetary and socio-economic boundaries.

2. WATER USE IN CAPTURE FISHERIES

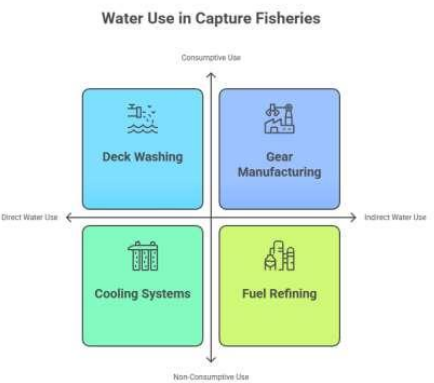


Figure 3. Water use in capture fisheries (visual created via Napkin AI using the original text provided by the authors).

Water scarcity is becoming a critical factor for capture fisheries worldwide. Fresh water is essential not only for life on board ships and in harbour facilities, but also for the industrial processes that make modern fishing possible in the first place, from the manufacture of steel and fishing gear to diesel refining and ice production. In water-scarce regions such as the Mediterranean, where droughts and the overexploitation of rivers and aquifers are already commonplace, understanding and managing the full range of water needs is critical to ensure both the resilience of ecosystems and the economic viability of fishing communities (Mekonnen & Hoekstra, 2012; FAO, 2024).

A comprehensive water footprint approach considers all freshwater used directly in fisheries as well as the "virtual" water embedded in upstream and downstream activities. By mapping consumptive withdrawals, non-consumptive use and polluted return flows, fisheries managers can identify hotspots where water efficiency measures will deliver the greatest benefits. In addition, integrating water footprint metrics into fisheries certification schemes and co-management plans creates economic incentives for operators to adopt water-efficient technologies and practices (Hoekstra et al., 2011; Symeonidou & Mente, 2024; FAO, 2024).

2.1. CLASSIFICATION OF WATER CONSUMPTION

Water consumption in capture fisheries is usually divided into three categories (Table 1) to distinguish between water that is effectively "lost" in the catchment area, water that remains available, and water whose value is reduced by pollution (Symeonidou & Mente, 2024; FAO, 2024; Hoekstra et al., 2011).

Table 1. Classification of Water Consumption in Capture Fisheries (Symeonidou & Mente, 2024; FAO, 2024; Hoekstra et al., 2011)

Type of water consumption	Definition
Consumptive use	Water withdrawn and not returned to its source.
Non-consumptive use	Water temporarily used and then returned to its source.
Polluted return flows	Water returned but degraded in quality.

- Consumptive use: fresh water extracted from rivers, aquifers or municipal water supplies and not returned to its source. Key examples include drinking water used for washing decks and nets, making ice to preserve the catch, and processing fish on board (Symeonidou & Mente, 2024).
- Non-consumptive use: water withdrawn, used temporarily and then returned to the environment with minimal change in quantity or quality. Cooling water in harbour cooling plants and temporary storage of water for emergency ballast fall into this category (FAO, 2024).
- Polluted return flows: water that flows back into natural systems but is of poorer quality and often contains residues of fuel, detergents or fish by-products. Even if the quantities remain unchanged, pollutants can affect downstream ecosystems and human use (Hoekstra et al., 2011).

2.2. DIRECT WATER USE

Direct water consumption in capture fisheries includes all freshwater withdrawn and used during fishing trips and at first landing sites. Although these quantities may seem modest at the vessel level, they become significant when multiplied across hundreds of small boats operating in water-scarce areas such as the Mediterranean (FAO, 2024; Symeonidou & Mente, 2024).

Cleaning decks and fishing gear alone can use 500 - 1,000 L of freshwater per day on small-scale Mediterranean fishing vessels, as hulls, nets, and lines are washed with pressurised freshwater to meet biosecurity and hygiene requirements (Symeonidou & Mente, 2024). Onboard processing - gutting, rinsing, and icing the catch to satisfy food safety standards - adds another 300 - 800 L of freshwater per trip, depending on catch volume and trip duration. The crew's water needs for drinking, cooking, and sanitary facilities on multi-day voyages are around 100 L per person per day (FAO, 2024).

At landing sites, municipal or well water is often used to wash fish before auction, clean holding tanks and maintain machinery, which further increases direct water consumption in fishing centres. In regions without water reuse infrastructure, direct water consumption can account for up to 10% of a fleet's total freshwater footprint. This highlights the need for low-flow taps, closed-loop washing systems and grey water recycling both on ships and in ports (Symeonidou & Mente, 2024).

2.3. INDIRECT WATER USE

Indirect water use, or "virtual water" refers to the freshwater involved in all off-site processes that enable fishing. These hidden flows often account for the most of a fishery's water use, but are overlooked in traditional water management plans (Hoekstra et al., 2011; FAO, 2024).

The construction of a 20-metre steel trawler can bind more than 1,000 m^3 of water through mining, smelting, machining and the production of antifouling paints, while nets made of synthetic fibres can require 150 l/kg of material produced (Hoekstra et al., 2011; Symeonidou & Mente, 2024). Fuel refining is another major burden: producing one litre of marine diesel consumes about 2–3 litres of freshwater in the processing and refining of crude oil (Hoekstra et al., 2011).

Producing ice to preserve catches usually requires 0.8 - 1 litres of drinking water per kilogram of ice, and maintaining the cold chain - refrigerated transport, storage and packaging - can mean up to 0.2 m^3 of hidden water per tonne of fish landed (FAO, 2024; Mekonnen & Hoekstra, 2012). The production of crates and containers, the operation of cold stores and additional services further increase the virtual water footprint of fisheries.

Life cycle analyses show that indirect water consumption can exceed direct consumption by a factor of ten or more, highlighting the importance of cross-sectoral water efficiency measures. Strategies such as sourcing materials with a low water footprint, extending the longevity of fishing gear and certifying fisheries with eco-labels that include water footprint criteria are crucial for reducing the sector's overall freshwater demand (Hoekstra et al., 2011; Mekonnen & Hoekstra, 2012).

Effective management of water use in fisheries depends on where freshwater is consumed or embedded in the operation. In Table 2 below, a distinction is made between 'direct' use - such as deck washing, fish rinsing and crew hygiene - and 'indirect' or virtual water flows embedded in gear manufacturing, fuel refining, ice production and packaging. By quantifying these categories side by side, fisheries managers can identify the most water-intensive hotspots. In water-scarce regions, particularly those dominated by small Mediterranean vessels, this clarity helps target efficiency improvements, such as low-flow cleaning systems or sourcing materials with a smaller water footprint. Ultimately, understanding both the visible and hidden water needs of capture fisheries is key to reducing the sector's overall freshwater footprint.

Table 2. Quantifying Water Use in Capture Fisheries

Category	Description	Reference
Vessel cleaning	Litres per trip, based on vessel size and sanitation frequency.	Ziegler et al., 2013
Onboard processing	Water required for rinsing, gutting, and packaging.	Tyedmers, 2004
Crew consumption	Drinking and hygiene water per person, per day.	FAO, 2001
Gear and vessel manufacturing	Water embedded in the production of materials such as steel, nylon and plastic.	Ziegler et al., 2013
Fuel production	Water used to extract, refine, and transport diesel.	Gerbens-Leenes et al., 2009
Ice production	Water and energy used to produce and store ice for preserving fish.	Bojanić et al., 2020

3. THE WATER FOOTPRINT OF VESSELS AND OPERATIONS

Fishing operations in the Mediterranean have a multi-layered water footprint, arising from both the vessels themselves and the land-based infrastructure. In addition to the well-documented impact on marine ecosystems, every fishing net washed, every tonne of ice produced, and every litre of marine diesel carries a hidden freshwater cost. In this semi-arid region, where many river basins are already suffering from overexploitation, these freshwater needs must be quantified and managed to safeguard ecosystem resilience and the

livelihoods of coastal communities (FAO, 2001; Mekonnen & Hoekstra, 2012).

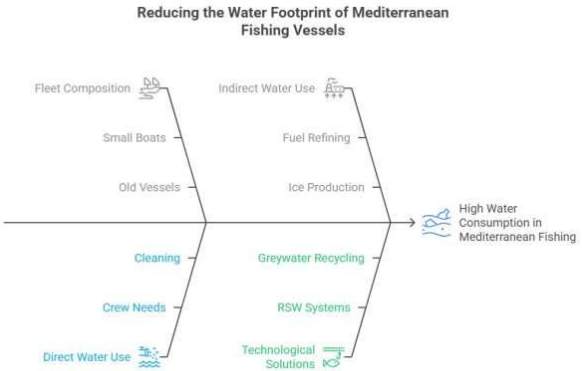


Figure 4. Reducing the water footprint of Mediterranean fishing vessels (visual created via Napkin AI using the original text provided by the authors).

3.1. TYPES OF VESSELS IN THE MEDITERRANEAN FISHERIES

The Mediterranean fleet is one of the most diverse in the world, with around 78,000 registered fishing vessels in 2020. Small boats less than 12 m in length dominate, making up 83% of the fleet, while large industrial trawlers and purse seiners more than 24 m long account for only 2%. Italy, Spain, Turkey and Greece together represent more than three quarters of all vessels, with Italy alone accounting for around 26% of the total (Table 3) (FAO, 2018; GFCM, 2020).

Table 3. Fleet Composition by Vessel Length, Main Flag States in Mediterranean Fisheries (GFCM, 2020; FAO, 2018; Sala & Lucchetti, 2019)

Length Class (m)	Number of Vessels	% of Fleet	Main Flag States (share)
< 12	64 740	83 %	Italy (20 %), Spain (18 %), Turkey (17 %)
12–18	7 800	10 %	Italy (22 %), Turkey (15 %), Spain (14 %)
18–24	4 000	5 %	Spain (24 %), Italy (20 %), Greece (12 %)
> 24	2 000	2 %	Spain (28 %), Italy (25 %), Turkey (15 %)

The age of the ships also affects the demand for freshwater: almost 45% are more than 20 years old and only 20% are less than ten years old (Table 4). Older hulls and outdated machinery require more frequent cleaning and overhauls, which increases both the direct and indirect water footprints (FAO, 2018).

Table 4. Fleet Composition by Vessel Age in Mediterranean Fisheries (FAO, 2018)

Age Class	% of Fleet
< 10 years	20%
10–20 years	35%

Age Class	% of Fleet
> 20 years	45%

3.2. WATER FOOTPRINT OF FISHING VESSELS AND GEAR

The water footprint of a fishing vessel encompasses direct freshwater use - drinking, cooking, sanitation, deck and gear cleaning, and onboard ice-making - and indirect ('virtual') water embedded in fuel production, purchased ice, and gear manufacturing (Table 5) (Mekonnen & Hoekstra, 2012). In water-scarce Mediterranean basins, quantifying both direct and virtual water flows is essential to identify hotspots and prioritise efficiency measures.

Table 5. Direct Freshwater Use by Fishing Vessels in the Mediterranean Sea. Hooks and materials such as nylon require water-intensive production (FAO, 2001; Tyedmers, 2004; Bojanić et al., 2020; Ziegler et al., 2013)

Vessel Type	Length (m)	Crew	Domestic Use (L/day)	Gear & Deck Cleaning (L/day)	Ice Prod. (L/tonne)	Engine Cooling (L/h)
Artisanal boats	< 12	1–5	20–50	ashore*	n/a	n/a
Polyvalent coastal vessels	12–18	5–10	100–200	50–100	1 000–2 000	n/a

Vessel Type	Length (m)	Crew	Domestic Use (L/day)	Gear & Deck Cleaning (L/day)	Ice Prod. (L/tonne)	Engine Cooling (L/h)
Bottom trawlers	12–24	8–12	50–100	300–500	1 000–3 000	50–200
Pelagic trawlers & purse seiners	15–30	10–15	100–150	200–300	1 000–3 000	n/a
Industrial freezer trawlers	> 24	15–30	200–300	500–800	2 000–5 000	100–300
Longliners	20–40	15–25	20–30/person	150–300/trip	n/a	n/a
Gillnetters and driftnetters	10–20	5–10	30–60	50–100	n/a	n/a
Trap and pot vessels	10–18	3–8	50–100	100–200	n/a	n/a
Dredgers	up to 25	8–12	50–80	100–250	n/a	n/a
Multi-purpose vessels (mixed gear)	12–24	8–15	80–150	100–400	1 000–3 000	50–200

*the cleaning takes place on land, typically in harbour facilities, and not on board the ship

Indirectly embedded water flows include 1,000-3,000 L per tonne for ice production (Bojanić et al., 2020), 2–3 L per litre for the refining of marine diesel (Mekonnen & Hoekstra, 2012), 150 L per kg for the production of synthetic net fibre, and over 1,000 m^3 per vessel for the production of steel hulls (Ziegler et al., 2013).

3.3. DAMAGE LIMITATION AND TECHNOLOGICAL PROGRESS

To limit the demand for fresh water, Mediterranean fisheries have adopted a number of innovations. Refrigerated seawater (RSW) systems replace freshwater ice with chilled seawater and reduce water consumption on board by up to 90% (Bojanić et al., 2020).

With closed-loop engine cooling, the coolant is recirculated, reducing water consumption by 50-70% (Tyedmers, 2004). Onboard filtration and grey water recycling treat wash water for reuse in deck cleaning, reducing freshwater withdrawal by 30-50% (Bojanić et al., 2020). Improvements on land include more efficient compressors for ice plants and best practice protocols for water conservation prescribed by ports.

Procuring nets made from recycled polymer and locally produced steel reduces the virtual water embedded in fishing gear and hull materials (Ziegler et al., 2013). Combined with eco-labelling schemes that incorporate water-footprint criteria, these measures support regional water resource constraints and advance the Sustainable Development Goals (SDGs), the UN's 17 global goals for 2030 - specifically SDG 12 (responsible consumption and production) and SDG 14 (life below water); where the focus includes freshwater stewardship, they also contribute to SDG 6 (clean water and sanitation).

4. IMPACTS OF OVERFISHING AND CLIMATE CHANGE

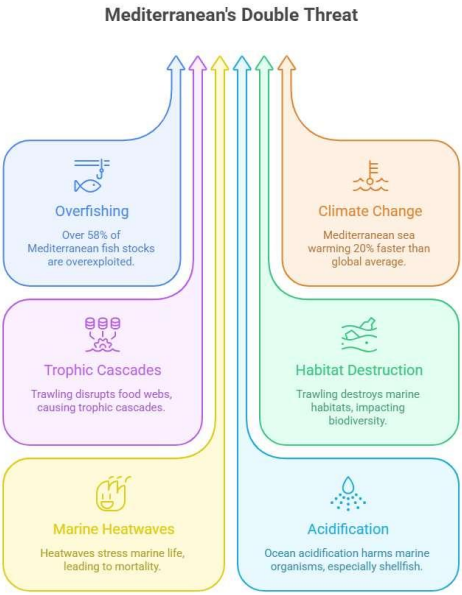


Figure 5. The Mediterranean's double threat: overfishing and climate change (visual created via Napkin AI using the original text provided by the authors).

The Mediterranean lies at the intersection of two of the most powerful global stressors - overfishing and climate change - which interact and could push marine ecosystems to critical limits. Each factor alone alters community structure, productivity and habitat integrity. Together, they accelerate the decline in biodiversity and undermine the long-term viability of fisheries and coastal livelihoods (FAO, 2020; IPCC, 2022).

Overfishing occurs when fishing mortality (F) exceeds the fishing mortality that would produce the maximum sustainable yield (FMSY), i.e. $F > FMSY$, causing stock biomass to decline towards an overfished state (FAO, 2020).

Since the 1950s, rapid improvements in engine power, sonar, gear design and navigation tools have enabled fleets to penetrate deeper habitats and operate year-round (Donaldson et al., 2022). In 2020, more than 34% of exploited marine stocks were classified as overfished, and a further 60% were fished at or above FMSY (FAO, 2020). Illegal, unreported and unregulated (IUU) fishing - estimated at 22% of global catches - further undermines management measures and distorts stock assessments (FAO, 2020).

Overfishing can cause the collapse of top predators, trophic cascades, habitat destruction by bottom trawling and the proliferation of opportunistic taxa such as jellyfish (FAO, 2024). Earlier FAO assessments estimated associated annual welfare losses at roughly USD 50–80 billion and noted livelihood impacts for some 200 million coastal fishers worldwide; these global estimates remain widely cited but have not been superseded by a single updated global figure in SOFIA 2024 (FAO, 2020; FAO, 2024). Table 6 summarises the main environmental and socio-economic impacts of overfishing in the Mediterranean.

Table 6. Major Ecological and Socio-Economic Impacts of Overfishing in the Mediterranean (FAO, 2018; 2020; Coll et al., 2012)

Impact category	Description	Reference
Trophic cascades	The removal of top predators (e.g. tuna, sharks) triggers mesopredator release and jellyfish blooms, undermining the stability of the food web and fisheries yields.	Coll et al. (2012)

Impact category	Description	Reference
Habitat destruction	Intensive bottom trawling is a major driver of seabed habitat degradation: it uproots benthic fauna, homogenises substrates and resuspends carbon-rich sediments, degrading nursery functions and other ecosystem services.	FAO (2024)
Bycatch & discards	Bycatch and discards remain a major threat to non-target species - including juveniles, sea turtles and elasmobranchs - and destructive gears such as bottom trawls exacerbate habitat damage and biodiversity loss.	FAO (2024)
Socio-economic impact	SOFIA 2024 highlights the socio-economic vulnerability of fisheries and aquaculture value chains and the need to protect livelihoods and equitable benefits (FAO, 2024); the previously published global estimates of annual welfare losses (USD 50–80 billion) and the scale of livelihoods affected (~200 million fishers) remain attributed to earlier FAO assessments.	FAO (2020, 2024)

The Mediterranean Sea is warming by around 0.29-0.44°C per decade, 20% faster than the global ocean average, and surface air temperatures are already 1.5°C above pre-industrial levels on average (IPCC, 2022). Ocean acidification has lowered average surface pH by about 0.1 units since the 18th century, threatening

calcifying organisms such as oysters, coralline algae and the coral-like communities that feed juvenile fish (UNEP/MAP, 2021).

Sea levels along Mediterranean coasts rose by 2.8 ± 0.1 mm per year between 1993 and 2018, contributing to coastal erosion, saltwater intrusion and habitat loss (IPCC 2022). Meanwhile, projected global warming of 2°C could reduce regional precipitation by 10–15%, and by as much as 30% under a 4°C scenario, exacerbating freshwater scarcity in catchment rivers and aquifers (UNEP/MAP, 2021).

The frequency of marine heatwaves - defined as long-lasting anomalous warming events - has quadrupled over the last forty years. In particular, the heatwaves of 2003, 2017 and 2019 triggered mass mortality in *Posidonia oceanica* meadows and coral reefs, which are important nursery habitats and carbon sinks (WWF, 2021). Since 2019, the Mediterranean has continued to experience significant marine heatwaves, most notably the unprecedented western-basin events of 2022, which - together with the earlier 2015–2019 sequence - have driven recurrent mass mortalities and major ecosystem change. Species distribution models suggest that the maximum catch potential in the Mediterranean could fall by up to 30% by 2050 under high emission scenarios, exacerbating the impact of overfishing on food security and economic resilience (Cheung et al., 2013).

Overfishing and climate change interact synergistically: depleted stocks have lower genetic diversity and reproductive capacity, which limits their adaptive capacity to thermal stress and acidification. Habitat degradation due to trawling further impairs the ecosystem's resilience to extreme events. The combined stressors increase the risk of stock collapse, particularly for long-lived, slow-growing species such as groupers and sharks, and accelerate the shift

towards low-value, opportunistic species (Cheung et al., 2013; IPCC, 2022).

Coastal communities - especially small-scale fishers - are particularly at risk. Declining catches force longer and more expensive trips, increasing fuel and labour costs. The loss of ecosystem services (coastal protection, carbon sequestration, tourism) exacerbates economic hardship. Adaptation strategies include dynamic fishery closures during heatwaves, ecosystem-based management that protects refugia (areas where local conditions such as temperature, currents, groundwater input and habitat complexity reduce exposure to regional climate extremes, allowing species or life stages to survive when surrounding areas suffer stress), and investment in climate-resilient fishing gear and aquaculture to reduce pressure on wild stocks (FAO, 2016; IPCC, 2022).

4.1. COMBINED EFFECTS ON THE MEDITERRANEAN

The semi-enclosed geography of the Mediterranean, with limited exchange with the Atlantic, high evaporation rates and densely populated coasts, exacerbates both overfishing and climate change, making it the most overfished sea in the world. According to the 2023 report on the state of fisheries in the Mediterranean and Black Seas, 62% of assessed stocks are fished above sustainable levels and fishing mortality exceeds FMSY by almost 100% on average. The regional fleet of around 80,000 vessels is predominantly artisanal (80% of boats), but contributes only 15% of the total landed biomass (FAO, 2023). According to the latest report on the state of Mediterranean and Black Sea fisheries:

- 62% of assessed stocks are harvested above sustainable levels, while fishing mortality exceeds FMSY by almost 100% on average.

- The regional fleet consists of approximately 80,000 vessels, with artisanal boats accounting for 80%, but contributing only 15% of the biomass (FAO-GFCM, 2023).
- Bottom trawling and purse seining dominate commercial fishing effort, with discard rates of non-target species reaching 30% in certain areas (Fiorentino & Vitale, 2021).

Projected warming (Figure 6) and acidification will further stress these depleted stocks. By 2100, average sea surface temperature anomalies in the Levant and Aegean basins could exceed +4°C, intensifying stratification and reducing nutrient upwelling.

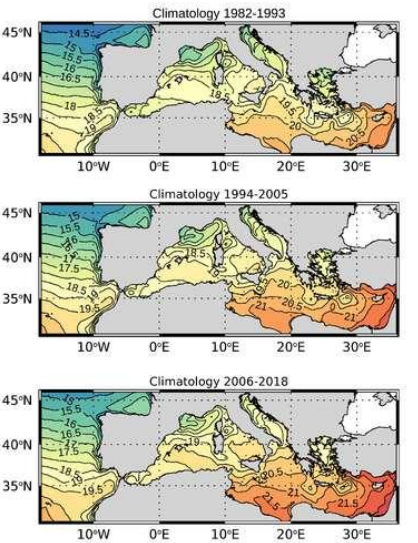


Figure 6. Mean sea surface temperature (SST, °C) from 1982 to 2018 in the Mediterranean region of the Copernicus Marine Environment Monitoring Service (CMEMS), including the Northeast Atlantic box (Pisano et al., 2020).

Primary productivity can decline by up to 15% due to reduced river inflows during prolonged droughts, while ocean acidification is already undermining coralline reef structures and

altering plankton communities. These changes are degrading nursery habitats and reducing carbon sequestration in *Posidonia* meadows and coralline algal beds (Pisano et al., 2020; IPCC, 2022; Fiorentino & Vitale, 2021). The interaction of overfishing and climate stressors amplifies the following effects:

- Reduced genetic diversity in overfished stocks limits their ability to adapt to thermal and acidification stress (Tramblay et al., 2020).
- Habitat degradation due to repeated trawling prevents recovery and increases the loss of benthic biomass.
- Invasive species in the Red Sea such as rabbitfish and lionfish now account for 11% of fish biomass in some areas, displacing native species and altering trophic pathways (UNEP/MAP, 2021).

These synergies shorten recovery periods and increase the risk of regime shifts towards low-value, opportunistic ecosystems.

4.2. OVERFISHING AND STRESS ON WATER RESOURCES: A RECIPROCAL RELATIONSHIP

Healthy fish populations and benthic communities help regulate water quality by recycling nutrients and maintaining sediment permeability. Overfishing removes important bioturbators[1], increasing nutrient enrichment, fuelling harmful algal blooms and spreading hypoxic “dead zones”, especially in enclosed bays and estuaries. At the same time, freshwater scarcity is undermining nursery areas in estuaries, which are crucial for species such as hake and mullet. Reduced inflows from major rivers (e.g. Po, Neretva) increase saltwater intrusion, disrupting brackish water

[1]Bioturbator: an organism (for example, sea cucumbers or mussels) that reworks sediments by burrowing, feeding or moving particles, thereby altering the physical and chemical properties of the substrate and influencing ecosystem processes such as nutrient recycling, sediment stability, habitat heterogeneity, oxygen penetration and carbon cycling.

habitats crucial for larval development and affecting recruitment success (IPCC, 2022).

Freshwater stress is measured by the Water Exploitation Index Plus (WEI+), the ratio of water abstraction to renewable supply. Seasonal WEI+ values above 20% indicate water stress, while values above 40% signal severe scarcity. In the southern catchment areas of the Mediterranean, the WEI+ regularly exceeds 40% in the summer months, leaving only minimal ecological flows and exacerbating the degradation of coastal ecosystems (European Environment Agency, 2022).

4.3. EFFECTS OF CLIMATE CHANGE ON THE AVAILABILITY OF FRESHWATER

Climate models predict a considerable decline in water resources in the Mediterranean region under high greenhouse-gas emission scenarios (SSP5-8.5)[2]:

- Groundwater recharge could decrease by 20–40% in the North African and Levantine aquifers by mid-century, due to lower precipitation and higher evapotranspiration (Pisano et al., 2020).
- Inflows to water reservoirs are expected to decrease by 10–15%, increasing the frequency and severity of irrigation shortages in agricultural plains (IPCC, 2022).
- The rapid growth of tourism and urban expansion in coastal areas could increase seasonal water demand by 15–25% and overtax supplies during peak drought periods (Fiorentino & Vitale, 2021).

Adaptation strategies currently under consideration include:

[2]SSP5-8.5 is a high-greenhouse-gas scenario combining a fossil-fuel-intensive socioeconomic pathway (SSP5) with a radiative forcing of about 8.5 $W \cdot m^{-2}$ by 2100, representing continued very high CO2 and other greenhouse-gas emissions.

- Deficit irrigation and drip systems that reduce agricultural water use by 30–50%.
- Controlled recharge of aquifers with treated wastewater to boost diminishing groundwater reserves (Pisano et al., 2020).
- Integrated hydrological models that link upstream water abstraction with environmental demands on water flow, enabling sustainable allocation between sectors (Hidalgo et al., 2022).

5. POLITICS AND ADMINISTRATION

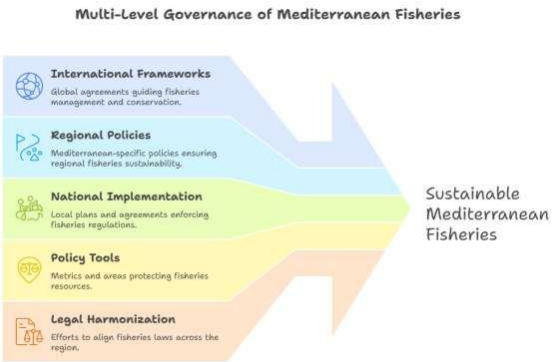


Figure 7. Multi-level governance of Mediterranean fisheries (visual created via Napkin AI using original text provided by the authors).

Water use in Mediterranean fisheries is governed by overlapping regional, national and international policies that aim to balance between resource sustainability, equitable access and ecosystem protection. The semi-enclosed geography of the Mediterranean, shared stocks and high water stress demand coordinated policies. This section outlines the main frameworks for regulating water use in fisheries, examines the legal instruments underpinning fisheries management in the Mediterranean, and highlights national differences and promising policy innovations.

5.1. IMPORTANT POLICIES REGULATING WATER USE IN FISHERIES

The General Fisheries Commission for the Mediterranean (GFCM), founded in 1949 within the FAO, is the most important regional body for fisheries policy. In 2021, GFCM members of the adopted the “Strategy 2030 for the Mediterranean and the Black Sea”, which sets targets for achieving sustainable levels of fishing mortality, restoring habitats and incorporating water use considerations into fisheries and aquaculture planning (GFCM 2021). The strategy explicitly calls for the following:

- Ecological water allocation volumes in watersheds that supply river-dependent rearing facilities.
- Water efficiency standards for aquaculture operations and harbour facilities.
- Cross-sector coordination with agricultural and urban water planners.

The European Union (EU) incorporates the recommendations of the GFCM into binding law for its ten Mediterranean Member States as part of the Common Fisheries Policy. Council Regulation (EC) No 1967/2006 sets out specific measures for the Mediterranean - gear restrictions, minimum mesh sizes, spatial and temporal closures and fishing effort limitations - that implicitly reduce freshwater demand by limiting overcapacity and protecting spawning grounds that depend on river inflows (EUR-Lex, 2006). The regulation was amended in 2019 to strengthen no-take zones and introduce mandatory reporting on the freshwater footprint of aquaculture operations.

At continental level, the European Environment Agency's Water Exploitation Index Plus (WEI+) has become an important indicator for assessing water stress in fisheries-dependent regions (EEA, 2022). WEI+ compares total annual freshwater abstraction -

including fisheries and aquaculture - with renewable supply. In 2020, WEI+ values for the main Mediterranean countries ranged from 9% in Italy to 48% in Greece and 72% in Malta, indicating an acute shortage in summer that threatens estuarine nursery areas (EEA, 2022). By linking WEI+ values to GFCM sub-areas, policymakers can prioritise water-saving measures where fisheries and aquaculture coincide with extreme water stress.

National policy also plays an important role. Spain's cross-sectoral river basin management plans under the EU Water Framework Directive integrate fisheries habitat requirements into ecological flow regimes, helping to stabilise seagrass beds in the Ebro Delta (Douro et al. 2023). Tunisia has pioneered participatory water-sharing agreements between fishing cooperatives and irrigation districts in the Gulf of Gabès, ensuring minimum freshwater releases for juvenile mullet habitats (Ben Souissi et al., 2022). In contrast, Croatia's territorial waters regime of 12 nautical miles - without an extended EEZ - limits its ability to control the impacts of water use in adjacent high seas areas, emphasising the need for cooperative GFCM measures beyond national jurisdiction.

5.2. LEGAL FRAMEWORK FOR FISHERIES IN THE MEDITERRANEAN

International law forms the structural backbone of fisheries policy in the Mediterranean. The United Nations Convention on the Law of the Sea (UNCLOS 1982) grants coastal states sovereignty over territorial waters (up to 12 nautical miles) and sovereign rights over exclusive economic zones (up to 200 nautical miles) for resource management. Some Mediterranean countries (Italy, Greece, Croatia) have not declared full EEZs, resulting in large areas of high seas within the basin that require coordination by Regional Fisheries Management Organizations to regulate fisheries-related water use and habitat protection (UNCLOS, 1982; GFCM, 2020).

The FAO's comparative study on fisheries legislation in the Mediterranean reveals considerable national differences in the legal framework, particularly for recreational and small-scale fisheries (de Young & Gaudin, 2007). While Spain and France have clear licence and water use permit systems for coastal aquaculture, other countries have no enforceable rules governing water allocation to fish farms. This legal fragmentation hinders the effective application of GFCM decisions, makes it difficult to monitor compliance and undermines regional water sustainability goals.

To harmonise these different legal structures, the European Commission has proposed transposing the GFCM decisions on multi-annual management plans and Fisheries Restricted Areas (FRAs) into EU law. The proposal for a 2024 EU regulation on fisheries in the Mediterranean would incorporate recent GFCM recommendations - such as the seasonal closure of estuaries and the mandatory labelling of the water footprint of farmed species - into the Common Fisheries Policy (EPRS, 2024). If adopted, these measures would align national rules on water use with international conservation goals and create a level playing field for coastal fishers.

6. REFERENCES

Ben Souissi, S., Reda, F., & Mansour, R. (2022). Participatory water-sharing agreements in the Gulf of Gabès: Balancing fisheries and irrigation needs. *Journal of Coastal Conservation,* 26(4), 15. https://doi.org/10.1007/s11852-022-00824-1

Bojanić, Ž., Šimović, K., & Novak, M. (2020). Water and energy use in ice production for fish preservation: A case study from the Adriatic Sea. *Journal of Food Engineering,* 279, 109907.

Cheung, W. W. L., Lam, V. W. Y., Sarmiento, J. L., Kearney, K., Watson, R., & Pauly, D. (2013). Projecting global marine biodiversity impacts under climate change scenarios. *Fish and Fisheries,* 10(3), 235–251.

Coll, M., Piroddi, C., Albouy, C., Ben Rais Lasram, F., Cheung, W. W. L., Christensen, V., ... & Palomera, I. (2012). The Mediterranean Sea under siege: Spatial overlap between marine biodiversity, cumulative threats and marine protected areas. *Global Ecology and Biogeography,* 21(4), 465–480.

Council of the European Union (EUR-Lex). (2006). *Council Regulation (EC) No 1967/2006 of 21 December 2006 concerning management measures for the sustainable exploitation of fishery resources in the Mediterranean Sea.* OJ L 409.

de Young, C., & Gaudin, M. (2007). *Comparative study on national fisheries legislation in the Mediterranean and the Black Sea.* FAO Fisheries and Aquaculture Technical Paper No. 504. Rome: FAO.

Douro, V., Martínez-Pérez, C., & López-Cruz, J. (2023). Integrating fisheries habitat needs into river basin plans: The Ebro Delta case. *Environmental Management,* 72(1), 24–36.

European Environment Agency (EEA). (2022). *Use of freshwater resources in Europe: Water Exploitation Index Plus (WEI+).* EEA Report No 15/2022.

European Environment Agency (EEA). (2025). *Water scarcity conditions in Europe.* Retrieved from eea.europa.eu.

European Parliamentary Research Service (EPRS). (2024). *Fisheries management measures in the Mediterranean: Transposition into EU law.* Directorate General for Parliamentary Research Services.

FAO. (2018). *The State of World Fisheries and Aquaculture 2018.* Rome.

FAO. (2023). *General Fisheries Commission for the Mediterranean.* Rome: FAO.

FAO. (2024). *Technical Guidelines for Responsible Fisheries: Classifying Water Use in Fisheries.* Food and Agriculture Organization of the United Nations.

Fiorentino, F., & Vitale, S. (2021). Patterns of IUU fishing and invasive species in the Mediterranean. *Mediterranean Marine Science,* 22(1), 95–110.

Food and Agriculture Organization of the United Nations (FAO). (2001). *Fishery statistics: Commodities, Vol. 93.* FAO Fisheries Series No. 65; FAO Statistics Series No. 175. Rome.

Food and Agriculture Organization of the United Nations (FAO). (2005). *The United Nations Convention on the Law of the Sea: A Key Instrument for the Sustained Management of Fisheries.* FAO Legislative Study 89. Rome.

Food and Agriculture Organization of the United Nations (FAO). (2016). *Climate change implications for fisheries and*

aquaculture: Summary of the findings of the Intergovernmental Panel on Climate Change Fifth Assessment Report. Fisheries and Aquaculture Circular No. C1122.

Food and Agriculture Organization of the United Nations (FAO). (2020). *The State of World Fisheries and Aquaculture 2020.* Rome: FAO.

Food and Agriculture Organization of the United Nations (FAO). (2022). *The State of World Fisheries and Aquaculture 2022.* Rome: FAO.

Food and Agriculture Organization/General Fisheries Commission for the Mediterranean (FAO/GFCM). (2023). *State of Mediterranean and Black Sea Fisheries 2023.* Rome.

García, S. M., & Newton, C. (2021). *Regional Plan of Action for Small-Scale Fisheries in the Mediterranean and the Black Sea.* FAO.

General Fisheries Commission for the Mediterranean (GFCM). (2020). *The State of Mediterranean and Black Sea Fisheries 2020.* FAO.

General Fisheries Commission for the Mediterranean (GFCM). (2021). *2030 Strategy for the Mediterranean and Black Sea.* FAO.

Gerbens-Leenes, P. W., Hoekstra, A. Y., & van der Meer, T. H. (2009). The water footprint of energy from biomass: A quantitative assessment and consequences of an increasing share of bio-energy in energy supply. *Ecological Economics,* 68(4), 1052–1060.

Hidalgo, M., El-Haweet, A. E., Tsikliras, A. C., et al. (2022). Risks and adaptation options for Mediterranean fisheries under

climate change. *ICES Journal of Marine Science,* 79(9), 2473–2488.

Hoekstra, A. Y., Chapagain, A. K., Aldaya, M. M., & Mekonnen, M. M. (2011). *The Water Footprint Assessment Manual: Setting the Global Standard.* Earthscan.

Intergovernmental Panel on Climate Change (IPCC). (2022). Cross-Chapter Paper 4: Mediterranean Region. In *Climate Change 2022: Impacts, Adaptation and Vulnerability.* Cambridge University Press.

Joint Research Centre (JRC). (2025). *Impact of River Flow Changes on Mediterranean Fisheries.* Publications Office of the European Union.

Mekonnen, M. M., & Hoekstra, A. Y. (2012). The water footprint of humanity. *Proceedings of the National Academy of Sciences,* 109(9), 3232–3237.

Pisano, A. J., Munarin, R., & Presti, M. (2020). *Mean sea surface temperature field (1982–2018) in the Mediterranean area.* Copernicus Marine Environment Monitoring Service data descriptor.

Sala, A., & Lucchetti, A. (2019). Fleet composition and dynamics in Mediterranean small-scale fisheries. *Fisheries Research,* 209, 10–18.

Springmann, M., Godfray, H. C. J., Rayner, M., & Scarborough, P. (2018). Analysis and valuation of the health and climate change co-benefits of dietary change. *Nature Climate Change,* 8, 996–1004.

Symeonidou, S., & Mente, E. (2024). Water footprint of capture fisheries in the Mediterranean: A life-cycle assessment

approach. *Journal of Environmental Management.* Advance online publication.

Tramblay, Y., Llasat, M. C., Randin, C., & Coppola, E. (2020). Climate change impacts on water resources in the Mediterranean. *Regional Environmental Change,* 20(3), 83.

Tyedmers, P. H. (2004). Fuel use and greenhouse gas emissions of world fisheries. *AMBIO: A Journal of the Human Environment,* 34(8), 635–638.

UNEP/MAP. (2021). *Climate change in the Mediterranean: UNEP/MAP factsheet.* UNEP/MAP.

United Nations Economic Commission for Europe (UNECE). (2019). *Indicator C2.3 Water exploitation index (WEI)—Methodology.* UNECE.

United Nations. (1982). *United Nations Convention on the Law of the Sea.* Montego Bay: United Nations.

World Wildlife Fund (WWF). (2021). *Mediterranean marine heatwaves and their impacts.* WWF.

WWF Mediterranean Marine Initiative. (2023). *State of Mediterranean Fisheries Report.* WWF.

Ziegler, F., Winther, U., Hognes, E. S., Emanuelsson, A., Sund, V., & Ellingsen, H. (2013). The carbon footprint of Norwegian seafood products on the global seafood market. *Journal of Industrial Ecology,* 17(1), 103–116.



MODULE 3. WATER FOOTPRINT IN AQUACULTURE

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WATER FOOTPRINT IN AQUACULTURE

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1. INTRODUCTION TO AQUACULTURE SYSTEMS

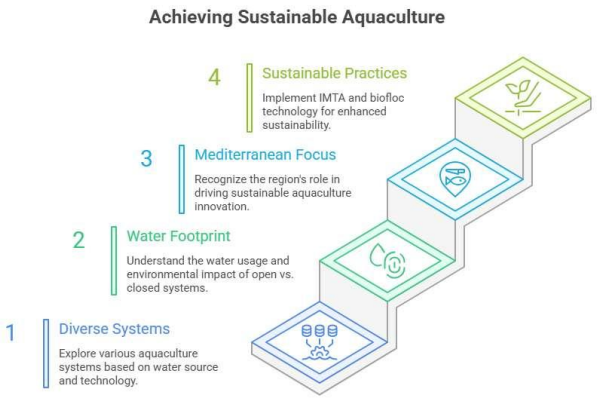


Figure 1. Achieving sustainable aquaculture (visual created via Napkin AI using original text provided by the authors).

The historical evolution of aquaculture spans thousands of years, with early practices documented in ancient China, Egypt, and

Rome, where carp and tilapia were cultivated in ponds (Beveridge & Little, 2002; Naylor et al., 2021). Modern aquaculture, however, has transformed into a highly diverse and technologically advanced industry, encompassing a range of systems tailored to species, environments, and economic contexts. These systems vary significantly in their design, water management practices, and environmental interactions, influencing their productivity, scalability, and ecological footprints.

Aquaculture systems are broadly categorized based on their water source (freshwater, brackish, or marine), degree of environmental integration (open, semi-closed, or closed), and technological sophistication (extensive, semi-intensive, or intensive). These distinctions directly impact the water footprint and environmental sustainability of the systems. For example, open systems like marine cage farming rely on natural water bodies for waste dilution, resulting in a low direct water footprint but potential ecological risks such as nutrient pollution (Telfer et al., 2009). In contrast, closed systems like Recirculating Aquaculture Systems (RAS) minimize water use through filtration and reuse but require significant energy inputs (Badiola et al., 2012).

The Mediterranean region, a focal point for aquaculture due to its favorable climate and extensive coastline, exemplifies the challenges of balancing productivity with environmental sustainability. Limited freshwater availability, high salinity, and competing demands from agriculture and tourism necessitate innovative approaches to water management in aquaculture (FAO, 2022, 2024). Emerging practices, such as Integrated Multi-Trophic Aquaculture (IMTA) and biofloc technology, aim to enhance water efficiency and reduce environmental impacts by recycling nutrients and minimizing waste (Avnimelech, 2009; Chopin et al., 2001; Klinger & Naylor, 2012).

As aquaculture continues to expand, understanding the interplay between system design, water use, and environmental outcomes is essential for developing sustainable practices.

2. TYPES OF AQUACULTURE SYSTEMS AND THEIR DIFFERENCES

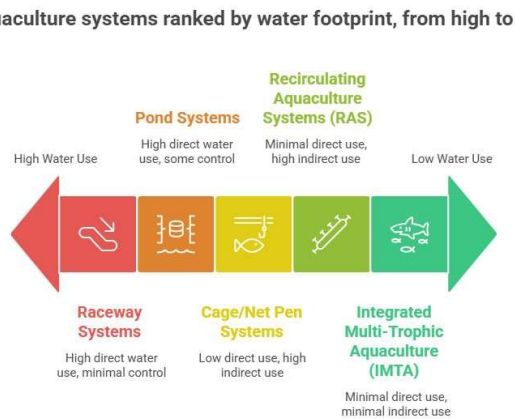


Figure 2. Aquaculture systems ranked by water footprint, from high to low (visual created via Napkin AI using original text provided by the authors).

Aquaculture systems are diverse, designed to accommodate various species, environmental conditions, and production goals. These systems differ in their water management practices, infrastructure requirements, environmental interactions, and water footprints, which are critical for assessing their sustainability. The primary types of aquaculture systems include pond systems, cage and net pen systems, raceway systems, recirculating aquaculture systems (RAS), and integrated multi-trophic aquaculture (IMTA). Each system has unique advantages, challenges, and implications for water use, particularly in water-scarce regions like the

Mediterranean. Below, we explore these systems in detail, emphasizing their operational mechanisms, suitability for different species, and environmental considerations.

Table 1. Aquaculture Systems in the Mediterranean

Type of Aquaculture System	Most Representative Species	Primary Cultivation Areas	Degree of Importance
Sea Cage Farming	Gilthead Seabream (Sparus aurata), European Seabass (Dicentrarchus labrax)	Greece, Turkey, Spain	Very High (dominant system for finfish production)
Shellfish Farming	Mediterranean Mussel (Mytilus galloprovincialis), Pacific Oyster (Crassostrea gigas)	Spain, Italy, France	High (widespread and environmentally benign)
Land-Based Tank Systems (Hatcheries/Nurseries)	Seabass, Seabream	Italy, Greece (coastal and inland facilities)	High (essential for supplying juveniles to other systems)
Raceway Systems	Rainbow Trout (Oncorhynchus mykiss)	Italy, Spain, Turkey (inland areas)	Moderate (significant for trout production, but water-intensive)

Type of Aquaculture System	Most Representative Species	Primary Cultivation Areas	Degree of Importance
Recirculating Aquaculture Systems (RAS)	Seabass, Tilapia (Oreochromis spp.), Sturgeon (Acipenser spp.)	Israel, Italy, France (inland and urban settings)	Emerging/Growing (key for water efficiency, but limited by cost)
Integrated Multi-Trophic Aquaculture (IMTA)	Seabass, Mussels, Macroalgae (e.g., Ulva spp.)	Greece, Spain, Israel (pilot projects)	Emerging/Niche (high sustainability potential, but not yet widespread)
Pond Systems	Carp (Cyprinus carpio), Tilapia	Southern Europe, North Africa (limited inland areas)	Low/Limited (constrained by water scarcity in the region)

2.1. POND SYSTEMS

Pond systems represent one of the oldest and most widespread forms of aquaculture, particularly for freshwater species such as tilapia (Oreochromis spp.), carp (Cyprinus carpio), and catfish (Ictalurus spp.). These systems typically consist of earthen or lined ponds filled with water sourced from surface water (rivers, lakes) or groundwater (wells). Water exchange is minimal, often static or occurring at low rates, with losses primarily due to evaporation, seepage, or periodic drainage for harvest or cleaning (Boyd & Tucker, 2012; Edwards, 2015). Pond systems are classified

as extensive or semi-intensive, depending on stocking density, feed inputs, and management intensity.

2.2. CAGE AND NET PEN SYSTEMS

Cage systems are cost-effective and scalable but pose environmental risks, including nutrient pollution and benthic degradation from organic waste accumulation (FAO, 2024). In the Mediterranean, these systems dominate aquaculture production in countries like Greece and Turkey, but their sustainability depends on site selection, stocking density, and monitoring to mitigate impacts on marine ecosystems (Telfer et al., 2009).

Innovations such as offshore cages aim to reduce environmental footprints by leveraging stronger currents for improved waste dispersal and dilution, which can lessen localized benthic impacts. However, it is important to note that these systems are not a complete solution. Offshore cages can still cause benthic degradation if waste deposition exceeds the environment's assimilation capacity and contribute to the dispersion of antibiotics and other chemicals in the marine environment, raising concerns about antimicrobial resistance and ecosystem health. Therefore, a comprehensive approach combining improved site selection, optimized feeding strategies, strict regulation of chemical use, and continuous environmental monitoring remains essential.

2.3. RACEWAY SYSTEMS

Raceway systems are characterized by long, narrow channels through which water flows continuously, ensuring high oxygenation and efficient waste removal. They are ideal for species requiring high water quality, such as rainbow trout (Oncorhynchus mykiss) and salmon (Salmo salar). Water is typically sourced from rivers or springs, with flow rates adjusted based on stocking density and species needs (Boyd & Tucker, 2012; Edwards, 2015). In the

Mediterranean, raceways are used in inland areas, particularly in Italy and Spain, for trout production.

Raceways are water-intensive, with water use estimates ranging from 10,000–15,000 liters per kilogram of trout produced due to the continuous flow requirement (Verdegem et al., 2006). Partial recirculation and water treatment technologies are increasingly adopted to reduce water consumption and mitigate environmental impacts, such as nutrient discharge into receiving waters (Badiola et al., 2012). The high water footprint and potential for downstream pollution make raceway systems less sustainable in water-scarce regions unless they are retrofitted with water-saving technologies.

2.4. RECIRCULATING AQUACULTURE SYSTEMS (RAS)

Recirculating Aquaculture Systems (RAS) are closed-loop systems that treat and reuse water, significantly reducing water consumption and environmental discharge. Water is filtered mechanically (to remove solids), biologically (to convert ammonia to nitrate), and sometimes chemically (e.g., UV sterilization or ozone treatment) before being recirculated (Ebeling & Timmons, 2010). RAS are suitable for high-value or sensitive species like sturgeon (Acipenser spp.), salmon, and tilapia, and are increasingly adopted in the Mediterranean for inland and urban aquaculture.

RAS achieve water savings of 90–99% compared to flow-through systems, with water use as low as 450–1,200 liters per kilogram of biomass produced (Verdegem et al., 2006). However, they require high capital investment, energy for filtration and aeration, and skilled management to prevent disease in high-density environments (Badiola et al., 2012). In water-scarce regions, RAS offers a sustainable solution by minimizing freshwater use, but their economic feasibility depends on market demand for premium species and supportive policies.

2.5. INTEGRATED MULTI-TROPHIC AQUACULTURE (IMTA)

Integrated Multi-Trophic Aquaculture (IMTA) combines species from different trophic levels—such as fish, shellfish (e.g., mussels, Mytilus galloprovincialis), and macroalgae (e.g., Ulva spp.)—within the same system to recycle nutrients and reduce environmental impacts. Fish waste provides nutrients for filter feeders and algae, which in turn improve water quality, creating a symbiotic system (Chopin et al., 2001). IMTA is gaining traction in the Mediterranean as a sustainable alternative to monoculture systems, particularly in marine cage settings. While not yet a dominant production method, its potential is being demonstrated through pilot projects in Greece, Spain, and Israel, paving the way for broader adoption in the region.

IMTA systems have a moderate to high water use efficiency, as they reduce the need for water exchange by maintaining water quality through nutrient uptake. While direct freshwater use is minimal in marine-based IMTA, indirect water use from feed production remains a concern (Pahlow et al., 2015). IMTA's environmental benefits include reduced eutrophication and enhanced ecosystem resilience, but challenges include complex system design, species compatibility, and market acceptance of co-cultured products (FAO, 2022).

3. AQUACULTURE SYSTEMS IN THE MEDITERRANEAN



Figure 3. Aquaculture in the Mediterranean (visual created via Napkin AI using original text provided by the authors).

The Mediterranean region is a global hotspot for aquaculture, driven by its favorable climate, extensive coastline, and growing demand for seafood. The region's aquaculture sector has expanded rapidly in recent decades to meet both domestic and international markets, particularly in response to declining wild fish stocks and increasing protein needs (FAO, 2024). However, the Mediterranean's semi-arid climate, limited freshwater resources, and intense competition for coastal and inland water from agriculture, tourism, and urban development pose significant challenges to sustainable aquaculture. This section explores the dominant aquaculture systems in the Mediterranean, their water use characteristics, species cultivated, environmental impacts, and emerging trends toward sustainability, with a focus on water footprint considerations.

3.1. DOMINANT AQUACULTURE SYSTEMS IN THE MEDITERRANEAN

Aquaculture in the Mediterranean is characterized by a diversity of systems tailored to local ecological and socioeconomic conditions. The main systems include:

3.1.1 Sea Cage Farming

Sea cage farming is the predominant aquaculture system in the Mediterranean, particularly in Greece, Turkey, and Spain, where it accounts for most of the finfish production. These systems involve floating or submerged cages in coastal or offshore marine environments, primarily used to culture euryhaline species such as gilthead seabream (Sparus aurata) and European seabass (Dicentrarchus labrax). Sea cages rely on natural water currents for oxygen supply and waste dispersal, resulting in a negligible direct freshwater footprint during the grow-out phase (Telfer et al., 2009). However, indirect water use is significant due to freshwater requirements in hatcheries, nurseries, and feed production, particularly for fishmeal and agricultural inputs like soy (Pahlow et al., 2015). Environmental concerns include nutrient pollution and benthic degradation, necessitating careful site selection and monitoring (FAO, 2022; Rosa et al., 2012).

3.1.2 Shellfish Farming

Shellfish farming, particularly of mussels (Mytilus galloprovincialis) and oysters (Crassostrea gigas), is widespread in coastal areas of Spain, Italy, and France. These systems use longlines, rafts, or racks in marine or brackish environments, relying on natural filtration by bivalves to feed on plankton and organic matter.

Due to this low-trophic, extractive nature, shellfish farming is widely regarded as one of the most sustainable methods for producing marine protein. It has a minimal direct water footprint, as it does not require freshwater inputs, feed, or water exchange. The primary environmental concerns are indirect water use from infrastructure and transport (Ayer & Tyedmers, 2009) and the potential for localized sediment enrichment under high-density farms (FAO, 2022). Furthermore, shellfish can improve water quality by filtering particulates and excess nutrients, providing a potential ecosystem service.

3.1.3 Land-Based Tank Systems

Land-based tank systems are primarily used for hatcheries and nurseries, supporting the early life stages of finfish like seabass and seabream. These systems require controlled environments with precise water quality parameters, often using freshwater or brackish water. In the Mediterranean, they are common in coastal and inland facilities in countries like Italy and Greece. Water use varies from moderate to high, depending on whether partial recirculation is employed, with estimates of 1,000–5,000 liters per kilogram of biomass produced in hatchery stages (Verdegem et al., 2006). These systems face challenges related to water availability and effluent management, particularly in water-scarce regions (Bostock et al., 2010).

3.1.4 Recirculating Aquaculture Systems (RAS)

RAS are gaining traction in the Mediterranean, particularly in inland and urban settings in countries like Italy, France, and Israel. These closed-loop systems recycle water through mechanical, biological, and chemical filtration, achieving water savings of up to 90–99% compared to flow-through systems (Ebeling & Timmons, 2010). RAS are used for high-value species like seabass, tilapia

(Oreochromis spp.), and sturgeon (Acipenser spp.), with water use as low as 450–1,200 liters per kilogram of biomass (Verdegem et al., 2006). While RAS reduce the water footprint, their high energy demands and capital costs limit widespread adoption, particularly for small-scale farmers (Badiola et al., 2012).

3.1.5 Emerging Integrated Multi-Trophic Aquaculture (IMTA)

IMTA is an emerging system in the Mediterranean, combining finfish (e.g., seabass), shellfish (e.g., mussels), and macroalgae (e.g., Ulva spp.) to recycle nutrients and improve water quality. Pilot projects in Greece, Spain, and Israel demonstrate IMTA's potential to reduce the environmental footprint of aquaculture by mitigating nutrient discharge and decreasing reliance on water exchange (Chopin et al., 2001). While IMTA does not directly reduce freshwater use in marine settings, it enhances system sustainability by lowering the need for external water inputs and addressing eutrophication risks (FAO, 2024).

3.2. ECOLOGICAL AND SOCIOECONOMIC CONSTRAINTS

The Mediterranean's aquaculture systems are shaped by unique ecological and socioeconomic factors:

- **Limited Freshwater Availability:** The region's semi-arid climate and seasonal precipitation patterns restrict freshwater use for inland systems, pushing reliance on marine-based systems like sea cages and shellfish farming (Mekonnen & Hoekstra, 2012; Rosa et al., 2012).
- **High Salinity and Temperature Variability:** Mediterranean waters have high salinity (36–39 ppt) and temperature fluctuations, influencing species selection and system design, particularly for euryhaline species (FAO, 2022).

- **Coastal Development Pressure:** Competition for coastal space from tourism, shipping, and urban development limits the expansion of cage and shellfish farming, necessitating offshore or integrated solutions (Beveridge & Little, 2002).
- **Economic Drivers:** High seafood demand in Europe and export markets drives intensive production, but economic viability is challenged by high operational costs in water-scarce regions and regulatory pressures for environmental compliance (EUMOFA, 2023).

3.3. WATER FOOTPRINT CONSIDERATIONS

The water footprint of Mediterranean aquaculture varies by system and species. Marine cage systems have the lowest direct freshwater footprint, as they rely on seawater, but their indirect footprint from feed production can be substantial, with estimates of 1,000–2,000 liters per kilogram of fish produced due to agricultural inputs (Pahlow et al., 2015). Land-based systems, such as tanks and raceways, have higher direct water footprints, particularly in hatcheries and freshwater species production (e.g., trout), with water use ranging from 3,000–15,000 liters per kilogram (Pahlow et al., 2015). RAS and IMTA offer the greatest potential for reducing water footprints, with RAS achieving minimal water use through recirculation and IMTA leveraging nutrient recycling to maintain water quality (Chopin et al., 2001; Ebeling & Timmons, 2010).

3.4. EMERGING TRENDS AND SUSTAINABILITY INITIATIVES

To address water scarcity and environmental concerns, Mediterranean aquaculture is adopting innovative practices:

- **Offshore Cage Farming:** Moving cages to deeper, high-current waters reduces benthic impacts and improves water

quality, though logistical and regulatory challenges remain (Telfer et al., 2009).

- **Water-Saving Technologies:** The adoption of RAS and biofloc technology (BFT) is increasing, particularly in water-scarce areas, to minimize water use and effluent discharge (Avnimelech, 2009).
- **Policy and Regulation:** The General Fisheries Commission for the Mediterranean (GFCM) promotes sustainable aquaculture through guidelines on water use, effluent management, and environmental impact assessments (FAO, 2022).
- **Sustainability Certifications:** Certifications like the Aquaculture Stewardship Council (ASC) encourage water-efficient practices and social responsibility, influencing market preferences in the region (FAO, 2022). A significant challenge, however, is the cost and administrative burden of the certification process itself. This can create an economic barrier that allows only large-scale, well-capitalized farms to certify their production, potentially marginalizing small-scale farmers and limiting the equitable distribution of market benefits.

These trends reflect a shift toward balancing productivity with environmental stewardship, critical for the long-term sustainability of Mediterranean aquaculture in the face of climate change and resource constraints.

4. CLASSIFICATION OF SYSTEMS BY WATER EXCHANGE

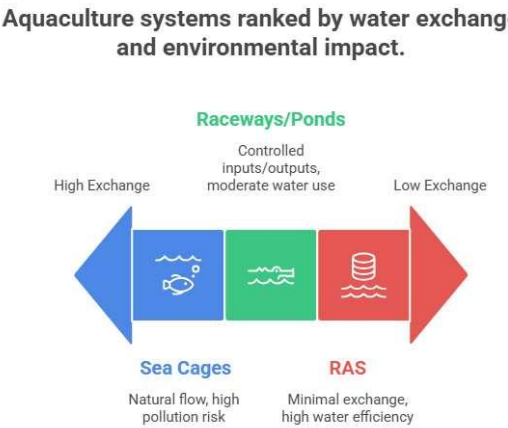


Figure 4. Aquaculture systems ranked by water exchange and environmental impact (visual created via Napkin AI using original text provided by the authors).

Aquaculture systems can be classified based on their water exchange dynamics, which directly influence their water footprint, environmental impact, and operational sustainability. These systems are broadly categorized into open, semi-closed, and closed systems, each defined by the degree of interaction with the surrounding environment and the extent of water replacement or recirculation. This classification is critical for understanding water use efficiency, particularly in water-scarce regions like the Mediterranean, where sustainable water management is a priority. In the following section we explore these categories in detail, focusing on their operational characteristics, water footprint implications, environmental considerations, and management strategies.

4.1. OPEN SYSTEMS

Despite their water efficiency, open systems pose environmental challenges. Waste, including uneaten feed and fecal matter, is released directly into the environment, potentially causing nutrient enrichment, eutrophication, and benthic degradation (FAO, 2024). For example, studies in the Mediterranean have shown that high-density cage farming can lead to localized nutrient loading, impacting benthic communities and water quality (Telfer et al., 2009). Management strategies to mitigate these impacts include:

- **Site Selection:** Positioning cages in areas with strong currents to enhance waste dispersal (FAO, 2022).
- **Feed Optimization:** Using high-digestibility feeds to reduce uneaten feed and nutrient output (Chopin et al., 2001).
- **Environmental Monitoring:** Implementing regular assessments to monitor water quality and benthic impacts, as mandated by regional regulations (EUMOFA, 2023).
- **Integrated Benthic Management:** The deployment of benthic scavengers, such as sea cucumbers or certain crab species, directly below cage farms can help reduce the accumulation of organic matter by consuming settled waste, mimicking a natural cleanup crew and mitigating benthic impacts.

Open systems are economically attractive due to low infrastructure costs but require careful management to balance productivity with environmental sustainability.

4.2. SEMI-CLOSED SYSTEMS

Semi-closed systems, such as flow-through raceways and some pond systems, involve controlled water inputs and outputs,

with water sourced from external supplies like rivers, springs, or groundwater. These systems provide greater control over water quality compared to open systems, allowing for adjustments in flow rates, aeration, and waste management (Boyd & Tucker, 2012). Semi-closed systems are used in the Mediterranean for freshwater species like rainbow trout (Oncorhynchus mykiss) and carp (Cyprinus carpio), particularly in inland areas of Italy and Spain.

The water footprint of semi-closed systems is moderate, with estimates ranging from 3,000–15,000 liters per kilogram of biomass produced, depending on species, system design, and management practices (Verdegem et al., 2006). For instance, flow-through raceways for trout require high water volumes due to continuous flow, while pond systems may have lower exchange rates but higher losses from evaporation and seepage (Bosma & Verdegem, 2011). Environmental impacts include nutrient-rich effluent discharge, which can contribute to downstream eutrophication if not managed properly (FAO, 2022). Strategies to improve water efficiency and sustainability include:

- **Partial Recirculation:** Retrofitting raceways with recirculation units to reduce water intake (Badiola et al., 2012).
- **Settling Ponds and Wetlands:** Treating effluents to remove solids and nutrients before discharge (Crab et al., 2007).
- **Precision Management:** Using sensors to monitor water quality and optimize flow rates, reducing unnecessary water use (Ebeling & Timmons, 2010).

Semi-closed systems offer a balance between control and cost but face challenges in water-scarce regions due to their reliance on consistent water supplies.

4.3. CLOSED SYSTEMS

Closed systems, primarily Recirculating Aquaculture Systems (RAS), are designed to minimize water exchange by treating and reusing water within the system. Water losses occur mainly through evaporation, sludge removal, and minor leaks, with fresh water added only to compensate for these losses (Ebeling & Timmons, 2010). RAS are increasingly adopted in the Mediterranean for high-value species like seabass, tilapia (Oreochromis spp.), and sturgeon (Acipenser spp.), particularly in inland and urban settings where water availability is limited.

RAS have the lowest water footprint among aquaculture systems, with water use ranging from 450–1,200 liters per kilogram of biomass produced, representing a 90–99% reduction compared to flow-through systems (Verdegem et al., 2006). Key components include mechanical filters (for solids removal), biofilters (for ammonia conversion), and disinfection units (e.g., UV or ozone treatment) to maintain water quality (Ahmed & Turchini, 2021; Badiola et al., 2012). Despite their water efficiency, RAS have high energy demands for filtration, aeration, and temperature control, as well as significant capital costs, which can limit adoption by small-scale farmers (FAO, 2022). Environmental benefits include minimal effluent discharge and enhanced biosecurity, reducing the risk of disease and pathogen spread. Management strategies to optimize RAS include:

- **Biofloc Integration:** Incorporating microbial flocs to enhance nutrient recycling and reduce feed costs (Avnimelech, 2009).
- **Automation and IoT:** Using real-time monitoring systems to optimize water quality and reduce operational costs (Ebeling & Timmons, 2010; Timmons & Ebeling, 2010).

- **Energy Efficiency:** Implementing renewable energy sources to offset high energy demands (Ahmed & Turchini, 2021; Badiola et al., 2012).

Closed systems are highly sustainable in terms of water use but require technological expertise and investment, making them suitable for high-value markets and regions with strict environmental regulations.

4.4. COMPARATIVE ANALYSIS OF WATER EXCHANGE SYSTEMS

The water exchange classification highlights trade-offs between water use, environmental impact, and operational feasibility:

- **Open Systems:** Lowest direct water footprint but highest environmental risk due to nutrient discharge. Ideal for marine environments but require robust management to mitigate ecological impacts.
- **Semi-Closed Systems:** Moderate water footprint with greater control over water quality. Suitable for freshwater species but vulnerable to water scarcity and effluent-related issues.
- **Closed Systems:** Highest water use efficiency but significant energy and capital costs. Best suited for water-scarce regions and high-value species.

Emerging technologies, such as biofloc systems and integrated multi-trophic aquaculture (IMTA), are blurring the lines between these categories by combining elements of semi-closed and closed systems to enhance water efficiency and reduce environmental impacts (Chopin et al., 2001; Avnimelech, 2009). In the Mediterranean, the choice of system is influenced by water availability, species requirements, and regulatory frameworks, with

a growing emphasis on closed and integrated systems to address water scarcity and environmental concerns (FAO, 2022).

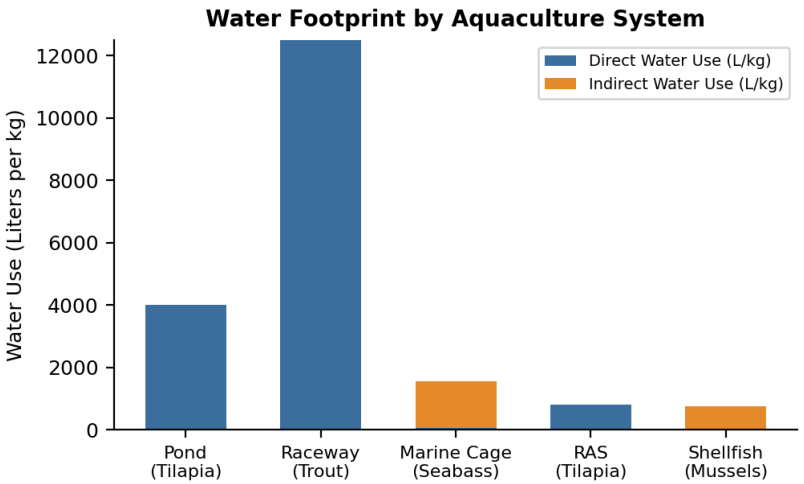


Figure 5. Comparative bar chart of water footprint by aquaculture system. Source: Ayer & Tyedmers, 2009; Bosma & Verdegem, 2011; Ebeling & Timmons, 2010; Pahlow et al., 2015.

Figure 5 illustrates the approximate water use (liters per kilogram of biomass produced) across different aquaculture systems, including pond systems (e.g., tilapia: 3,000–5,000 L/kg), raceway systems (e.g., trout: 10,000–15,000 L/kg), marine cage systems (e.g., seabass: <100 L/kg direct, 1,000–2,000 L/kg indirect), recirculating aquaculture systems (RAS) (e.g., tilapia: 450–1,200 L/kg), and shellfish farming (e.g., mussels: negligible direct, 500–1,000 L/kg indirect). The figure highlights the superior water efficiency of RAS and shellfish farming compared to water-intensive raceways.

5. FRESHWATER USE IN AQUACULTURE

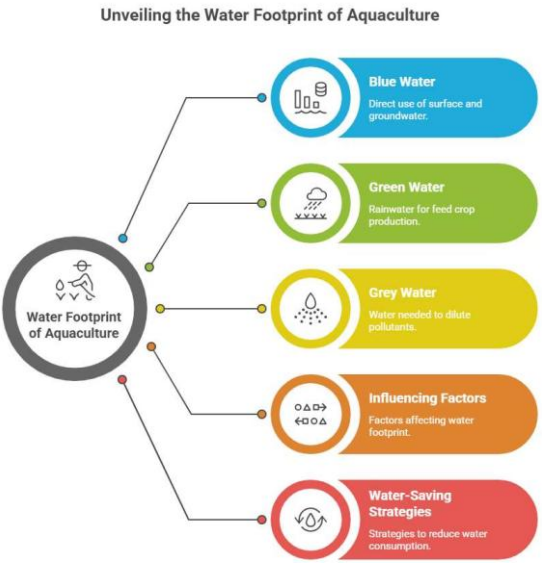


Figure 6. Unveiling the water footprint of aquaculture (visual created via Napkin AI using original text provided by the authors).

Freshwater is a critical resource in aquaculture, influencing the feasibility, sustainability, and environmental impact of production systems. The water footprint of aquaculture quantifies the volume of freshwater consumed or polluted throughout the production chain, encompassing direct use (e.g., for rearing, cleaning, and processing) and indirect use (e.g., for feed production and infrastructure). Freshwater use varies significantly across aquaculture systems, species, management practices, and geographical contexts, making it a key focus for sustainable aquaculture, particularly in water-scarce regions like the Mediterranean (Klinger & Naylor, 2012; Mekonnen & Hoekstra, 2012). This section explores the components of freshwater use, species-specific requirements, system variations, and strategies to

enhance water efficiency, with an emphasis on minimizing environmental impacts.

5.1. COMPONENTS OF THE WATER FOOTPRINT IN AQUACULTURE

The water footprint in aquaculture is composed of three main components, as defined by the Water Footprint Network (Hoekstra et al., 2011):

- **Blue Water Footprint:** The volume of surface or groundwater consumed in rearing, cleaning, and processing. This includes water lost through evaporation, seepage, or discharge in systems like ponds and raceways (Boyd & Tucker, 1998).
- **Green Water Footprint:** The volume of rainwater used, primarily in feed crop production (e.g., soy, wheat) for aquaculture feeds. This is significant for intensive systems reliant on formulated feeds (Gephart et al., 2021; Pahlow et al., 2015).
- **Grey Water Footprint:** The volume of freshwater required to assimilate pollutants, such as nitrogen and phosphorus from effluents, to meet environmental quality standards (Gephart et al., 2021; Mekonnen & Hoekstra, 2012).

Direct water use is highest in freshwater-based systems like ponds and raceways, while indirect use dominates in marine systems like sea cages, where feed production accounts for a substantial portion of the water footprint (FAO, 2022). For example, producing 1 kg of fishmeal-based feed can require 1,000–2,000 liters of water, primarily due to agricultural inputs (Pahlow et al., 2015).

5.2. FACTORS INFLUENCING FRESHWATER USE

Freshwater use in aquaculture is influenced by several factors:

- **System Design:** Open systems (e.g., sea cages) have minimal direct freshwater use, while semi-closed (e.g., raceways) and closed systems (e.g., RAS) vary widely in water efficiency (Ebeling & Timmons, 2010). Ponds and raceways often require high water inputs due to evaporation and continuous flow, whereas RAS minimize use through recirculation (Badiola et al., 2012).
- **Species Physiology:** Freshwater species like tilapia and carp require consistent water replacement, increasing the blue water footprint. Euryhaline species like seabass and seabream, primarily farmed in marine cages, have lower freshwater needs except in hatchery stages (Verdegem et al., 2006).
- **Management Practices:** Stocking density, feeding efficiency, and water treatment technologies significantly affect water use. High-density systems increase waste loads, necessitating more water for dilution in open and semi-closed systems (Boyd & Tucker, 2012).
- **Geographical Context:** In the Mediterranean, water scarcity and high evaporation rates exacerbate freshwater demands, particularly for inland systems. Coastal systems benefit from seawater availability but face indirect water costs from feed production (FAO, 2022).

5.3. WATER CONSUMPTION BY SPECIES AND PRODUCTION SYSTEMS

Freshwater use varies significantly by species and system, reflecting differences in physiological requirements and operational designs. Table 2 summarizes approximate water use for key species and systems, based on literature estimates.

Table 2. Approximate Water Use for Key Species and Systems

Species	System Type	Approx. Water Use (L/kg)	Reference
Tilapia (Oreochromis spp.)	Pond systems	3,000–5,000	Verdegem et al., 2006
Trout (Oncorhynchus mykiss)	Flow-through raceways	10,000–15,000	Verdegem et al., 2006
Seabass (Dicentrarchus labrax)	Marine cage systems	<100 (direct); 1,000–2,000 (indirect)	Pahlow et al., 2015
Seabream (Sparus aurata)	Marine cage systems	<100 (direct); 1,000–2,000 (indirect)	Pahlow et al., 2015
Tilapia (Oreochromis spp.)	Recirculating systems (RAS)	150–500	Symeonidou & Mente, 2024
Salmonids (e.g., Trout, Salmon)	Recirculating systems (RAS)	500–1,000	Symeonidou & Mente, 2024

Species	System Type	Approx. Water Use (L/kg)	Reference
Mussels (Mytilus galloprovincialis)	Longlines/rafts	Negligible (direct); 500–1,000 (indirect)	Ayer & Tyedmers, 2009

- **Freshwater Species:** Tilapia and trout in ponds and raceways have high blue water footprints due to water replacement needs. Ponds lose water through evaporation and seepage, while raceways require continuous flow for oxygenation and waste removal (Bosma & Verdegem, 2011).
- **Euryhaline Species:** Seabass and seabream in marine cages have negligible direct freshwater use during grow-out but require freshwater in hatcheries and nurseries, contributing to a moderate indirect footprint through feed production (Pahlow et al., 2015).
- **Shellfish:** Mussels and oysters have minimal direct water use, as they rely on natural filtration in marine environments, but indirect water use from infrastructure and transport can be notable (Ayer & Tyedmers, 2009).
- **RAS:** Closed systems like RAS achieve the lowest water footprints by recycling 90–99% of water, with losses primarily from evaporation and sludge removal (Ebeling & Timmons, 2010).

5.4. REGIONAL VARIATIONS IN FRESHWATER USE

In the Mediterranean, freshwater use is heavily influenced by regional water scarcity and system preferences:

- **Greece and Turkey:** Dominated by marine cage farming, these countries have low direct freshwater footprints but significant indirect footprints due to feed production for seabass and seabream (EUMOFA, 2023). Hatcheries and nurseries require 1,000–5,000 liters per kilogram of juvenile fish produced (Verdegem et al., 2006).
- **Italy and Spain:** Inland trout and carp farming in flow-through systems consume large water volumes, with estimates of 10,000–15,000 liters per kilogram in raceways, exacerbated by evaporation in semi-arid climates (FAO, 2022).
- **Emerging RAS Adoption:** Countries like Israel and France are investing in RAS for tilapia and seabass, reducing water use to 450–1,200 liters per kilogram, though high energy costs remain a barrier (Badiola et al., 2012).

Climate change exacerbates these challenges, with rising temperatures and reduced precipitation increasing evaporation losses and limiting freshwater availability, particularly for inland systems (FAO, 2024).

5.5. STRATEGIES FOR REDUCING FRESHWATER USE

To enhance water efficiency and reduce the water footprint of aquaculture, several strategies are being implemented:

- **Recirculating Aquaculture Systems (RAS):** By recycling water through filtration and treatment, RAS reduces water use by up to 99% compared to flow-through systems. They are particularly effective in water-scarce regions but require high capital and energy inputs (Ebeling & Timmons, 2010).
- **Biofloc Technology (BFT):** BFT promotes microbial flocs to recycle nitrogenous waste, minimizing water exchange in

semi-closed systems like shrimp and tilapia farms (Avnimelech, 2009). This reduces the blue water footprint and feed costs.

- **Integrated Multi-Trophic Aquaculture (IMTA):** IMTA combines fish, shellfish, and macroalgae to recycle nutrients, reducing the need for water exchange and mitigating the grey water footprint by lowering effluent pollution (Chopin et al., 2001).
- **Employing AI for Precision Water Management:** Instead of performing preventive and often excessive water exchanges, AI-driven systems use real-time sensors to monitor water quality parameters (e.g., dissolved oxygen, ammonia). The system can then automatically activate specific aerators or initiate a minimal and controlled water exchange only when strictly necessary, drastically reducing water waste (Wei et al., 2020).
- **Feed Optimization:** Using high-digestibility feeds and precision feeding reduces nutrient waste and the green water footprint associated with feed crop production (Chopin et al., 2001).
- **Nature-Based Solutions:** Constructed wetlands and settling ponds treat effluents, enabling water reuse and reducing the grey water footprint in semi-intensive systems (Crab et al., 2007).
- **Policy and Monitoring:** Implementing water-use audits, effluent standards, and sustainability certifications (e.g., Aquaculture Stewardship Council) encourages efficient water management (FAO, 2022).

These strategies align with the Mediterranean's need for sustainable aquaculture, balancing productivity with environmental and resource constraints.

6. CASE STUDY: MEDITERRANEAN AQUACULTURE

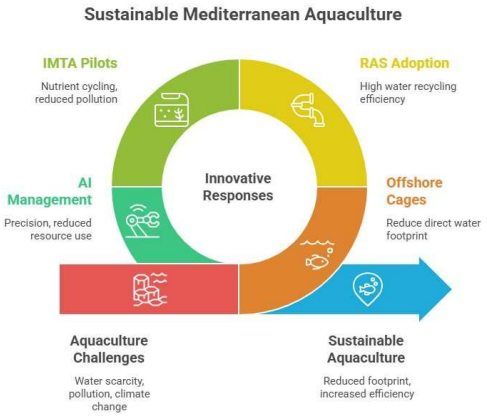


Figure 7. Sustainable Mediterranean aquaculture (visual created via Napkin AI using original text provided by the authors).

The Mediterranean Sea is a global hub for aquaculture, driven by increasing seafood demand, declining wild fish stocks, and economic incentives for coastal communities. The region's semi-arid climate, limited freshwater resources, and competing demands from agriculture, tourism, and urban development make water management a critical issue for sustainable aquaculture (FAO, 2022). This case study examines the Mediterranean aquaculture sector, focusing on production trends, water footprint dynamics, environmental and socioeconomic challenges, climate change impacts, and innovative strategies to enhance water efficiency, particularly in the context of the region's water scarcity.

6.1. REGIONAL OVERVIEW AND PRODUCTION DATA

Mediterranean aquaculture has grown significantly over the past few decades, contributing to food security and economic development in countries such as Greece, Turkey, Italy, and Spain. According to the European Market Observatory for Fisheries and Aquaculture Products (EUMOFA, 2023), the region produced approximately 1.2 million tons of aquaculture products in 2022, with finfish and shellfish dominating output.

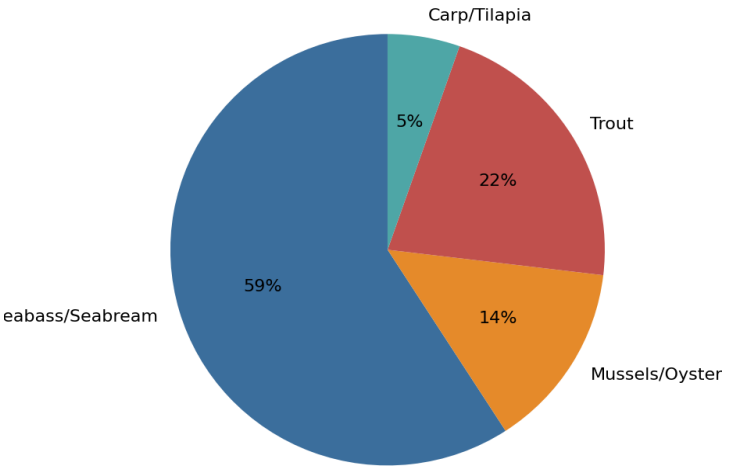


Figure 8. Mediterranean aquaculture production by species, 2022. Source: Bostock et al., 2010; EUMOFA, 2023; FAO, 2022; Troell et al., 2017.

Figure 8 visualizes the distribution of aquaculture production in the Mediterranean in 2022, showcasing the dominance of key species groups: seabass and seabream (550,000 tons, primarily from Greece and Turkey), mussels and oysters (130,000 tons, mainly from Spain and Italy), trout (200,000 tons, from inland systems), and carp/tilapia (50,000 tons, from limited inland ponds). The chart emphasizes the prevalence of marine cage farming and shellfish production due to limited freshwater availability, providing context

for the regional water footprint dynamics discussed in this case study.

Key species and production volumes include:

- **Gilthead Seabream (Sparus aurata) and European Seabass (Dicentrarchus labrax):** These euryhaline species dominate marine cage farming, particularly in Greece (150,000 tons) and Turkey (400,000 tons, including trout) (EUMOFA, 2023).
- **Mussels (Mytilus galloprovincialis) and Oysters (Crassostrea gigas):** Shellfish farming is prevalent in Spain (50,000 tons, primarily mussels) and Italy (80,000 tons, mixed production) (FAO, 2022).
- **Rainbow Trout (Oncorhynchus mykiss):** Farmed in inland freshwater systems in Italy and Turkey, contributing to mixed production volumes (EUMOFA, 2023).
- **Carp (Cyprinus carpio) and Tilapia (Oreochromis spp.):** Cultured in limited inland pond systems, particularly in southern Europe and North Africa (Bostock et al., 2010; Troell et al., 2017).

The region's aquaculture is characterized by a mix of marine and freshwater systems, with marine cage farming and shellfish production dominating due to limited freshwater availability. However, hatcheries, nurseries, and inland systems rely heavily on freshwater, making water footprint management a priority (Mekonnen & Hoekstra, 2012).

6.2. WATER FOOTPRINT DYNAMICS IN MEDITERRANEAN AQUACULTURE

The water footprint of Mediterranean aquaculture varies by system, species, and production stage, encompassing direct (blue water) and indirect (green and grey water) components:

- **Marine Cage Systems:** Dominant in Greece and Turkey, these systems have a negligible direct freshwater footprint during grow-out, as they rely on seawater exchange. However, indirect water use is significant, with feed production (e.g., fishmeal, soy) requiring 1,000–2,000 liters per kilogram of fish produced (Pahlow et al., 2015). Hatcheries and nurseries for seabass and seabream require 1,000–5,000 liters per kilogram of juvenile fish, contributing to the blue water footprint (Verdegem et al., 2006).

- **Shellfish Farming:** Mussel and oyster production in Spain and Italy has minimal direct freshwater use, as bivalves filter feed in marine environments. Indirect water use from infrastructure (e.g., ropes, rafts) and transport is estimated at 500–1,000 liters per kilogram (Ayer & Tyedmers, 2009).

- **Inland Freshwater Systems:** Trout and carp farming in flow-through raceways and ponds in Italy, Spain, and Turkey consumes 3,000–15,000 liters per kilogram due to continuous water flow and evaporation losses, particularly in semi-arid climates (FAO GFCM, 2022).

- **Recirculating Aquaculture Systems (RAS):** Emerging in Israel, France, and Italy, RAS reduce water use to 450–1,200 liters per kilogram for species like tilapia and seabass, but high energy costs pose challenges (Badiola et al., 2012).

The Mediterranean's water scarcity, exacerbated by climate change, underscores the need for systems that minimize freshwater use while maintaining productivity (FAO, 2022).

6.3. ENVIRONMENTAL AND SOCIOECONOMIC CHALLENGES

Mediterranean aquaculture faces several challenges related to water use and sustainability:

- **Water Scarcity:** The region's semi-arid climate and seasonal precipitation limit freshwater availability for inland systems. For example, the Po River Basin in Italy and southern Spain face restrictions on water withdrawals due to competing demands from agriculture and urban use (Beveridge & Little, 2002).
- **Nutrient Pollution:** Marine cage systems in Greece and Turkey release nutrients (nitrogen, phosphorus) into coastal waters, contributing to eutrophication and benthic degradation (Telfer et al., 2009). This impacts water quality and conflicts with tourism and wild fisheries.
- **Socioeconomic Conflicts:** Large-scale aquaculture operations, particularly sea cages, face opposition from local communities due to visual impacts and perceived environmental degradation, especially in tourism-dependent areas like Greece and Spain (EUMOFA, 2023).
- **Economic Viability:** High operational costs for water-efficient systems like RAS limit adoption by small-scale farmers, creating inequities in access to sustainable technologies (Belton et al., 2018).

These challenges highlight the need for integrated approaches that balance environmental, social, and economic priorities.

6.4. CLIMATE CHANGE IMPACTS

Climate change poses significant risks to Mediterranean aquaculture, particularly through its effects on water availability and quality:

- **Rising Temperatures:** Increased water temperatures enhance evaporation rates in ponds and raceways, exacerbating water losses. For example, summer temperatures in southern Spain can exceed 30 °C, increasing water demand (FAO, 2022; FAO GFCM, 2022).
- **Reduced Precipitation:** Declining rainfall and prolonged droughts limit surface and groundwater availability, particularly for inland trout and carp farming in Italy and Turkey (Mekonnen & Hoekstra, 2012; Rosa et al., 2012).
- **Sea Level Rise and Salinity Changes:** Coastal cage systems face risks from rising sea levels and altered salinity, affecting species like seabass and seabream, which require specific salinity ranges in early life stages (FAO, 2024).
- **Extreme Weather:** Increased frequency of storms and heatwaves disrupts cage and shellfish farming, damaging infrastructure and affecting water quality (FAO GFCM, 2022).

These impacts necessitate adaptive strategies to ensure the resilience of aquaculture systems in the Mediterranean.

6.5. INNOVATIVE PRACTICES FOR WATER EFFICIENCY

To address water scarcity and environmental concerns, Mediterranean aquaculture is adopting innovative practices to reduce water footprints:

- **Recirculating Aquaculture Systems (RAS):** RAS are expanding in Israel and Italy, reducing water use by 90–99% through filtration and recirculation. They are particularly suited for inland tilapia and seabass production but require investment in energy-efficient technologies (Ebeling & Timmons, 2010).
- **Biofloc Technology (BFT):** BFT is being piloted in shrimp and tilapia farms in Spain and Israel, using microbial flocs to recycle nutrients and minimize water exchange, reducing the blue water footprint (Avnimelech, 2009).
- **Integrated Multi-Trophic Aquaculture (IMTA):** IMTA projects in Greece and Spain combine seabass with mussels and macroalgae to recycle nutrients, reducing the grey water footprint and improving water quality (Chopin et al., 2001).
- **Offshore Cage Farming:** Moving cages to deeper waters with stronger currents, as practiced in Turkey, reduces benthic impacts and nutrient accumulation, indirectly supporting water quality (Telfer et al., 2009).
- **Feed Optimization:** Using high-digestibility feeds and precision feeding systems in Greece and Turkey reduces nutrient waste and the green water footprint associated with feed production (Chopin et al., 2001).
- **Policy and Certification:** The General Fisheries Commission for the Mediterranean (GFCM) promotes water-efficient practices through guidelines and environmental impact

assessments. Certifications like the Aquaculture Stewardship Council (ASC) incentivize sustainable water use (FAO, 2022).

6.6. FUTURE OUTLOOK

The Mediterranean aquaculture sector must navigate water scarcity, environmental pressures, and socioeconomic demands to remain sustainable. Investments in RAS, BFT, and IMTA, coupled with policy support for water-use audits and sustainability certifications, offer a pathway to reduce water footprints. To further optimize water efficiency, the integration of Artificial Intelligence (AI) is pivotal. AI-driven systems can leverage real-time sensor data to predict water quality issues, enabling proactive interventions such as the automated activation of aerators or targeted, minimal water exchanges instead of excessive preventive ones. This precise management drastically reduces freshwater consumption and waste. Furthermore, computer vision for precision feeding minimizes uneaten feed, a major source of water pollution, thereby maintaining water quality for longer periods and reducing the need for renewal.

Community engagement and participatory governance can address socioeconomic conflicts, ensuring equitable access to resources (Belton et al., 2018). As climate change intensifies, integrating aquaculture into broader water resource management frameworks, such as Integrated Water Resource Management (IWRM), will be critical for balancing productivity with environmental stewardship (Beveridge & Little, 2002).

7. NUTRIENT MANAGEMENT AND POLLUTION

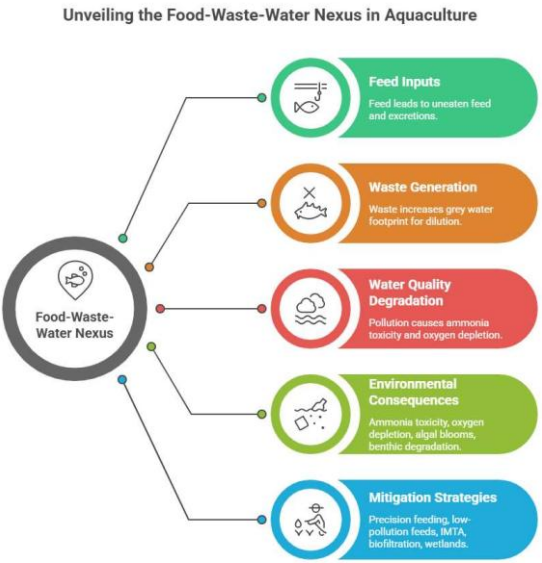


Figure 9. Unveiling the food-waste-water nexus in aquaculture (visual created via Napkin AI using original text provided by the authors).

Nutrient management is a cornerstone of sustainable aquaculture, as the sector's interaction with aquatic environments through nutrient inputs and waste outputs can significantly impact water quality and ecosystem health. Inefficient nutrient management leads to pollution, including eutrophication, oxygen depletion, and habitat degradation, particularly in sensitive regions like the Mediterranean (FAO, 2022). This section explores the nutrient dynamics in aquaculture, sources and impacts of pollution, advanced management strategies, and the role of policy and technology in mitigating environmental impacts, with a focus on reducing the grey water footprint associated with pollutant assimilation.

7.1. THE FOOD-WASTE-WATER NEXUS

The nutrient dynamics in aquaculture are governed by the interplay of feed inputs, biomass growth, waste generation, and water as a transport medium, often referred to as the food-waste-water nexus (Boyd & Tucker, 2012):

- **Feed Input:** Feed is the primary source of nutrients, introducing nitrogen (N) and phosphorus (P) into the system. Only 20–50% of these nutrients are retained in fish biomass, with the remainder lost as uneaten feed, feces, or dissolved excretions (Chopin et al., 2001). For example, in seabream cage farming, feed conversion ratios (FCR) of 1.0–1.2 result in 40–50% nutrient retention, while extensive carp ponds with FCR >2.0 retain only 20–30% (Verdegem et al., 2006).
- **Waste Generation:** Waste includes solid particles (uneaten feed, feces) and dissolved compounds (ammonia, nitrate, phosphate) excreted by fish. Solid waste settles in ponds or below cages, while dissolved nutrients are transported by water, contributing to the grey water footprint (Mekonnen & Hoekstra, 2012).
- **Water as Transport Medium:** In open and flow-through systems, water carries waste into the environment, potentially causing nutrient enrichment. In closed systems like RAS, water is treated to remove waste, minimizing external discharge (Ebeling & Timmons, 2010).

This nexus underscores the importance of optimizing feed efficiency and system design to reduce nutrient losses and pollution.

7.2. NUTRIENT MANAGEMENT AND WATER QUALITY

Excess nutrients in aquaculture systems can trigger a cascade of environmental impacts, increasing the grey water footprint

required to dilute pollutants to acceptable levels (Hoekstra et al., 2011):

- **Ammonia Toxicity:** High ammonia levels, common in intensive systems at high pH and temperature, are toxic to fish and aquatic organisms. For example, Mediterranean cage systems in summer conditions can experience ammonia spikes, requiring careful monitoring (Boyd & Tucker, 2012).
- **Oxygen Depletion:** Microbial decomposition of organic waste consumes oxygen, leading to hypoxic conditions. This is a concern in ponds and below cage systems, where sediment accumulation creates anoxic zones (Sarà et al., 2018; Telfer et al., 2009).
- **Algal Blooms:** Excess nitrogen and phosphorus stimulate algal growth, potentially causing harmful blooms that produce toxins and reduce light penetration, affecting aquatic ecosystems (FAO, 2022).
- **Benthic Degradation:** In marine cage systems, organic waste accumulation below cages can smother benthic communities, reducing biodiversity and altering sediment chemistry (FAO GFCM, 2022).

Effective nutrient management strategies to maintain water quality include:

- **Precision Feeding:** Using demand feeders and automated systems to match feed delivery to fish appetite, reducing uneaten feed (Chopin et al., 2001).
- **Low-Polluting Feeds:** Developing feeds with high digestibility and balanced protein-to-energy ratios to minimize nutrient excretion (Verdegem et al., 2006).

- **Integrated Multi-Trophic Aquaculture (IMTA):** Co-culturing fish with extractive species like mussels and macroalgae to absorb dissolved nutrients, reducing environmental impacts (Chopin et al., 2001).
- **Water Quality Monitoring:** Deploying sensors to track nutrient levels, dissolved oxygen, and pH in real-time, enabling proactive management (Ebeling & Timmons, 2010).

7.3. SOURCES OF POLLUTION IN AQUACULTURE

Aquaculture pollution arises from multiple sources, each associated with specific pollutants and system types.

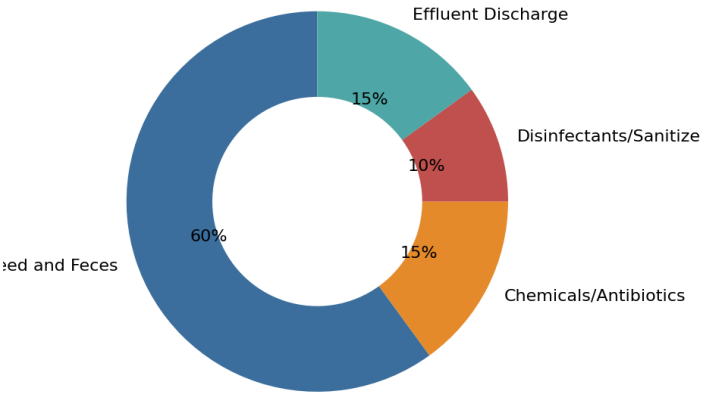


Figure 10. Sources of pollution in aquaculture. Source: Badiola et al., 2012; FAO, 2022; Telfer et al., 2009; Verdegem et al., 2006.

Figure 10 depicts the relative contributions of pollution sources in aquaculture, including feed and feces (60%, causing eutrophication and benthic degradation), chemicals/antibiotics (15%, leading to bioaccumulation), disinfectants/sanitizers (10%, toxic to non-target organisms), and effluent discharge (15%, degrading downstream water quality). The figure underscores the

need for nutrient management strategies like precision feeding and IMTA, aligning with the focus on reducing the grey water footprint.

Table 3. Aquaculture Pollution Sources, Associated Pollutants and System Types

Pollution Source	Pollutants	System Type Most Affected	Key Risk Areas
Feed and Feces	Organic matter, nitrogen, phosphorus	Cages, ponds, raceways	Eutrophication, benthic degradation
Chemicals and Antibiotics	Residues, metabolites	All intensive systems	Bioaccumulation, antimicrobial resistance
Disinfectants/Sanitizers	Chlorine, formalin	Hatcheries, RAS	Toxicity to non-target organisms
Effluent Discharge	Suspended solids, pathogens	Flow-through, pond systems	Downstream water quality degradation

- **Feed and Feces:** The primary pollution source in open and semi-closed systems, contributing to nutrient loading. In Mediterranean cage systems, nitrogen and phosphorus discharge can exceed 50 kg/ton of fish produced (Sarà et al., 2018; Telfer et al., 2009).
- **Chemicals and Antibiotics:** Used to control diseases, these can persist in the environment, promoting antimicrobial

resistance. Their use is tightly regulated in the Mediterranean under EU directives (FAO, 2022).

- **Disinfectants/Sanitizers:** Common in hatcheries and RAS, these chemicals can harm aquatic ecosystems if released untreated (Badiola et al., 2012).
- **Effluent Discharge:** Flow-through and pond systems release nutrient-rich effluents, increasing the grey water footprint. For example, trout raceways in Italy discharge effluents requiring 10,000–15,000 liters of dilution water per kilogram of fish (Verdegem et al., 2006).

7.4. POLLUTION MITIGATION STRATEGIES

Mitigating pollution in aquaculture requires a combination of technological, managerial, and regulatory approaches:

7.4.1 Improved Feed Efficiency

Adopting feeds with high nutrient retention and low FCR reduces waste. For example, precision-formulated feeds for seabass in Greece have reduced nitrogen output by 20–30% (Chopin et al., 2001). Automated feeding systems, using sensors to detect fish behavior, minimize uneaten feed in cage and RAS systems (Ebeling & Timmons, 2010).

7.4.2 System Design and Engineering

RAS and biofiltration use mechanical and biological filters to remove solids and convert ammonia to nitrate, reducing effluent discharge by 90–99% (Badiola et al., 2012). Settling ponds and wetlands, in semi-intensive systems, are nature-based solutions that trap nutrients and solids before discharge, lowering the grey water footprint (Crab et al., 2007). Biofloc technology (BFT) promotes microbial flocs to recycle nitrogenous waste, reducing nutrient

discharge in shrimp and tilapia systems (Avnimelech, 2009). IMTA systems in the Mediterranean, such as those combining seabass with mussels and macroalgae, absorb up to 50% of dissolved nutrients, reducing eutrophication risks (Chopin et al., 2001); pilot projects in Greece and Spain demonstrate IMTA's potential to lower the grey water footprint by improving water quality (FAO GFCM, 2022).

7.4.3 Regulatory and Monitoring Tools

EU regulations and GFCM guidelines set effluent standards limiting nutrient discharge, requiring farms to monitor effluents (EUMOFA, 2023). Environmental Impact Assessments (EIAs) are mandatory for new aquaculture projects in the Mediterranean, evaluating nutrient impacts and proposing mitigation measures (Telfer et al., 2009). Region-specific Best Management Practices (BMPs), such as site rotation for cages and feed quotas, reduce pollution (FAO, 2022). Sustainability certifications like the Aquaculture Stewardship Council (ASC) incentivize low-pollution practices, influencing market preferences (FAO GFCM, 2022). However, it is important to note that the high cost and administrative complexity of obtaining such certifications can create a significant barrier. This often limits access to large-scale producers, while smaller-scale producers, who may have lower overall environmental impacts, can be excluded from the market advantages that certification provides.

7.4.4 Emerging Technologies

Nanofiltration and membrane bioreactors are advanced systems that recover nutrients from effluents, enabling water reuse and reducing the grey water footprint, though high costs limit adoption (Badiola et al., 2012). AI-driven management, using models integrated with real-time sensor data, is increasingly used to optimize feeding and predict water quality fluctuations in RAS and

cage systems; these systems can reduce nutrient waste by up to 15% in pilot studies by enabling precise, proactive interventions (Ebeling & Timmons, 2010; Zhou et al., 2019; Aung et al., 2025).

7.5. FUTURE DIRECTIONS

Effective nutrient management in Mediterranean aquaculture requires integrating technological innovation with robust policy frameworks. Expanding IMTA and BFT, coupled with investments in RAS and precision technologies, can significantly reduce pollution and the grey water footprint. Policy incentives, such as subsidies for low-impact systems and mandatory water footprint reporting, are critical for scaling sustainable practices (FAO, 2022). Additionally, stakeholder collaboration, including farmers, regulators, and researchers, is essential to develop context-specific solutions that balance productivity with environmental health (Belton et al., 2018).

8. TECHNOLOGICAL ADVANCES FOR WATER REUSE

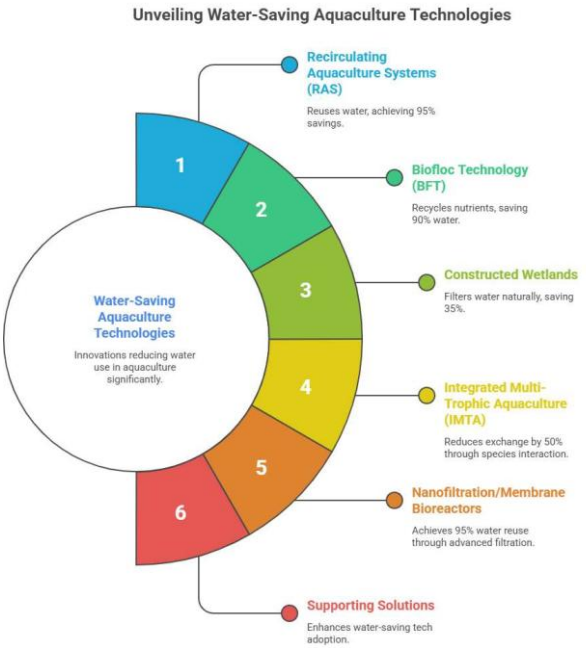


Figure 11. Unveiling water-saving aquaculture technologies (visual created via Napkin AI using original text provided by the authors).

The increasing scarcity of freshwater resources, particularly in regions like the Mediterranean, necessitates innovative technologies to reduce the water footprint of aquaculture. Technological advances in water reuse and treatment have revolutionized the sector, enabling systems to retain, treat, and recycle water, thereby minimizing consumption and environmental discharge. These innovations are critical for sustainable aquaculture, balancing productivity with ecological and economic constraints. This section explores key technologies for water reuse, their applications, benefits, challenges, and proposed solutions to enhance

their adoption, with a focus on reducing both the blue and grey water footprints.

8.1. INNOVATIONS TO REDUCE WATER CONSUMPTION

Several advanced technologies and management practices have emerged to enhance water efficiency in aquaculture, particularly in water-scarce regions. These innovations focus on recycling water, treating effluents, and optimizing nutrient management to reduce the need for freshwater inputs.

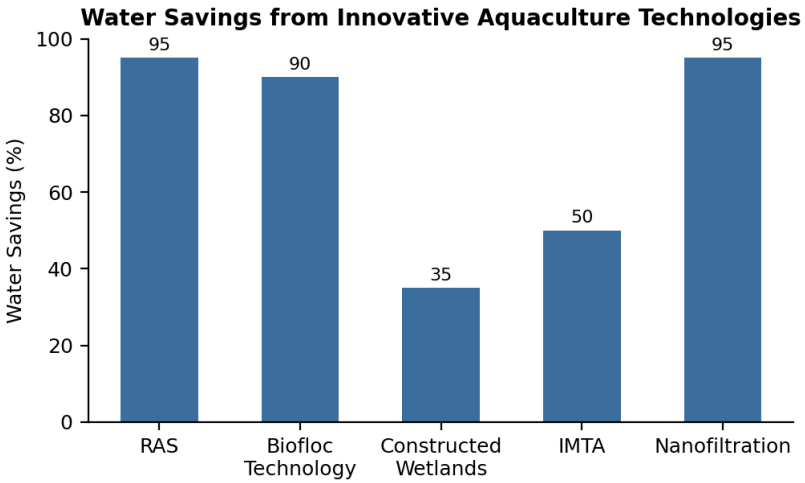


Figure 12. Water savings from innovative aquaculture technologies. Source: Badiola et al., 2012; Ebeling & Timmons, 2010; FAO GFCM, 2022; Verdegem et al., 2006.

Figure 12 compares the percentage of water savings achieved by innovative aquaculture technologies, including RAS (95% savings), biofloc technology (BFT) (90%), constructed wetlands (35%), IMTA (50%), and nanofiltration (95%), relative to traditional systems like flow-through raceways or ponds. The chart illustrates the transformative potential of these technologies in reducing blue

and grey water footprints, particularly in water-scarce regions like the Mediterranean.

8.1.1 Recirculating Aquaculture Systems (RAS)

RAS are closed-loop systems that recycle water through a series of filtration and treatment processes, including mechanical filtration (to remove solids), biological filtration (to convert ammonia to nitrate), oxygenation, degassing, and disinfection (e.g., UV or ozone treatment) (Badiola et al., 2018; Ebeling & Timmons, 2010). They are widely used for high-value species like salmon (Salmo salar), sturgeon (Acipenser spp.), and tilapia (Oreochromis spp.). RAS achieve water savings of 90–99% compared to flow-through systems, with water use as low as 450–1,200 liters per kilogram of biomass produced (Verdegem et al., 2006); losses occur primarily through evaporation and sludge removal. In the Mediterranean, RAS are gaining traction in inland and urban settings in countries like Israel, Italy, and France for species such as seabass (Dicentrarchus labrax) and tilapia (FAO GFCM, 2022). Benefits include minimal water discharge, enhanced biosecurity, and precise control over water quality parameters, making RAS ideal for water-scarce regions and sensitive species (Badiola et al., 2012, 2018). Challenges include high capital costs, energy demands for pumping and aeration, and the need for skilled management to prevent disease outbreaks in high-density environments (Ebeling & Timmons, 2010).

8.1.2 Biofloc Technology (BFT)

BFT promotes the growth of microbial flocs (bacteria, algae, protozoa) that absorb nitrogenous waste, converting it into microbial protein that can be consumed by cultured species like shrimp (Litopenaeus vannamei) and tilapia (Avnimelech, 2009). BFT operates in semi-closed systems with minimal water exchange,

reducing water use by up to 90% compared to traditional pond systems, as it relies on microbial processes rather than dilution to manage waste (Crab et al., 2007). Widely used in shrimp farming in Asia and Latin America, BFT is emerging in Mediterranean countries like Spain and Israel for tilapia and shrimp production (FAO, 2022). Benefits include reduced feed costs, minimal waste discharge, and improved water quality, lowering both blue and grey water footprints (Avnimelech, 2009). Challenges include careful management of carbon-to-nitrogen ratios and aeration, and limited suitability for all species or large-scale operations (Crab et al., 2007).

8.1.3 Constructed Wetlands and Settling Ponds

These nature-based solutions treat aquaculture effluents through sedimentation, plant uptake, and microbial activity. Constructed wetlands use aquatic plants (e.g., reeds) to absorb nutrients, while settling ponds allow solids to settle before water is discharged or reused (Boyd & Tucker, 2012). They enable partial water reuse in semi-intensive systems, reducing water consumption by 20–50% compared to traditional ponds (Crab et al., 2007), and are common in small-scale and semi-intensive pond systems in the Mediterranean, particularly for carp and tilapia farming in inland areas of Spain and Italy (FAO GFCM, 2022). Benefits include cost-effectiveness, low energy requirements, and dual-purpose use (e.g., supporting biodiversity or irrigation), reducing the grey water footprint (Boyd & Tucker, 2012). Challenges include land availability requirements, and treatment efficiency depends on climate and plant species, limiting scalability in urban or coastal areas (Crab et al., 2007).

8.1.4 Integrated Multi-Trophic Aquaculture (IMTA)

IMTA co-cultures species from different trophic levels, such as fish (e.g., seabass), shellfish (e.g., mussels, Mytilus

galloprovincialis), and macroalgae (e.g., Ulva spp.), to recycle nutrients. Extractive species absorb fish waste, improving water quality and reducing the need for water exchange (Chopin et al., 2001). While not a direct reuse technology, IMTA reduces water exchange requirements by maintaining water quality, indirectly lowering the blue and grey water footprints (FAO, 2024). Pilot IMTA projects in Greece, Spain, and Israel combine seabass with mussels and algae, showing promise for marine cage systems (FAO GFCM, 2022). Benefits include reduced nutrient pollution, enhanced ecosystem resilience, and diversified production, mitigating the grey water footprint (Chopin et al., 2001). Challenges include complex system design, species compatibility, and market acceptance of co-cultured products (FAO, 2022); this low market acceptance often stems from a lack of consumer awareness, underdeveloped supply chains for species like seaweed, and the perception that these "extractive" species (e.g., seaweeds, sea cucumbers) are lower-value or non-traditional food items.

8.1.5 Nanofiltration and Membrane Bioreactors

These advanced technologies use semi-permeable membranes to remove contaminants and recover nutrients from aquaculture effluents, enabling water reuse in high-intensity systems (Badiola et al., 2012). They can achieve near-zero discharge, with up to 95% water reuse in hatcheries and RAS, significantly reducing the blue water footprint (Ebeling & Timmons, 2010). Applications are emerging in Mediterranean hatcheries for seabass and seabream, where strict effluent regulations apply, and in experimental RAS setups (FAO GFCM, 2022). Benefits include high treatment efficiency, recovery of valuable nutrients (e.g., for fertilizers), and compliance with stringent environmental standards (Badiola et al., 2012). Challenges include high capital and maintenance costs,

technical complexity, and energy requirements that limit adoption to large-scale or high-value operations (Ebeling & Timmons, 2010).

8.1.6 Precision Monitoring and IoT Integration

Internet of Things (IoT) sensors and artificial intelligence (AI) systems monitor water quality parameters (e.g., dissolved oxygen, pH, ammonia) in real-time, optimizing water use and feed delivery (Ebeling & Timmons, 2010). This reduces water waste by detecting leaks, optimizing exchange rates, and minimizing nutrient loading, potentially lowering water use by 10–20% in RAS and semi-closed systems (Badiola et al., 2012). These tools are used in Mediterranean RAS facilities in Israel and Italy, and increasingly in cage systems in Greece for automated feeding (FAO, 2022). Benefits include enhanced water efficiency, reduced labor costs, and improved fish health by maintaining optimal conditions (Ebeling & Timmons, 2010). Challenges include the need for investment in infrastructure and technical training, which may be inaccessible to small-scale farmers (FAO GFCM, 2022).

8.2. PROPOSED SOLUTIONS FOR REDUCING WATER CONSUMPTION IN AQUACULTURE

To promote widespread adoption of water-efficient technologies at various scales, the following solutions are proposed:

8.2.1 System Redesign and Retrofitting

- **Transition to Partial Recirculation:** Retrofitting flow-through raceways and ponds with biofilters and recirculation units can reduce water use by 50–80% while maintaining productivity (Badiola et al., 2012).
- **Hatchery Upgrades:** Equipping hatcheries with UV treatment, drum filters, and flow restrictors minimizes water

consumption during early life stages of species like seabass and seabream (Ebeling & Timmons, 2010).

8.2.2 Policy and Incentive Frameworks

- **Subsidies and Grants:** Governments can provide financial support for farms adopting RAS, BFT, or IMTA, particularly for small-scale operators in the Mediterranean (FAO, 2022).
- **Water-Use Audits:** Mandating water footprint assessments as part of aquaculture licensing ensures accountability and encourages efficient practices (EUMOFA, 2023).
- **Ecosystem-Based Management:** Integrating aquaculture with climate-resilient agriculture (e.g., aquaponics) aligns with Integrated Water Resource Management (IWRM) principles (Beveridge & Little, 2002).

8.2.3 Training and Capacity Building

- **Education Programs:** Training operators in best management practices (BMPs) for water reuse technologies, such as RAS operation and BFT management, enhances adoption (Avnimelech, 2009).
- **Technical Guides:** Disseminating manuals on low-discharge systems, like those developed by the FAO, supports farmers in implementing water-efficient practices (FAO GFCM, 2022).

8.2.4 Research and Development

- **Cost Reduction:** Research into low-cost filtration systems and energy-efficient designs can make RAS and nanofiltration more accessible (Badiola et al., 2012).

- **Scalable IMTA Models:** Developing standardized IMTA designs for Mediterranean conditions can accelerate adoption and market acceptance (Chopin et al., 2001).

8.2.5 Community and Stakeholder Engagement

- **Participatory Governance:** Involving local communities and small-scale farmers in planning aquaculture projects ensures social acceptance, addresses concerns about water use, and incorporates valuable local knowledge (Belton et al., 2018).
- **Sustainability Certifications:** Promoting certifications like the Aquaculture Stewardship Council (ASC) encourages water-efficient practices and enhances market competitiveness (FAO, 2022).

8.3. FUTURE OUTLOOK

As water scarcity intensifies under climate change scenarios, water-smart aquaculture technologies will be critical for the sector's sustainability. In the Mediterranean, scaling up RAS, BFT, and IMTA, supported by policy incentives and technological innovation, can significantly reduce water footprints while maintaining productivity. Advances in AI-driven monitoring and energy-efficient systems will further enhance the feasibility of closed-loop and integrated systems (Ebeling & Timmons, 2010). Collaborative efforts among researchers, policymakers, and farmers are essential to develop cost-effective, context-specific solutions that address regional challenges, ensuring aquaculture contributes to food security without compromising environmental health (FAO GFCM, 2022).

9. SOCIOECONOMIC DIMENSIONS OF WATER USE IN AQUACULTURE

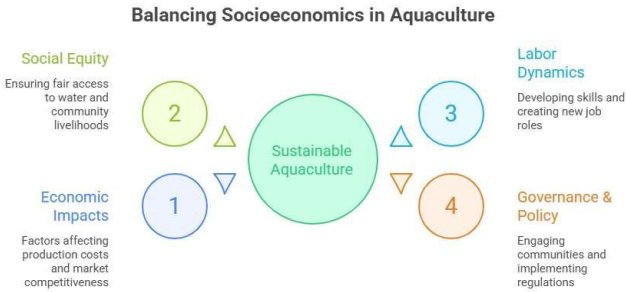


Figure 13. Balancing socioeconomics in aquaculture (visual created via Napkin AI using original text provided by the authors).

The socioeconomic dimensions of water use in aquaculture are critical to understanding the sector's sustainability, particularly in water-scarce regions like the Mediterranean. Water management decisions in aquaculture influence economic viability, social equity, community livelihoods, and environmental justice. These decisions are shaped by access to resources, market dynamics, labor conditions, and governance frameworks, which can either exacerbate or alleviate pressures on water resources (Belton et al., 2018; Klinger & Naylor, 2012). This section explores the economic impacts, social implications, labor dynamics, community engagement, and policy frameworks related to water use in aquaculture, emphasizing strategies to balance productivity with socioeconomic and environmental goals.

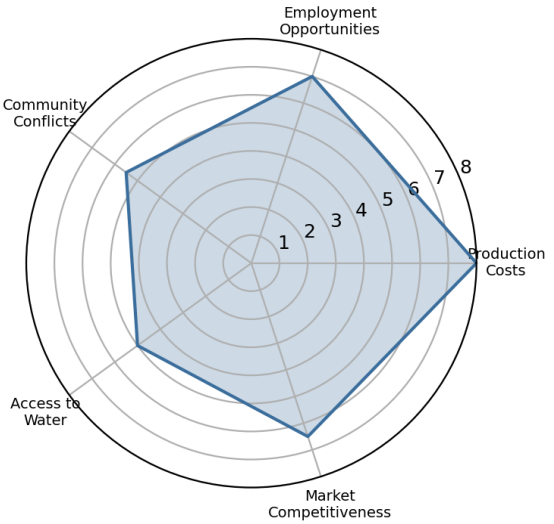


Figure 14. Socioeconomic impacts of water use in Mediterranean aquaculture. Source: Badiola et al., 2012; Belton et al., 2018; EUMOFA, 2023; Pahlow et al., 2015.

Figure 14 evaluates the socioeconomic dimensions of water use in Mediterranean aquaculture, scoring factors such as production costs (high due to water-intensive systems), employment opportunities (significant in shellfish farming), community conflicts (moderate due to water competition), access to water (challenging in semi-arid climates), and market competitiveness (enhanced by sustainable practices). The chart provides a holistic view of trade-offs and opportunities, reinforcing the need for integrated policies and community engagement to balance economic, social, and environmental goals.

9.1. ECONOMIC IMPACTS OF WATER USE IN AQUACULTURE

Water use in aquaculture has direct and indirect economic implications, affecting production costs, market competitiveness, and regional development:

- **Production Costs:** Water-intensive systems like flow-through raceways and ponds incur higher costs for water sourcing, treatment, and disposal, particularly in regions with limited freshwater availability. For example, trout farming in Mediterranean raceways requires 10,000–15,000 liters of water per kilogram of fish, increasing operational costs in water-scarce areas like southern Spain (Verdegem et al., 2006). In contrast, water-efficient systems like RAS reduce water costs but require significant capital investment, often prohibitive for small-scale farmers (Badiola et al., 2012).

- **Market Competitiveness:** Efficient water use enhances competitiveness by lowering production costs and meeting consumer demand for sustainable products. Mediterranean countries like Greece and Turkey, which dominate seabass and seabream production, benefit from low direct water use in marine cage systems but face indirect costs from feed production, estimated at 1,000–2,000 liters per kilogram of fish (Pahlow et al., 2015). Certifications like the Aquaculture Stewardship Council (ASC) incentivize water-efficient practices, enhancing market access to EU consumers (Barange et al., 2018; FAO, 2022, 2024).

- **Regional Economic Development:** Aquaculture supports livelihoods and economic growth in coastal and rural Mediterranean communities. For instance, shellfish farming in Spain and Italy generates employment for over 10,000 workers, with minimal direct water use, contributing to local economies (Barange et al., 2018; EUMOFA, 2023). However, competition for water with agriculture and tourism can limit aquaculture expansion, necessitating integrated resource management (Beveridge & Little, 2002).

- **Economic Risks:** Water scarcity, exacerbated by climate change, poses risks to economic stability. Reduced precipitation and increased evaporation in the Mediterranean increase water costs, particularly for inland systems, threatening profitability (FAO GFCM, 2022).

9.2. SOCIAL IMPLICATIONS AND EQUITY

Water use in aquaculture has profound social implications, influencing access to resources, community well-being, and social equity:

- **Access to Water Resources:** In water-scarce regions, aquaculture competes with other sectors for freshwater, often leading to conflicts. For example, inland trout farming in Italy's Po River Basin faces restrictions due to agricultural water demands, disproportionately affecting small-scale farmers with limited access to groundwater (Mekonnen & Hoekstra, 2012). Equitable water allocation policies are essential to prevent marginalization.

- **Community Livelihoods:** Aquaculture provides income and food security for coastal and rural communities. In Greece, marine cage farming employs thousands, supporting local economies, but large-scale operations can displace small-scale fishers, creating social tensions (Belton et al., 2018). Shellfish farming, with its low water footprint, offers inclusive opportunities for women and youth, as seen in Spain's mussel sector (Barange et al., 2018; FAO, 2022).

- **Health and Well-Being:** Poor water management, such as nutrient pollution from cage systems, can degrade water quality, affecting community health and tourism-dependent livelihoods in Mediterranean coastal areas (Telfer et al., 2009). Conversely, sustainable practices like IMTA enhance

water quality, benefiting local ecosystems and communities (Chopin et al., 2001).

- **Gender and Social Inclusion:** Women play significant roles in aquaculture, particularly in shellfish processing in countries like Spain and Italy, and in small-scale farming in areas of Greece and North Africa. However, they often face barriers to accessing capital-intensive, water-efficient technologies like RAS due to financial and educational constraints (Barange et al., 2018; FAO, 2022).

9.3. LABOR DYNAMICS AND SKILLS DEVELOPMENT

Water use efficiency in aquaculture depends on skilled labor and workforce capacity:

- **Labor Requirements:** Water-efficient systems like RAS and biofloc technology (BFT) require specialized skills for system operation, water quality monitoring, and disease management. In the Mediterranean, RAS facilities in Israel and Italy employ technicians trained in automation and filtration, but the high skill barrier limits adoption among traditional farmers (Badiola et al., 2012).

- **Training and Education:** Capacity-building programs are critical for transitioning to water-smart technologies. For example, FAO and GFCM workshops in Spain and Greece train farmers in BFT and IMTA, enhancing water efficiency and productivity (FAO GFCM, 2022). Universities and vocational schools can integrate water footprint concepts into aquaculture curricula to prepare future professionals.

- **Employment Opportunities:** Water-efficient technologies create new job roles, such as IoT specialists for real-time monitoring and engineers for system maintenance. In Turkey,

the adoption of precision feeding systems in cage farming has increased demand for skilled workers, supporting economic diversification (EUMOFA, 2023).

- **Challenges:** Low wages and seasonal employment in aquaculture, particularly in shellfish and small-scale farming, can deter skilled labor, necessitating policies to improve working conditions and job security (Belton et al., 2018).

9.4. COMMUNITY ENGAGEMENT AND GOVERNANCE

Community engagement and effective governance are essential for sustainable water use in aquaculture:

- **Participatory Planning:** Involving local communities in aquaculture project planning reduces conflicts and ensures social acceptance. In Greece, stakeholder consultations for offshore cage farming have mitigated tensions with tourism operators, aligning water use with community priorities (FAO, 2024). Furthermore, when integrated thoughtfully, aquaculture sites can themselves become tourist attractions through organized visits, tastings, and educational activities, turning potential conflict into a synergistic relationship that benefits both sectors.

- **Traditional Knowledge:** Incorporating indigenous and local knowledge enhances water management. For example, traditional pond management practices in North Africa optimize water retention, reducing evaporation losses in semi-arid climates (Beveridge & Little, 2002).

- **Conflict Resolution:** Water allocation disputes between aquaculture and other sectors require transparent governance. Integrated Water Resource Management

(IWRM) frameworks, as promoted by the FAO, facilitate equitable water sharing in the Mediterranean (FAO GFCM, 2022).

- **Public Awareness:** Educating communities about the water footprint of aquaculture fosters support for sustainable practices. Campaigns in Spain highlight the low water use of mussel farming, enhancing consumer preference for eco-friendly products (EUMOFA, 2023).

9.5. POLICY FRAMEWORKS AND ECONOMIC INCENTIVES

Policy frameworks play a pivotal role in shaping water use practices in aquaculture:

- **Regulatory Measures:** The General Fisheries Commission for the Mediterranean (GFCM) enforces effluent standards and environmental impact assessments (EIAs) to minimize water pollution from aquaculture, particularly in cage systems (FAO GFCM, 2022). EU water directives, such as the Water Framework Directive, set guidelines for sustainable water use, influencing Mediterranean aquaculture practices (Telfer et al., 2009).
- **Economic Incentives:** Subsidies for water-efficient technologies, such as RAS and BFT, encourage adoption. For example, Spain offers grants for farmers transitioning to low-discharge systems, reducing the blue water footprint (FAO, 2022). Tax breaks for ASC-certified farms further promote sustainability.
- **Water Pricing and Quotas:** Implementing water pricing for aquaculture, as piloted in Italy, incentivizes efficient use,

though it must be balanced to avoid burdening small-scale farmers (Mekonnen & Hoekstra, 2012).

- **International Cooperation:** Regional agreements, such as those under the GFCM, promote knowledge sharing and technology transfer, supporting water-smart aquaculture across Mediterranean countries (FAO GFCM, 2022).

9.6. FUTURE DIRECTIONS

Addressing the socioeconomic dimensions of water use in aquaculture requires integrated strategies that align economic, social, and environmental goals. Scaling up training programs and microfinance can empower small-scale farmers and women to adopt water-efficient technologies. Strengthening participatory governance and IWRM frameworks will ensure equitable water access and conflict resolution. Policy incentives, such as subsidies and certifications, can drive investment in sustainable practices, while public-private partnerships can fund research into cost-effective water reuse systems (Belton et al., 2018). In the Mediterranean, fostering community resilience and economic diversification through aquaculture will be critical for adapting to water scarcity and climate change, ensuring the sector's long-term contribution to food security and livelihoods (FAO, 2022, 2024).

10. FURTHER READING

Ahmed, N., & Turchini, G. M. (2021). Recirculating aquaculture systems (RAS): Environmental solution and climate change adaptation. *Journal of Cleaner Production,* 297, 126604.

Aung, T., Abdul Razak, R., & Rahiman Bin Md Nor, A. (2025). Artificial intelligence methods used in various aquaculture applications: A systematic literature review. *Journal of the World Aquaculture Society,* 56(1), e13107.

Avnimelech, Y. (2009). *Biofloc technology: a practical guide book.* The World Aquaculture Society.

Ayer, N. W., & Tyedmers, P. H. (2009). Assessing alternative aquaculture technologies: life cycle assessment of salmonid culture systems in Canada. *Journal of Cleaner Production,* 17(3), 362–373.

Badiola, M., Basurko, O. C., Piedrahita, R., Hundley, P., & Mendiola, D. (2018). Energy use in recirculating aquaculture systems (RAS): a review. *Aquacultural Engineering,* 81, 57–70.

Badiola, M., Mendiola, D., & Bostock, J. (2012). Recirculating Aquaculture Systems (RAS) analysis: Main issues on management and future challenges. *Aquacultural Engineering,* 51, 26–35.

Barange, M., Bahri, T., Beveridge, M. C., Cochrane, K. L., Funge-Smith, S., & Poulain, F. (2018). Impacts of climate change on fisheries and aquaculture. *United Nations' Food and Agriculture Organization,* 12(4), 628–635.

Belton, B., Bush, S. R., & Little, D. C. (2018). Not just for the wealthy: Rethinking farmed fish consumption in the Global South. *Global Food Security,* 16, 85–92.

Beveridge, M. C. M., & Little, D. C. (2002). The history of aquaculture in traditional societies. *Ecological Aquaculture: The Evolution of the Blue Revolution,* 3–29.

Bosma, R. H., & Verdegem, M. C. J. (2011). Sustainable aquaculture in ponds: Principles, practices and limits. *Livestock Science,* 139(1–2), 58–68.

Bostock, J., McAndrew, B., Richards, R., Jauncey, K., Telfer, T., Lorenzen, K., Little, D., Ross, L., Handisyde, N., & Gatward, I. (2010). Aquaculture: global status and trends. *Philosophical Transactions of the Royal Society B: Biological Sciences,* 365(1554), 2897–2912.

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

Chopin, T., Buschmann, A. H., Halling, C., Troell, M., Kautsky, N., Neori, A., Kraemer, G. P., Zertuche-González, J. A., Yarish, C., & Neefus, C. (2001). Integrating seaweeds into marine aquaculture systems: a key toward sustainability. *Journal of Phycology,* 37(6), 975–986.

Crab, R., Avnimelech, Y., Defoirdt, T., Bossier, P., & Verstraete, W. (2007). Nitrogen removal techniques in aquaculture for a sustainable production. *Aquaculture,* 270(1–4), 1–14.

Ebeling, J. M., & Timmons, M. B. (2010). *Recirculating aquaculture.* Cayuga Aqua Ventures.

Edwards, P. (2015). Aquaculture environment interactions: past, present and likely future trends. *Aquaculture,* 447, 2–14.

EUMOFA. (2023). *The EU Fish Market.* European Market Observatory for Fisheries and Aquaculture Products.

FAO GFCM. (2022). *The State of Mediterranean and Black Sea Fisheries.* General Fisheries Commission for the Mediterranean. Rome.

FAO. (2022). *The State of World Fisheries and Aquaculture: Towards Blue Transformation.* Rome.

FAO. (2024). *The State of World Fisheries and Aquaculture – Blue Transformation in Action.* Rome.

Gentry, R. R., Froehlich, H. E., Grimm, D., Kareiva, P., Parke, M., Rust, M., Gaines, S. D., & Halpern, B. S. (2017). Mapping the global potential for marine aquaculture. *Nature Ecology & Evolution,* 1(9), 1317–1324.

Gephart, J. A., Henriksson, P. J. G., Parker, R. W. R., Shepon, A., Gorospe, K. D., Bergman, K., Eshel, G., Golden, C. D., Halpern, B. S., & Hornborg, S. (2021). Environmental performance of blue foods. *Nature,* 597(7876), 360–365.

Hoekstra, A., Chapagain, A., Aldaya, M., & Mekonnen, M. (2011). *The Water Footprint Assessment Manual: Setting the Global Standard.* Earthscan.

Klinger, D., & Naylor, R. (2012). Searching for solutions in aquaculture: charting a sustainable course. *Annual Review of Environment and Resources,* 37(1), 247–276.

Little, D. C., Newton, R. W., & Beveridge, M. C. M. (2016). Aquaculture: a rapidly growing and significant source of sustainable food? Status, transitions and potential. *Proceedings of the Nutrition Society,* 75(3), 274–286.

Mekonnen, M. M., & Hoekstra, A. Y. (2012). A global assessment of the water footprint of farm animal products. *Ecosystems,* 15(3), 401–415.

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

Pahlow, M., Van Oel, P. R., Mekonnen, M. M., & Hoekstra, A. Y. (2015). Increasing pressure on freshwater resources due to terrestrial feed ingredients for aquaculture production. *Science of the Total Environment,* 536, 847–857.

Rosa, R., Marques, A., & Nunes, M. L. (2012). Impact of climate change in Mediterranean aquaculture. *Reviews in Aquaculture,* 4(3), 163–177.

Sarà, G., Mangano, M. C., Johnson, M., & Mazzola, A. (2018). Integrating multiple stressors in aquaculture to build the blue growth in a changing sea. *Hydrobiologia,* 809, 5–17.

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

Symeonidou, S., & Mente, E. (2024). Water Consumption and the Water Footprint in Aquaculture: A Review. *Water,* 16(23), 3376.

Telfer, T. C., Atkin, H., & Corner, R. A. (2009). Review of environmental impact assessment and monitoring in aquaculture in Europe and North America. *FAO Fisheries and Aquaculture Technical Paper,* 527, 285–394.

Troell, M., Jonell, M., & Henriksson, P. J. G. (2017). Ocean space for seafood. *Nature Ecology & Evolution,* 1(9), 1224–1225.

UN. (2019). *World Population Prospects: Highlights.* United Nations, Department of Economic and Social Affairs, Population Division (ST/ESA/SER.A/423).

Verdegem, M. C. J., Bosma, R. H., & Verreth, J. A. J. (2006). Reducing water use for animal production through aquaculture. *Water Resources Development,* 22(1), 101–113.

Zhou, C., Xu, D., Chen, L., Zhang, S., Sun, C., Yang, X., & Wang, Y. (2019). Evaluation of fish feeding intensity in aquaculture using a convolutional neural network and machine vision. *Aquaculture,* 507, 457–465.

MODULE 4. WATER FOOTPRINT IN FISH PROCESSING FACILITIES



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WATER FOOTPRINT IN FISH PROCESSING FACILITIES

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1. WATER FOOTPRINT IN FISH PROCESSING FACILITIES

1.1.1. EXECUTIVE SUMMARY

This report explores the water footprint associated with fish processing facilities, focusing on the full water flow, from intake to treatment and discharge. It identifies key processing stages, critical water use hotspots, and hygiene-related water demands, while also discussing wastewater treatment methods and the application of digital monitoring tools. The objective is to guide in comprehension in reducing water usage and improving efficiency without compromising product quality or safety.

1.1.2. REGIONAL CONTEXT: MEDITERRANEAN FISH-PROCESSING INDUSTRY

Fish processing in the Mediterranean basin represents a cornerstone of the region's blue economy, integrating both capture fisheries and an expanding aquaculture sector (FAO, 2022). The industry is led by Türkiye, Italy, and Egypt, which together account for a large share of Mediterranean seafood production and processing. It spans from small-scale, traditional curing and salting operations to highly industrialized plants employing modern preservation and packaging technologies. Across the Mediterranean and Black Sea, combined fisheries and aquaculture production reach approximately 2 million tonnes per year, generating more than USD 20 billion in revenue and supporting over 700,000 jobs (FAO, 2022; OECD, 2021). Within this context, Italy's processing sector alone was valued at roughly €2.1 billion in 2022, underlining its strategic role in Europe's seafood value chain (European Commission – Eurostat, 2023).

The sector's product portfolio reflects both tradition and innovation. Prepared and preserved tuna, particularly prominent in Italy, remains one of the region's major processed fish products. Frozen whole fish and aquaculture-derived species—including molluscs and freshwater fish—constitute growing market segments, while canned and semi-canned goods such as tuna, anchovies, sardines, and mackerel are key staples of regional diets (FAO, 2020). In addition, value-added products like surimi and processed cephalopods are increasingly important in the export market. Mediterranean fish processors combine ancient artisanal methods with modern technologies such as high-pressure processing, irradiation, and pulsed electric fields, which improve hygiene, product quality, and shelf life (OECD, 2021).

Sustainability is a central concern for the Mediterranean fish-processing industry. The General Fisheries Commission for the Mediterranean (GFCM) plays a vital role in coordinating management plans and conservation efforts across the region (GFCM, 2023). These initiatives aim to mitigate overfishing, preserve marine ecosystems, and promote the responsible use of resources. However, aligning industrial growth with sustainability remains complex. Future competitiveness will depend increasingly on investments in efficient water management, wastewater treatment, and resource recovery technologies to minimize the sector's water footprint and environmental impact (FAO, 2022; Hurriyet Daily News, 2025).

From a market perspective, the Mediterranean region is not only a major production area but also a crucial consumption and trade hub for seafood. Countries like Italy rely heavily on imports to satisfy consumer demand, highlighting the interconnected nature of the regional seafood economy (FAO, 2020; Eurostat, 2023). In this context, initiatives such as the EU-backed WANTOFISH project provide promising pathways for measuring and reducing water use in fisheries and fish-processing facilities, addressing one of the most critical sustainability challenges in the region (Hurriyet Daily News, 2025). Overall, the Mediterranean fish-processing sector stands at the intersection of economic opportunity and environmental responsibility, offering a vital context for assessing and improving water footprint management in seafood transformation facilities.

1.1.3. REFERENCE FRAMEWORK: THE WATER FOOTPRINT ASSESSMENT MANUAL

A fundamental reference for measuring and managing water use in industrial operations is The Water Footprint Assessment Manual: Setting the Global Standard (Arjen et al., 2011). Developed under the Water Footprint Network, this manual provides a globally

recognized methodology for quantifying water use across products, processes, and supply chains. The framework distinguishes three main water components: blue water (surface and groundwater used), green water (rainwater stored in soil and used by plants), and grey water (the volume of freshwater required to assimilate pollutants). It also defines four stages of assessment: (1) setting goals and scope, (2) water footprint accounting, (3) sustainability assessment, and (4) response formulation. Available through the Water Footprint Network's website (www.waterfootprint.org), the manual offers open-access tools, data resources, and case studies demonstrating how to apply water footprint analysis across industrial sectors. For fish processing facilities, this framework allows managers to quantify both direct and indirect water use, from washing, chilling, and cooking operations to the embedded water in energy and packaging materials. Moreover, it emphasizes spatial and temporal dimensions, enabling users to assess how local water scarcity and quality affect operational sustainability. Integrating the Water Footprint Assessment methodology thus ensures that evaluations of water consumption within fish processing plants align with international standards and support transparent sustainability reporting.

The methodology presented in The Manual represents the cornerstone of modern water use analysis. Developed under the Water Footprint Network, it defines a systematic approach to measure the volume, source, and quality impacts of freshwater use across the entire life cycle of a product or process. The manual introduces the concept of the water footprint (WF) as the total volume of freshwater used to produce goods and services, distinguishing three critical components:

- Blue Water Footprint – water withdrawn from surface and groundwater resources and not returned to the same catchment (e.g., process water, cooling water).

- Green Water Footprint – rainwater stored in soil, mainly relevant to aquaculture and feed production for farmed fish.
- Grey Water Footprint – the volume of freshwater required to assimilate pollutants generated by a process to meet specific water quality standards.

The Water Footprint Network provides open-access resources, data templates, and case studies at https://www.waterfootprint.org.

1.1.4. APPLYING THE WATER FOOTPRINT FRAMEWORK TO FISH PROCESSING

While the manual primarily addresses agricultural and industrial processes, its methodology applies effectively to fish processing facilities, where multiple unit operations rely heavily on water. A comprehensive assessment follows the four core phases described by Hoekstra et al. (2011):

- **Setting Goals and Scope –** The assessment begins by defining boundaries and objectives. For a fish processing facility, this includes determining whether to measure the WF of the entire plant or specific product lines (e.g., frozen fillets, canned fish, ready-to-eat meals). Key boundaries include intake water (blue), embedded water in inputs like packaging and energy (indirect blue/grey), and wastewater discharge quality (grey).
- **Sustainability Assessment –** According to the manual, water footprint values must be evaluated within the local hydrological and ecological context. For a coastal fish-processing plant, this involves assessing whether the withdrawal of water from municipal or groundwater sources exceeds regional availability, or whether the discharge of nutrient-rich effluents (high biochemical oxygen demand) threatens aquatic ecosystems. The grey water footprint is particularly relevant here, as it quantifies the dilution volume needed to meet effluent discharge standards.

1.1.5. BENEFITS OF APPLYING THE MANUAL TO FISHERIES TRANSFORMATION PLANTS

Applying the Water Footprint Assessment to fish processing brings several advantages:

- **Standardization:** Ensures water-use reporting aligns with international benchmarks, improving comparability with other food industries.
- **Transparency:** Facilitates sustainability reporting for certifications such as ASC (Aquaculture Stewardship Council) or ISO 14046.
- **Operational Efficiency:** Identifies critical hotspots where water and energy savings overlap.
- **Regulatory Compliance:** Supports adherence to water quality and wastewater discharge regulations under national and EU directives.

Additionally, because many fish-processing facilities operate in coastal or semi-urban zones, where water availability and effluent discharge are constrained, applying the Water Footprint methodology helps assess not just consumption volumes but also water dependency risks and catchment impacts.

1.1.6. LITERATURE GAP: WATER FOOTPRINT IN FISHERIES TRANSFORMATION FACILITIES

Recent scientific literature has significantly advanced the understanding of water consumption and footprint assessment within aquaculture production systems; however, there remains a notable scarcity of research focusing on the transformation and processing stages of the fisheries value chain. For instance, Symeonidou and Mente (2024), in their comprehensive review Water Consumption and the Water Footprint in Aquaculture, reported that only about 15% of examined studies addressed post-harvest or processing phases. Their findings emphasize that current methodologies concentrate mainly on on-farm water uses, such as evaporation,

seepage, and feed production, while overlooking the substantial water volumes consumed during cleaning, chilling, cooking, and sanitation within processing facilities. Similarly, Pérez-Rincón et al. (2017), in Water Footprint Measure Method for Tilapia, Cachama and Trout Production: Study Cases in Valle del Cauca (Colombia), developed a structured framework for quantifying blue and grey water footprints in aquaculture operations but concluded their analysis at the point of harvest, excluding the transformation operations that follow, such as filleting, packaging, and thermal processing.

Complementary studies reinforce this observation. Guzmán-Luna, Gerbens-Leenes, and Vaca Jiménez (2021), in The Water, Energy, and Land Footprint of Tilapia Aquaculture in Mexico: A Comparison of the Footprints of Fish and Meat, presented detailed footprint metrics for aquaculture systems and compared them to livestock production. Despite incorporating transport and distribution stages, the research remained primarily focused on farm-gate processes, offering limited insights into industrial fish-processing water use. Berger (2021), in Advancing the Water Footprint into an Instrument to Support Sustainable Development, further highlighted the maturity of water-footprint theory yet acknowledged the lack of empirical application in industrial food-processing contexts, particularly in seafood transformation plants. Collectively, these works reveal a persistent research gap: while aquaculture water footprints are increasingly well-defined, the water footprint of fish-processing and transformation facilities remains poorly characterized and largely absent from current life-cycle or sustainability assessments.

Bridging this gap is vital for establishing a comprehensive water-footprint perspective encompassing the entire fisheries supply chain, from aquaculture and capture to transformation and distribution. A systematic assessment of water consumption in fish-

processing facilities will enable the identification of high-impact stages, promote efficient resource management, and support compliance with emerging sustainability and circular-economy standards in the seafood sector (Berger et al., 2021; Guzmán-Luna et al., 2021; Pérez Rincón et al., 2017; Symeonidou & Mente, 2024; Viglia et al., 2022).

Importantly, the existence of the WANTOFISH project offers a promising future data source, addressing this exact gap. The project aims to measure and evaluate water footprints across Mediterranean fisheries—including processing facilities in countries such as Spain, Italy, Croatia and Greece—and thus represents an opportunity to generate much-needed empirical data. Referencing WANTOFISH underscores the urgency and timeliness of conducting targeted assessments in the seafood transformation sector, and highlights a path forward for improved data collection and analysis.

2. OVERVIEW OF PROCESSING STEPS AND WATER NEEDS

Globally, only 45% of seafood production is consumed as fresh fish, while the remaining 55% undergoes processing and is consumed in alternative forms: 29% as frozen, 14% as canned, and 12% as cured products (Pedro & Nunes, 2007). Fish processing facilities are among the largest industrial consumers of water, as large volumes are required across multiple stages, including washing, cleaning, product conveyance, and freezing. According to the Food and Agriculture Organization (FAO), a medium-scale processing plant may utilize several thousand cubic meters of water per day. Water usage varies from 2 to 12 cubic meters per metric ton of seafood, depending on the type of processing involved. Primary areas of water application include seafood cleaning and washing, cooking, freezing and thawing, brine preparation, equipment and

floor sanitation, as well as storage and transport (Henriksson et al., 2018).

Data from the United Nations Environment Programme (UNEP) Cleaner Production Assessment in Fish Processing further specifies that freshwater usage per metric ton of fish varies by processing type: 5–11 m^3 for filleting, 15 m^3 for canning, and 0.5 m^3 for fish meal production (UNEP, 1999).

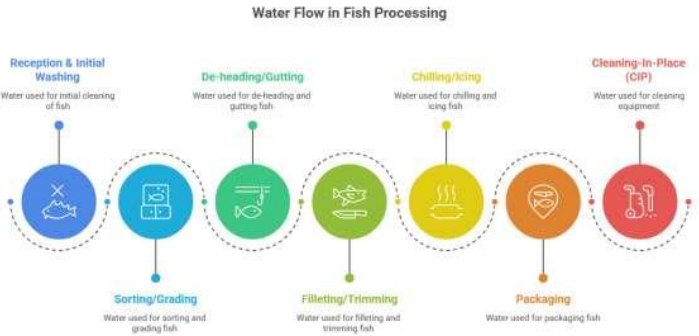


Figure 1. Flow chart showing the fish processing, cleaning procedure and ice production in the plant studied. Reprinted from (Ferraciolli et al., 2017)

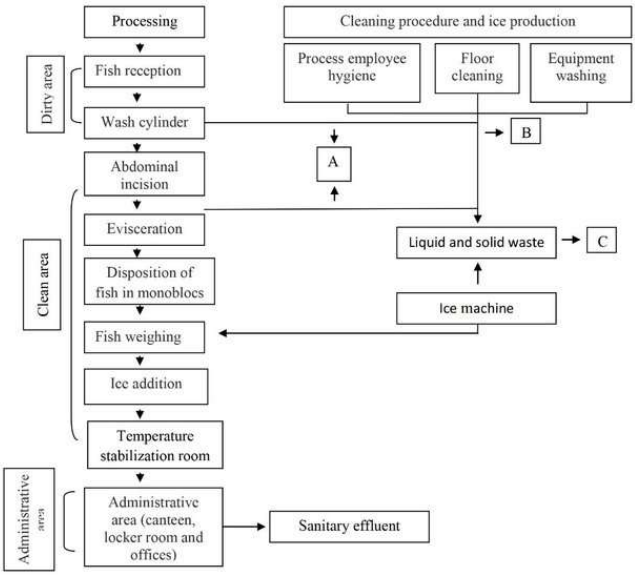


Figure 2. Water consumption pattern in a typical seafood industry. Source: (BIM, 2017)

2.1.2. RECEPTION AND INITIAL WASHING

Upon delivery to processing facilities, whether by sea vessels or land transport, raw fish undergo an initial washing procedure aimed at eliminating surface contaminants such as slime, scales, blood, and extraneous debris. In large-scale operations, this process is frequently automated, relying on a continuous flow of water to ensure effective cleaning.

2.1.3. SORTING AND GRADING

Subsequently, the fish are categorized based on parameters such as size, species, and quality. Although this step is not inherently water-intensive, the mechanical equipment employed often requires intermittent cleaning between processing batches to mitigate the risk of cross-contamination, thereby contributing to overall water use.

2.1.4. DE-HEADING AND GUTTING

This phase involves the removal of heads and internal organs. As these operations generate considerable quantities of organic waste, there is a need for continuous rinsing of tools, including knives and cutting boards, as well as conveyor systems. Water plays a dual role in this context: maintaining hygiene and facilitating the removal of waste via drainage systems.

2.1.5. FILLETING AND TRIMMING

During filleting and trimming, water is used both functionally and hygienically. Whether performed manually or by automated systems, these operations necessitate frequent rinsing of processing lines. Water jets are often employed to eliminate residual tissue, while cold-water sprays are implemented to suppress bacterial proliferation, particularly in warm environments.

2.1.6. CHILLING AND ICING

Maintaining low temperatures is vital for preserving the freshness and safety of fish products. Water is utilized in this stage either directly, as in the form of ice, or indirectly through chilled water systems. In certain instances, slurry ice, a mixture of ice crystals and water, is applied to achieve rapid chilling. This phase can be highly water-intensive, sometimes requiring several hundred liters per metric ton of product, especially under high ambient temperatures or during long-distance transportation.

2.1.7. PACKAGING

Although not as water dependent as earlier stages, the packaging process requires a sterile environment. Water, often in combination with chemical sanitizers, is used to disinfect surfaces, machinery, and protective gear such as gloves. Additionally, final

rinsing of products may be conducted prior to sealing, to ensure compliance with hygiene standards.

2.1.8. CLEANING-IN-PLACE (CIP) AND GENERAL SANITATION

The final and continuous phase within the processing facility is dedicated to cleaning and sanitation. CIP systems, which clean tanks and pipelines, employ recirculating water and chemical agents in a closed-loop configuration to enhance efficiency and reduce waste. Open surfaces within the facility are washed down multiple times daily, particularly between operational shifts, to maintain strict hygiene standards.

3. WATER FOOTPRINT HOTSPOTS IN PROCESSING

Within fish processing facilities, water footprint hotspots refer to specific operational areas where water usage is exceptionally high relative to other stages of production. The identification of these critical points is fundamental for the implementation of effective and targeted water conservation strategies.

Water consumption throughout the processing workflow can be categorized into four distinct stages: the initial stage, the primary process, the secondary process, and the final stage. Among the various operations, thawing, washing, peeling, and glazing have been identified as the most water-intensive activities within the seafood processing sector. Collectively, these processes account for approximately 79.15% of the total water usage. Furthermore, substantial volumes of wastewater are generated during the thawing of raw materials, routine washing procedures, and the cutting and butchering stages of fish processing (Murali et al., 2021).

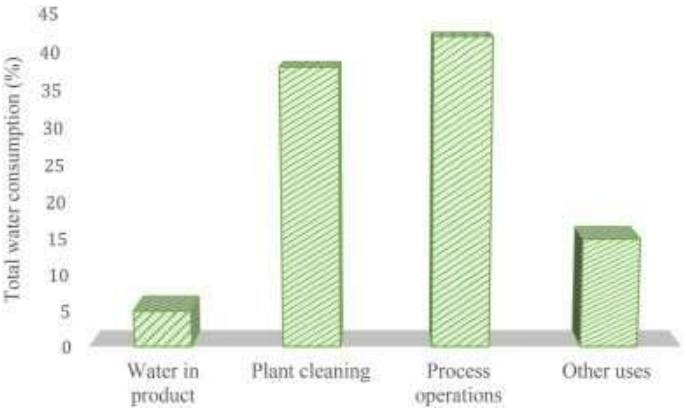


Figure 3. Various stages of water consumption in the seafood processing unit. Reprinted from (Murali et al., 2021)

3.1.1. CRITICAL AREAS IN WATER CONSUMPTION – WATER FOOTPRINT AUDITS IN SEAFOOD PROCESSING

A comprehensive water footprint audit typically begins with an evaluation of the facility's water balance. This process entails quantifying the inflow of water (i.e., incoming supply), identifying the specific usage points across processing stages, and monitoring the outflow in the form of wastewater. Advanced monitoring instruments such as sub-meters, flow sensors, and smart meters are instrumental in mapping real-time water consumption patterns throughout the facility.

3.1.2. CRITICAL AREAS IDENTIFIED

- **Washing and Cleaning Stations:** This category encompasses wash basins, fish washers, and areas designated for equipment rinsing. These stations often operate on continuous water flow systems that lack automatic shut-off mechanisms, leading to significant and unnecessary water wastage.
- **Chilling Systems:** In facilities employing flow-through chilling methods, water is utilized once for cooling and

subsequently discharged without recirculation. This single-use approach results in substantial water consumption, particularly in high-throughput operations.

- **Floor and Surface Sanitation:** Routine sanitation procedures involve the daily washing of floors, walls, and workstations, typically using hoses or high-pressure jets. These activities account for a substantial proportion of the facility's total sanitation-related water usage.
- **Handwashing Stations:** Hand hygiene is mandatory in seafood processing environments, and repeated use of handwashing stations, especially in facilities operating multiple shifts, contributes to a consistent baseline of water consumption throughout the day.

EXAMPLES OF WATER CONSUMPTION IN SHRIMP PROCESSING AND FISH FILLETING

Water consumption in the seafood processing industry is primarily influenced by two factors: the type of product being processed and the specific unit operations involved. These factors determine the intensity and volume of water required at each stage of production.

In shrimp processing, water usage is particularly high due to the steps taken to enhance peeling efficiency. Typically, raw shrimp are stored in ice for approximately two days before undergoing the peeling process. Following thawing, a continuous flow of water is used to wash away inert materials and surface contaminants. During this phase, substantial volumes of water are released through floor drains as wastewater.

Shrimp are processed into either PUD (peeled undeveined) or PD (peeled and deveined) forms, depending on market demands, and are then sorted by count. The water used during this stage, laden with organic waste and processing residues, is discharged through drainage systems. Subsequent to sorting, shrimp are visually

inspected according to established quality standards. Additional washing is carried out using mechanical washer units, followed by an impurity detection step, further contributing to water use and wastewater generation.

The processed shrimp are then frozen, either individually or in blocks, based on market requirements. The final products are packaged and stored at –18 °C in cold storage facilities prior to export (Murali et al., 2021; Thomas, 2016).

Fish filleting also involves significant water usage, particularly during the initial and intermediate cleaning stages. Whole fish are first cleaned in large wash tanks. Once the skin is removed, the fillets undergo a second round of washing. The wash water at this stage becomes heavily contaminated with organic matter and is subsequently directed to sedimentation systems for the separation of solid waste from water (Thomas, 2016).

After quality inspection, the cleaned fillets are packed and transferred to cold storage, maintained at –18 °C (Thomas, 2016). The wastewater produced during fish filleting contains high levels of soluble, colloidal, and particulate contaminants. This leads to elevated values of chemical oxygen demand (COD) and biological oxygen demand (BOD), both of which are indicative of high pollution loads (Tay et al., 2006).

Common pollutants in seafood processing wastewater include fats, oils, grease, suspended solids, and nutrients such as nitrogen and phosphates. The degree of contamination is closely linked to the specific processes employed. For instance, washing tends to produce lightly contaminated effluent, filleting yields moderately contaminated water, and fishmeal processing results in heavily polluted wastewater (Murali et al., 2021; Tay et al., 2006).



Figure 4. Flow diagram for shrimp processing (a, left) and for fish filleting (b, right). Adapted from (Thomas, 2016)

3.1.3. TOOLS FOR WATER USAGE DETECTION AND EFFICIENCY ASSESSMENT

To effectively manage water consumption in seafood processing facilities, a variety of tools and techniques can be employed to detect inefficiencies and identify opportunities for conservation:

- **Flow Meter Readings:** Real-time monitoring through flow meters provides granular data on water usage patterns, capturing hourly and daily fluctuations across different

processing stages. This data is essential for identifying peak consumption periods and pinpointing excessive usage.

- **Benchmarking:** Facility-level water usage can be compared against established industry benchmarks, such as liters of water used per ton of fish processed. This comparative analysis helps evaluate operational efficiency and guides strategic improvements.
- **Thermal Imaging and Leak Detection:** Advanced thermal imaging techniques can detect temperature anomalies, which are often indicative of leaks or unintentional water flow. These methods enable early intervention, thereby minimizing water loss and potential equipment damage.

3.1.4. RECOMMENDATIONS FOR IMPROVED WATER EFFICIENCY

To optimize water use and reduce wastage in seafood processing operations, the following measures are recommended:

- **Installation of Automatic Shut-Off Nozzles:** Replacing manual hoses with automatic shut-off nozzles in wash stations can significantly reduce unnecessary water flow during idle periods.
- **Implementation of Scheduled, Demand-Based Sanitation:** Transitioning from routine, time-based cleaning schedules to need-based sanitation can help align water use with actual hygiene requirements, thereby minimizing overuse.
- **Upgrade to Closed-Loop Chilling Systems:** Replacing flow-through chilling methods with closed-loop systems allows for water recirculation, drastically reducing the volume of water required for temperature control.

3.1.5. HYGIENE, FOOD SAFETY, AND WATER CONSUMPTION

Ensuring microbiological safety and overall quality of fishery products necessitates rigorous hygiene protocols, which

inherently require substantial water use. However, with careful planning and the application of modern technologies, water consumption can be significantly reduced without compromising compliance with food safety standards.

3.1.6. OBJECTIVES: LINKING SANITARY REQUIREMENTS TO WATER UTILIZATION

Sanitation procedures in fish processing facilities are typically governed by structured protocols, often based on the principles of Hazard Analysis and Critical Control Points (HACCP), as well as national and international food safety regulations. These protocols identify critical areas requiring water-based sanitation to prevent contamination and ensure consumer safety.

3.1.7. WATER-DEPENDENT HYGIENE PROTOCOLS INCLUDE:

- **Hand Hygiene:** Personnel are required to wash their hands thoroughly before entering processing areas, after any interruption (e.g., breaks), and following exposure to potential contaminants.
- **Tool and Equipment Sanitation:** Filleting knives, cutting boards, conveyors, and machinery must be cleaned and sanitized multiple times during each shift to prevent cross-contamination and bacterial proliferation.
- **Facility Cleaning:** Production floors, drainage systems, storage areas, and contact surfaces are subject to daily, and often repeated, cleaning regimens involving water and approved sanitizers.
- **Product Washing:** Certain fish products undergo rinsing prior to packaging to remove residual slime, blood, or surface contaminants, thereby improving both hygiene and appearance.

3.1.8. WATER USE OPTIMIZATION STRATEGIES

While hygiene cannot be compromised, several techniques can be employed to reduce water usage while maintaining or even enhancing sanitation effectiveness:

- **Installation of Low-Flow Faucets and High-Efficiency Sprayers:** These devices limit water flow without reducing cleaning power, thereby minimizing waste.
- **Implementation of Cleaning-In-Place (CIP) Systems:** CIP systems utilize closed-loop circulation of cleaning solutions and water, allowing for effective cleaning of internal surfaces (e.g., tanks, pipes) while significantly reducing total water demand.
- **Application of Foam-Based Detergents:** Foam cleaning agents require less water compared to traditional methods and offer visual confirmation of surface coverage, improving cleaning efficacy and ensuring compliance with sanitation standards.

EXAMPLE: ROBOTIZATION IN CLEANING SYSTEMS

The study conducted by Giske et al. (2019) provides compelling evidence that robotic systems can achieve effective sanitation in fish processing facilities while simultaneously reducing the risk of cross-contamination. The proposed robotic cleaning concept supports the automation of hygiene operations, resulting in decreased dependency on manual labor, improved process consistency, and enhanced overall profitability within the industry. One of the key advantages highlighted by the authors is the potential for significant resource savings. By calibrating the robotic system to dispense only the precise quantity of water and cleaning agents required for each task, the system avoids the inefficiencies commonly associated with conventional manual cleaning methods, where water and chemical usage often exceed actual needs. Such precision not only conserves resources but also contributes to the

sustainability and operational efficiency of seafood processing facilities (Giske et al., 2019).

3.1.9. WASTEWATER GENERATION AND TREATMENT

Wastewater in fish processing is rich in organic matter, fats, oils, and sometimes harmful cleaning chemicals. It must be treated before being discharged or reused.

3.1.10. SOURCES OF WASTEWATER

- **Washing Water:** Originates from initial fish cleaning; contains blood, mucus, scales, and fecal residues, contributing to high biological oxygen demand (BOD).
- **Gutting and Filleting Lines:** These lines release wastewater laden with proteinaceous material, suspended solids, and lipids, often resulting in high chemical oxygen demand (COD) and total suspended solids (TSS).
- **Chiller Discharge:** Water from chilling systems can be nutrient-rich and may contain residual amounts of chlorine or refrigerants depending on the method used.
- **Sanitation Wastewater:** Contains detergents, disinfectants, surfactants, and fine particulate matter, which can disrupt biological treatment systems if not pretreated.

Processing Step	Purpose
Initial washing	Debris and slime removal
Gutting and de-heading	Waste transport, hygiene
Filleting	Equipment and hand washing
Chilling	Product preservation
Packaging	Surface cleaning

Processing Step	Purpose
CIP systems	Sanitation of closed systems

Table 1. Estimated water use per processing step in fish processing plants (Aurora & Maria, 1995; Bykowski & Dutkiewicz, 1996)

3.1.11. WASTEWATER TREATMENT TECHNOLOGIES

The selection of wastewater treatment technologies depends on influent characteristics, discharge standards, operational costs, and facility layout. The following are commonly adopted methods in the fish processing industry:

3.1.12. PRELIMINARY TREATMENT

- **Screening and Sedimentation:** Removes coarse solids such as fish scales, bone fragments, and packaging residues through mechanical or gravity separation.
- **Oil and Grease Traps:** Separates FOG components to prevent clogging and improve downstream treatment efficiency.

3.1.13. PRIMARY TREATMENT

- **Dissolved Air Flotation (DAF):** Microbubbles are introduced to float fine suspended solids and oils to the surface, which are then skimmed off. DAF systems are highly effective for seafood industry effluents due to high FOG and protein content.

3.1.14. SECONDARY (BIOLOGICAL) TREATMENT

- **Activated Sludge Systems:** Aerobic microorganisms break down organic pollutants. Requires careful control of oxygen

levels and retention times due to high variability in seafood waste composition.

- **Membrane Bioreactors (MBR):** Combines activated sludge with membrane filtration to produce high-quality effluent. Offers compact design and reduced sludge production, though it requires high capital investment.
- **Anaerobic Digestion:** Suitable for high-strength waste streams (e.g., from fishmeal or gutting operations), producing biogas as a renewable energy source. Effective at reducing COD/BOD but requires post-treatment for complete decontamination.

3.1.15. TERTIARY TREATMENT

- **Sand or Carbon Filtration:** Removes fine particulates and residual organics.
- **Advanced Oxidation Processes (AOPs):** Employs ozone, UV, or hydrogen peroxide to degrade persistent organic pollutants and disinfect effluent.
- **Disinfection (UV or Chlorination):** Ensures microbial safety before discharge or reuse.

3.1.16. REGULATORY THRESHOLDS AND COMPLIANCE

Wastewater discharge is regulated under national environmental protection frameworks, often aligned with international standards such as those from the European Union Water Framework Directive (WFD) or the U.S. Environmental Protection Agency (EPA).

Parameter	**Typical Regulatory Limit**
BOD_5	≤ 30 mg/L
COD	≤ 100 mg/L

Parameter	Typical Regulatory Limit
TSS	≤ 50 mg/L
Oil & Grease	≤ 10 mg/L
Total Nitrogen	≤ 15 mg/L
pH	6.5–8.5

Table 2. Example of typical discharge limits for seafood processing effluent for Canned and Preserved Seafood Processing (U.S. Environmental Protection Agency, 2025)

Effluents that do not meet these limits must undergo additional treatment or be redirected to centralized municipal wastewater systems, if permitted.

3.1.17. WASTE RECYCLING AND REUTILIZATION IN FISH-PROCESSING FACILITIES

The study by Kurniasih et al. (2018) highlights how implementation of a waste-minimisation framework in a fish-processing facility led to substantial water and waste savings through targeted reuse and recycling of process streams. Specifically, the authors report a water-savings of 89.76 m³ (≈27.2%) of fresh water per week and a 30% reduction in water use for the washing stage following adoption of reuse strategies. Key measures included separating water flows from thawing, cooking and cooling, enabling internal reuse of condensate and low-BOD/COD process water, and segregating high-pollutant loads (e.g., floor washings) from reuse streams to preserve water quality. The authors further report that solid-waste valorisation (e.g., fish skin for snacks, bone for meal)

accounted for approximately 26% of raw material waste, while liquid-waste reuse reached about 51% of water consumption; these findings illustrate the co-benefits of recycling for both water footprint reduction and resource recovery. In the context of wastewater treatment, such reuse practices reduce the volume and pollutant load entering downstream systems, thereby lowering the grey water footprint component and improving the sustainability profile of the facility. Integrating these strategies into treatment plans can significantly reduce both water withdrawals and effluent flows, aligning with circular-economy principles and offering operational cost savings alongside environmental gains (Kurniasih et al., 2018).

Minimization Effort	Volume (m^3)	Waste Quantity	Quality Standard of Waste Quantity	BOD Levels	COD Levels	Waste Load of BOD	Waste Load of COD	Quality Standard of BOD Waste Load	Quality Standard of COD Waste Load
	(m^3)	(m^3/tonnes of raw material)	(m^3/tonnes of material)	(kg/m^3)	(kg/m^3)	(kg/tonnes of raw material)		(kg/tonnes of raw material)	
Outlet (Before)	55,3	6,14	15	2,33	6,41	14,29	39,38	1,125	2,25
Outlet (After)	32,8	3,64		0,79	2,52	2,87	9,18		
Percentage decrease	40,7%		-	66,1%	60.1%	79,9 %	76,7 %	-	-

Table 3. Before and after of waste minimization. Reprinted from (Kurniasih et al., 2018)

3.1.18. TRENDS AND FUTURE DIRECTIONS

- **Water Reuse and Recycling:** Treated water can be reused for non-potable applications such as floor cleaning, chiller water makeup, or fire safety systems.
- **Integration with Circular Economy Models:** Recovery of byproducts such as fish oil, protein hydrolysates, or biogas aligns with sustainable processing frameworks.
- **Digital Monitoring Systems:** Real-time sensors and smart analytics platforms are increasingly deployed to track water quality and ensure continuous compliance.
- **Nutrient Recovery:** Systems that recover nitrogen and phosphorus from wastewater for fertilizers.

Success cases include HAV (Norway), which utilizes salmon by-products to produce high-value ingredients, and Biomega (Denmark), which extracts bioactive peptides from fish processing by-products.

3.1.19. MONITORING AND REPORTING TOOLS

Contemporary fish processing facilities are increasingly adopting digital technologies to enhance operational efficiency, particularly with respect to water resource management.

3.1.20. LEVERAGING DIGITAL TOOLS FOR WATER MONITORING

Accurate and granular data collection is foundational to informed decision-making processes, particularly in identifying opportunities for water conservation and efficiency improvements.

- **Flow Meters and Sensors:** These are strategically installed at various processing lines and equipment to quantify water consumption at specific stages, enabling precise monitoring and accountability.
- **SCADA Systems (Supervisory Control and Data Acquisition):** SCADA systems facilitate real-time monitoring and control of water usage through automation of valves, detection of irregularities, and system alerts, thereby improving responsiveness and system optimization.
- **IoT-Based Water Management Platforms:** Internet of Things (IoT) platforms provide cloud-integrated dashboards that not only track water use but also analyze historical trends, forecast future consumption, and benchmark performance across different shifts or facilities.
- **Water Footprint Calculators:** Tools compliant with ISO 14046 are used to quantify both direct and indirect water use within a facility. These calculators support the establishment of reduction targets and long-term water sustainability strategies.

Reporting standards used in this domain include:

- **ISO 14046 – Environmental Management: Water Footprint:** Offers principles and guidelines for evaluating the environmental impact associated with water use.
- **Global Reporting Initiative (GRI 303) – Water and Effluents:** Establishes standardized metrics and disclosure practices for water withdrawals, discharges, and consumption within corporate sustainability reports.
- **Internal CSR Reports:** Customizable dashboards and reporting frameworks developed for internal stakeholders, particularly operations and sustainability teams, to track performance against environmental key performance indicators (KPIs).

3.1.21. WATER OPTIMIZATION METHODOLOGIES

Water use in seafood processing is considerably high due to the water-intensive operations involved throughout the production line (Tomczak-Wandzel et al., 2015). Furthermore, inefficient water handling exacerbates losses through excessive freshwater withdrawal and suboptimal wastewater discharge.

3.1.22. AUTOMATION OF EQUIPMENT AND PROCESSING LINES

Automation of water distribution systems enhances process control and offers substantial water savings. Replacing manual water fixtures with solenoid-operated one-way valves, integrated with Internet of Things (IoT) controllers, enables real-time flow tracking and distribution (BIM, 2017). Automation tools such as flow meters, diversion valves, and shut-off devices are vital in optimizing water use.

Oklahoma State University highlighted that enhanced equipment design and material selection can lead to greater water efficiency (Bowser, 2016). Seferlis similarly noted that automating

existing processing equipment improves water and energy use (Seferlis & Voutetakis, 2008). Souza and colleagues demonstrated successful implementation of automated water controls in Atlantic salmon (Salmo salar) and dolphinfish (Coryphaena hippurus) processing, allowing reuse of cleaner wastewater for ancillary operations (Souza et al., 2018).

3.1.23. MONITORING WATER USE PATTERNS AND QUALITY

Real-time monitoring of water usage through strategically placed flow meters and sensors can reveal inefficiencies such as leaks and excessive use (UNEP, 1999). Predictive models have been developed to support water quality monitoring. For instance, Partalas et al. (2008) applied ensemble regression techniques, while Liu et al. (2020) developed a hybrid model using support vector regression and genetic algorithms. Wang et al. (2011) proposed a ZigBee and GPRS-based online monitoring system suitable for the detection of various waterborne chemicals. Similarly, Yu et al. (2016) employed a hybrid intelligent algorithm to forecast dissolved oxygen levels in aquaculture (Liu et al., 2020; Partalas et al., 2008; Wang et al., 2011; Yu et al., 2016).

3.1.24. RECIRCULATION AND RECYCLING

Compliance with industry hygiene standards necessitates advanced water reuse and recycling technologies. Water reuse potential increases when segregating streams from different unit operations, which supports both reuse strategies and treatment optimization (Guimarães et al., 2018).

A recycling unit in thawing systems, for example, can cut water use by up to 60% (Murali et al., 2021). Additional insights by (Danielsson & Spuhler, 2018) and (Theobald, 2017) suggest that even household-level water optimization strategies can inform

industrial practices. Recycled water can be reused for restrooms, effluent treatment plants, and groundwater recharge.

3.1.25. UPGRADING CONVENTIONAL SYSTEMS

Small but strategic modifications to water use systems can yield large water savings. Installing shut-off nozzles, timers, or pedal-operated valves can reduce discharge while maintaining performance (Bowser, 2016). Pressurized water applications have been shown to reduce usage by up to 40% (Murali et al., 2021).

3.1.26. WASTE MINIMIZATION IN THE SEAFOOD INDUSTRY

A fundamental strategy for waste reduction in seafood processing involves the early-stage segregation of waste originating from various production operations. By categorizing waste based on its composition, solid, liquid, or mixed, industries can streamline subsequent treatment processes, ultimately reducing both the volume of waste and the associated treatment costs. Tomczak-Wandzel et al. (2015) emphasize that the prompt separation of waste materials from used water within processing plants can significantly simplify treatment efforts and improve overall resource efficiency (Tomczak-Wandzel et al., 2015).

Solid waste reduction is largely achievable through recovery and transformation into value-added products, while wastewater can be treated and reintegrated into the processing cycle where feasible. Seafood processing generates substantial by-products, such as fish skins, bones, and muscle remnants, that are often rich in proteins, amino acids, and other bioactive compounds. According to Ghaly and colleagues, between 20% and 80% of this waste can be repurposed into products like fish silage, fishmeal, and fish sauce, thereby diverting a significant volume of waste from disposal streams (Ghaly et al., 2013).

Beyond these traditional applications, fish and seafood by-products can be further processed into high-value derivatives, including protein isolates, amino acids, collagen, enzymes, bioactive peptides, and mineral supplements. The integrated valorization of these waste streams not only reduces the burden on wastewater treatment systems but also contributes to energy and water savings, as reaffirmed by (Tomczak-Wandzel et al., 2015).

Kurniasih et al. (2018) underscore the quantifiable benefits of implementing waste minimization practices in seafood industries. Their findings indicate that such strategies can result in a 27.2% reduction in freshwater use over the span of a single week, with the reuse and recycling of liquid waste potentially reclaiming up to 51% of the freshwater normally required in production processes (Kurniasih et al., 2018).

3.1.27. MODELING AND OPTIMIZATION TOOLS FOR WATER MINIMIZATION

Water minimization in the seafood industry entails the dual objective of decreasing both freshwater intake and wastewater output, thereby enhancing overall process efficiency (Seferlis & Voutetakis, 2008). A key approach to achieving this involves developing models that enable the systematic integration of water inflows and outflows across different unit operations within the processing line.

To ensure practical application, these models must strike a balance between computational efficiency and predictive accuracy. Commonly applied optimization methodologies include mathematical programming, P-graph techniques for network design, and stochastic search algorithms, all of which are instrumental in designing effective water-use strategies (Seferlis & Voutetakis, 2008).

Furthermore, tailoring model inputs to the specific characteristics of seafood processing enables the identification of optimal solutions to operational constraints and enhances the reliability of the optimization process. According to (Liu et al., 2020) this targeted modeling approach can substantially refine existing computational tools, thereby facilitating the design of robust and efficient water management networks.

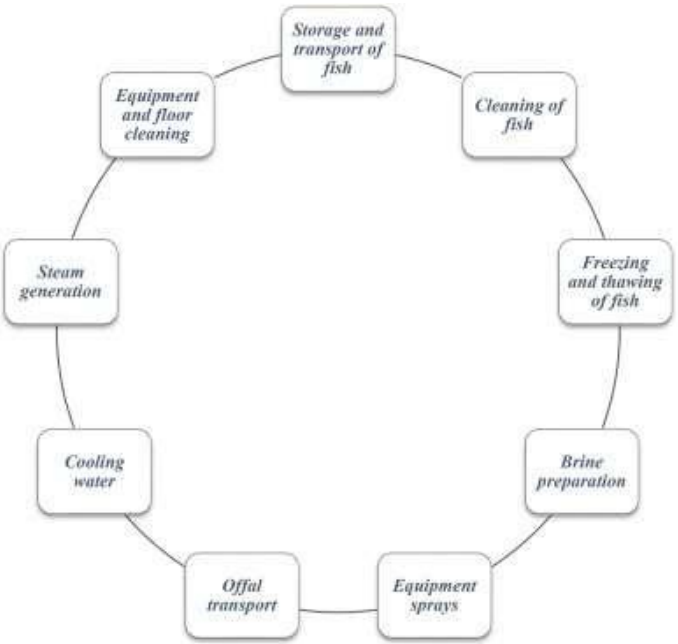


Figure 6. Fish processing by-product generation and end use opportunities. Reprinted from (Khawli et al., 2019)

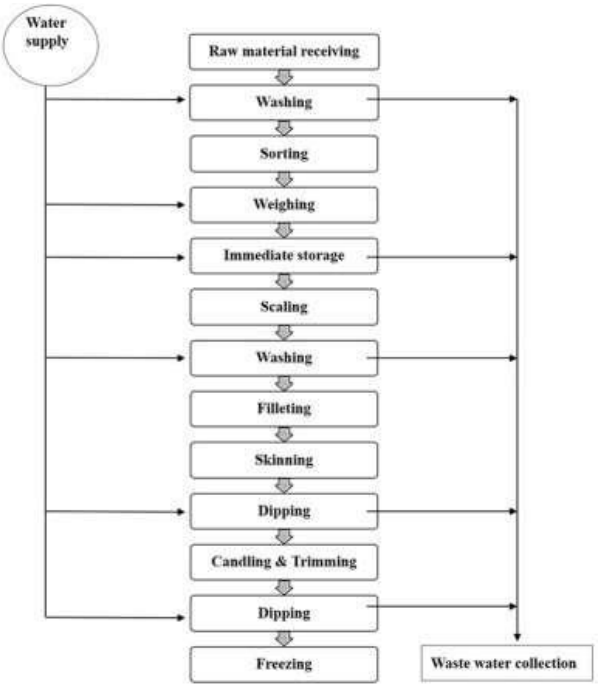


Figure 5. Wastewater generation sources in the seafood industry

4. CONCLUSIONS AND RECOMMENDATIONS

Water remains a critical yet increasingly scarce resource in the seafood processing industry. As demonstrated across multiple studies and technical assessments (Tomczak-Wandzel et al., 2015; Ghaly et al., 2013; Souza et al., 2018), optimizing water usage not only supports environmental stewardship but also enhances regulatory compliance, operational efficiency, and economic resilience. The integration of automation technologies, real-time monitoring systems, and water recirculation frameworks offers promising pathways to minimize the freshwater footprint without compromising hygiene or food safety standards (ISO 14046; GRI 303).

To this end, several evidence-based recommendations can be proposed:

- **Implement Regular Water Audits:** Use real-time metering and data analytics platforms (e.g., IoT-based SCADA systems) to assess consumption patterns and identify inefficiencies (Liu et al., 2020; Souza et al., 2018).
- **Retrofit Equipment with Water-Saving Technologies:** Upgrade legacy systems with solenoid shut-off valves, pressure nozzles, and timer-based dispensers to reduce wastage during sanitation and processing operations (BIM, 2017; Bowser, 2016).
- **Optimize Sanitation Scheduling:** Transition from fixed cleaning intervals to risk-based, need-driven cleaning protocols grounded in microbial hazard analysis, as supported by HACCP principles (UNEP, 1999).
- **Enable Safe Water Reuse:** Deploy appropriate wastewater treatment and filtration systems to facilitate the internal reuse of process water, where legally and microbiologically safe (Guimarães et al., 2018).
- **Capacity Building and Training:** Educate facility personnel on water conservation practices, equipment operation, and hygiene protocols to foster a culture of sustainable water use (Kurniasih et al., 2018).
- **Establish and Track KPIs:** Set annual water reduction targets and monitor progress through standardized reporting frameworks such as ISO 14046 (Environmental management, Water footprint) and GRI 303 (Water and Effluents), supported by internal CSR dashboards (GRI STANDARDS, 2021; ISO 14046, 2014).

When systematically implemented, these interventions can significantly lower the industry's environmental footprint, foster long-term resource security, and ensure product quality and safety are maintained at the highest standard.

5. BIBLIOGRAPHY

Arjen, Y. H., Ashok, K. C., Maite, M. A., & Mesfin, M. M. (2011). The Water Footprint Assessment Manual Setting the Global Standard. www.earthscan.co.uk

Aurora, Z., & Maria, A. P. (1995). Economic engineering applied to the fishery industry (Chapter 4).

Berger, M., Campos, J., Carolli, M., Dantas, I., Forin, S., Kosatica, E., Kramer, A., Mikosch, N., Nouri, H., Schlattmann, A., Schmidt, F., Schomberg, A., & Semmling, E. (2021). Advancing the Water Footprint into an Instrument to Support Achieving the SDGs – Recommendations from the "Water as a Global Resources" Research Initiative (GRoW). Water Resources Management, 35(4), 1291–1298. https://doi.org/10.1007/s11269-021-02784-9

BIM. (2017). Ireland's Seafood Development Agency - Resource Efficiency Guide for Seafood Processors. https://Bim.Ie/Wp-Content/Uploads/2021/01/BIM-Resource-Efficiency-Guide-for-Seafood-Processors.Pdf.

Bowser, T. (2016). Reducing Water Use in Food Processing. Food Technology Fact Sheet.

Bykowski, P., & Dutkiewicz, D. (1996). Freshwater fish processing and equipment in small plants.

Danielsson, M., & Spuhler, D. (2018). Reduce Water Consumption in Industry. https://Www.Watertechonline.Com/Wastewater/Article/15550480/Challenges-Trends-in-Food-Industry-Water-Management.

Ferraciolli, L. M. R. V. D., Luiz, D. D. B., & Naval, L. P. (2017). Potential for reuse of effluent from fish-processing industries. Ambiente e Agua - An Interdisciplinary Journal of

Applied Science, 12(5), 730. https://doi.org/10.4136/ambi-agua.2045

Ghaly, A. E., Ramakrishnan, V. V., Brooks, M. S., Budge, S. M., & Dave, D. (2013). Fish processing wastes as a potential source of proteins, amino acids and oils: A critical review. Journal of Microbial and Biochemical Technology, 5(4), 107–129. https://doi.org/10.4172/1948-5948.1000110

Giske, L. A. L., Bjørlykhaug, E., Løvdal, T., & Mork, O. J. (2019). Experimental study of effectiveness of robotic cleaning for fish-processing plants. Food Control, 100, 269–277. https://doi.org/10.1016/j.foodcont.2019.01.029

GRI STANDARDS. (2021). Water and Effluents Global Reporting Initiative (GRI). (2018). GRI 303: Water and Effluents 2018. https://www.globalreporting.org/publications/documents/english/gri-303-water-and-effluents-2018/

Guimarães, J. T., Souza, A. L. M., Brígida, A. I. S., Furtado, A. A. L., Patrícia, P. C. M., Santos, V. R. V., Alves, R. R., Luiz, D. B., & Mesquita, E. F. M. (2018). Quantification and characterization of effluents from the seafood processing industry aiming at water reuse: A pilot study. Journal of Water Process Engineering, 26, 138–145. https://doi.org/10.1016/j.jwpe.2018.10.006

Guzmán-Luna, P., Gerbens-Leenes, P. W., & Vaca-Jiménez, S. D. (2021). The water, energy, and land footprint of tilapia aquaculture in mexico, a comparison of the footprints of fish and meat. Resources, Conservation and Recycling, 165. https://doi.org/10.1016/j.resconrec.2020.105224

Henriksson, P. J. G., Belton, B., Murshed-E-Jahan, K., & Rico, A. (2018). Measuring the potential for sustainable intensification of aquaculture in Bangladesh using life cycle assessment. Proceedings of the National Academy of

Sciences of the United States of America, 115(12), 2958–2963. https://doi.org/10.1073/pnas.1716530115

ISO 14046. (2014). International Organization for Standardization - Environmental management — Water footprint — Principles, requirements and guidelines. https://www.iso.org/standard/43263.html

Khawli, F. Al, Pateiro, M., Domínguez, R., Lorenzo, J. M., Gullón, P., Kousoulaki, K., Ferrer, E., Berrada, H., & Barba, F. J. (2019). Innovative green technologies of intensification for valorization of seafood and their by-products. In Marine Drugs (Vol. 17, Issue 12). MDPI AG. https://doi.org/10.3390/md17120689

Kurniasih, S. D., Soesilo, T. E. B., & Soemantojo, R. W. (2018). Water resources management at the fish processing industry using waste minimization approach. E3S Web of Conferences, 74. https://doi.org/10.1051/e3sconf/20187406004

Liu, G., Arthur, M., Viglia, S., Xue, J., Meng, F., & Lombardi, G. V. (2020). Seafood-energy-water nexus: A study on resource use efficiency and the environmental impact of seafood consumption in China. Journal of Cleaner Production, 277. https://doi.org/10.1016/j.jclepro.2020.124088

Murali, S., Krishnan, V. S., Amulya, P. R., Alfiya, P. V., Delfiya, D. S. A., & Samuel, M. P. (2021). Energy and water consumption pattern in seafood processing industries and its optimization methodologies. In Cleaner Engineering and Technology (Vol. 4). Elsevier Ltd. https://doi.org/10.1016/j.clet.2021.100242

Partalas, I., Tsoumakas, G., Hatzikos, E. V., & Vlahavas, I. (2008). Greedy regression ensemble selection: Theory and an application to water quality prediction. Information

Sciences, 178(20), 3867–3879. https://doi.org/10.1016/j.ins.2008.05.025

Pedro, S., & Nunes, M. L. (2007). Reducing salt in seafood products. In Reducing Salt in Foods: Practical Strategies (pp. 256–282). Elsevier Ltd. https://doi.org/10.1533/9781845693046.3.256

Pérez Rincón, M. A., Hurtado, I. C., Restrepo, S., Bonilla, S. P., Calderón, H., & Ramírez, A. (2017). Metodología para la medición de la huella hídrica en la producción de tilapia, cachama y trucha: estudios de caso para el Valle del Cauca (Colombia). INGENIERÍA Y COMPETITIVIDAD, 19(2). https://doi.org/10.25100/iyc.v19i2.5298

Seferlis, P., & Voutetakis, S. (2008). Measurement and process control for water and energy use in the food industry. In J. Klemes, R. Smith, & J.-K. Kim (Eds.), Handbook of Water and Energy Management in Food Processing (pp. 387–418). Elsevier Inc. https://doi.org/10.1533/9781845694678.3.367

Souza, A. L. M., Guimarães, J. T., Brigida, A. I. S., Luiz, D. B., Franco, R. M., & Mesquita, E. F. M. (2018). Water management applied to the processing of Atlantic Salmon (Salmo salar) and Dolphinfish (Coryphaena hippurus) in a fish cold storage warehouse in Rio de Janeiro, Brazil. Arquivo Brasileiro de Medicina Veterinaria e Zootecnia, 70(4), 1240–1248. https://doi.org/10.1590/1678-4162-10056

Symeonidou, S., & Mente, E. (2024). Water Consumption and the Water Footprint in Aquaculture: A Review. In Water (Switzerland) (Vol. 16, Issue 23). Multidisciplinary Digital Publishing Institute (MDPI). https://doi.org/10.3390/w16233376

Tay, J., Show, K., & Hung, Y. (2006). Seafood Processing Wastewater Treatment. ChemInform, 37(13). https://doi.org/10.1002/chin.200613273

Theobald, D. (2017). Challenges & trends in food industry water management. https://Www.Watertechonline.Com/Wastewater/Article/15550480/Challenges-Trends-in-Food-Industry-Water-Management.

Thomas, S. (2016). Wastewater generation by seafood processing plants located in and around aroor, kerala, india: status, characterization and treatment using stringed bed suspended bioreactor.

Tomczak-Wandzel, Renata., Vik, E. Arctander., & Wandzel, Tomasz. (2015). Bat in fish processing industry: Nordic perspective. Nordic Council of Ministers.

UNEP. (1999). United Nations Environment Programme Cleaner Production Assessment in Fish Processing.

U.S Environmental Protection Agency. (2025). Canned and Preserved Seafood Processing Point Source Category (40 CFR Part 408). Code of Federal Regulations.

Viglia, S., Brown, M. T., Love, D. C., Fry, J. P., Scroggins, R., & Neff, R. A. (2022). Analysis of energy and water use in USA farmed catfish: Toward a more resilient and sustainable production system. Journal of Cleaner Production, 379. https://doi.org/10.1016/j.jclepro.2022.134796

Wang, X., Ma, L., & Yang, H. (2011). Online water monitoring system based on ZigBee and GPRS. Procedia Engineering, 15, 2680–2684. https://doi.org/10.1016/j.proeng.2011.08.504

Yu, H., Chen, Y., Hassan, S., & Li, D. (2016). Dissolved oxygen content prediction in crab culture using a hybrid intelligent

method. Scientific Reports, 6. https://doi.org/10.1038/srep27292

FAO (Food and Agriculture Organization of the United Nations). (2022). The State of Mediterranean and Black Sea Fisheries 2022. General Fisheries Commission for the Mediterranean (GFCM), Rome.

GFCM (General Fisheries Commission for the Mediterranean). (2023). GFCM Management Plans and Regional Measures for Sustainable Fisheries.

European Commission – Eurostat. (2023). Fishery Statistics: Aquaculture Production and Processing in Europe.

OECD (Organisation for Economic Co-operation and Development). (2021). Fisheries and Aquaculture in the Mediterranean Region. Paris: OECD Publishing.

FAO. (2020). Fishery and Aquaculture Country Profiles – Italy, Türkiye, Egypt. Rome: FAO Fisheries Division.

MODULE 5. INNOVATIONS FOR REDUCING WATER FOOTPRINT IN FISHERIES AND AQUACULTURE



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INNOVATIONS FOR REDUCING WATER FOOTPRINT IN FISHERY AND AQUACULTURE

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SUMMARY

Addressing the water footprint (WF) in capture fisheries sector and aquaculture is essential for sustainable marine resource management. This module highlights innovative strategies to reduce the WF in capture fisheries, focusing on technological, operational, and systemic improvements. One of the key innovations is to use smart fishing technologies. Improved cold chain logistics, renewable energy integration, and eco-designed fishing gear also contribute to reducing water-intensive processes. Furthermore, port-based water recycling systems and environmentally certified landing practices can enhance water efficiency post-harvest. Governance mechanisms such as eco-labels, traceability systems, and water stewardship frameworks encourage responsible practices across the value chain. Together, these strategies offer a comprehensive approach to

minimizing the water footprint of capture fisheries while enhancing ecological sustainability and economic resilience.

The WF of aquaculture, encompassing direct and indirect water use, presents significant sustainability challenges. This module secondly explores innovative strategies aimed at reducing the WF in aquaculture operations. Key approaches include the adoption of recirculating aquaculture systems (RAS), integrated multi-trophic aquaculture (IMTA), and the use of digital technologies for smart water monitoring and control. These strategies enable efficient water reuse, reduce discharge volumes, and optimize water quality management. Additionally, circular economy principles including wastewater valorization, nutrient recovery, and aquaponics promote resource efficiency and closed-loop systems. Advances in feed formulation, such as the use of alternative protein sources and precision feeding, further minimize virtual water use associated with feed production.

The global fish processing industry is facing increasing pressure to minimize its environmental impact, particularly its WF. This module thirdly describes innovative strategies aimed at reducing water use and improving water quality management in fish processing operations. Key issues include the adoption of water-efficient technologies, integration of digital tools and automation, and circular economy principles.

In conclusion, these innovations represent a multidimensional response to environmental constraints, supporting the transition towards sustainable aquaculture systems with minimized WFs.

INTRODUCTION

Wild-caught fisheries and aquaculture are essential to global food systems and contribute significantly to human nutrition

(Elegbede et al., 2025). Together, these sectors provide more than half of the global fish supply supporting food security, employment, and trade (FAO, 2022). In fact, as capture fisheries have leveled off, continued increases in production from aquaculture will be required to maintain or increase per capita fish consumption (FAO, 2020). However, their increasing scale has raised significant environmental concerns, particularly regarding freshwater consumption and pollution. WF has emerged as a crucial sustainability indicator for aquatic food systems (Hoekstra et al., 2011). Reducing the WF of fisheries and aquaculture has become a global imperative.

In capture fisheries, direct WF is minimal compared to aquaculture; however, indirect WFs in marine and inland fisheries stems from upstream and downstream processes (Mekonnen and Hoekstra, 2012). Although wild capture does not consume freshwater in the harvesting phase, innovations such as fuel-efficient vessels, real-time GPS tracking, reduced bycatch gear, and improved post-harvest handling have emerged as effective strategies to minimize both water use and environmental impacts (FAO, 2020; Sala et al., 2021).

In aquaculture, the WF includes blue water (surface and groundwater), green water (rainwater), and grey water (water needed to dilute pollutants). Water in aquaculture is used not only for the basic needs of aquatic organisms but also for feed production, waste removal, temperature control, and processing activities. The increasing demand for sustainable aquaculture necessitates a deeper understanding of its WF and strategies to reduce it. Aquaculture, in contrast, exerts a more direct water demand, particularly in flow-through and pond systems. It also contributes to grey WFs due to effluent discharges rich in nutrients, chemicals, and organic matter (Bostock et al., 2010).

Innovative approaches such as Recirculating Aquaculture Systems (RAS), Integrated Multi-Trophic Aquaculture (IMTA), and Biofloc Technology (BFT) have shown promise in reducing water withdrawal, improving reuse, and enhancing overall water efficiency (Martins et al., 2010; Crab et al., 2012). Aquaculture needs disruptive technologies, including genome editing, artificial intelligence, offshore farming, RAS, alternative proteins and oils for sustainable and profitable aquaculture (Yue and Shen, 2022).

One of the critical drivers of aquaculture's WF is feed production. Feed production contributes significantly to green and blue WFs (Pahlow et al., 2015). As a response, innovations in feed formulation such as insect-based protein, microalgae, and fermentation-derived ingredients are increasingly being explored to reduce freshwater inputs and improve sustainability (Turchini et al., 2019; Gasco et al., 2020). Optimizing feed conversion ratios (FCR) through selective breeding, multiobjective and net energy-based diet formulations and precision feeding technologies also offer considerable potential for water footprint reduction.

Processing (washing, gutting, filleting, freezing, and packaging) fish and other seafood from capture fisheries or aquaculture and preparing them for marketing also requires significant water use. These processes contribute to the overall WF of fisheries (Mungkung et al., 2013). Wastewater generated in processing facilities often contains high organic loads and poses risks of aquatic pollution. To address this, water-saving strategies such as closed-loop water systems, membrane filtration, enzymatic cleaning, and zero-liquid discharge technologies are increasingly adopted to improve water efficiency and meet regulatory standards (Buchmann et al., 2022). Digitalization, automation, and smart monitoring further enhance the precision and accountability of water use in processing plants.

This module/chapter provides a comprehensive analysis of innovative strategies to reduce the WF in three key domains of aquatic food production including fisheries, aquaculture systems and feed production, and fish and seafood processing. The integration of these strategies is vital to decrease WFs in fish and aqua food production in a water-constrained world.

1. INNOVATIVE STRATEGIES TO DECREASE WATER FOOTPRINT IN FISHERIES

Although capture fisheries rely primarily on marine or inland water bodies rather than direct freshwater withdrawals, their operations involve significant indirect water use for fuel production, vessel construction and maintenance, ice production, gear manufacturing, and post-harvest processing. As water scarcity intensifies, there is growing interest in innovative strategies to reduce the water footprint of fisheries (Roberts et al., 2024). In the context of fisheries, "innovation" refers to the development and adoption of new ideas, technologies, practices, and approaches that lead to improvements in the sustainability, efficiency, and overall performance of the fishing industry (Lucchetti et al., 2023).



Figure 1. Potential of technological innovations in fisheries to benefit the environment, (Source: Lucchetti et al., 2023)

1.1. HYBRID AND RENEWABLE ENERGY TO IMPROVE FUEL EFFICIENCY

While direct water use in marine capture fisheries is low, fossil fuel production is highly water-intensive, making fuel use a key component of indirect WF. Hybrid vessels can significantly cut fuel consumption. These systems reduce diesel dependency and associate virtual water use by leveraging regenerative technologies and smart power management. Hybrid vessels for small-scale fisheries in Norway reduced fuel use by up to 40%, lowering lifecycle WF by over 30% (Smith et al., 2020). Solar-powered fishing gear also contributes to environmental sustainability and reduces the environmental footprint of fishing activities by reducing dependence on fossil fuels (Mills et al., 2014). Solar-powered systems are particularly beneficial in remote coastal communities (Hungevu et al., 2025). Solar-powered cold storage units reduce reliance on grid electricity or diesel generators. Biomass-fueled dryers, which use agricultural or fish waste, can replace traditional diesel-based fish drying methods. It was reported that replacing diesel dryers with biomass dryers in Indian coastal fisheries cut WFs by 25%, with similar reductions in greenhouse gas emissions (Dutta et al., 2020). Technological upgrades of older vessels resulted in a 20% decrease in fuel consumption and an equivalent drop in WF (Sala et al., 2013). Energy audits and crew efficiency training for vessel crews can improve energy and water efficiency (15% drop in fuel use) (FAO, 2016).

1.2. ECO-FRIENDLY FISHING GEAR AND WATER-SAVING TECHNOLOGIES

Solar technologies help decrease the carbon footprint of fishing operations and reduce greenhouse gas emissions. The adoption of solar-powered technologies in fishing gear represents a sustainable and cost-effective solution to the energy demands of

small-scale fisheries. Solar-powered systems, such as solar powered lights and navigation equipment, reduce the reliance on fossil fuels. Traditional night fishing often relies on costly kerosene lamps. Solar-powered lights offer a cleaner, more energy-efficient alternative (Mills et al., 2014).

Gear type is a major determinant of energy. The environmental benefits of solar-powered gear are significant. Solar power can also power other critical fishing equipment, such as refrigeration units for storing catches and water pumps for maintaining proper aquaculture conditions (Hungevu et al., 2025). High-energy gear like bottom trawls and dredges demand substantial fuel to tow and require greater indirect water use. In contrast, passive gears such as traps, gillnets, and longlines require minimal vessel movement, significantly reducing fuel needs. Trawling, often associated with high fuel use, can be replaced with selective passive gear like traps and long lines that require less towing power and reduce habitat impact. The passive gear types reduce the fuel-related WF by up to 80% compared to trawl-based operations (Parker and Tyedmers, 2014). On the other hand, fishing nets and trawls are typically made from polypropylene and nylon, materials that have high WFs due to their petrochemical origin and intensive processing. Biodegradable and low-water gear eco-designs using cotton blends, bioplastics, or algae-based polymers are being explored for gear manufacturing. Biodegradable fishing gear not only reduces water use during production but also limits microplastic pollution. Eco-labels or eco-gear certification such as Marine Stewardship Council (MSC) or Friend of the Sea (FOS) encourage the use of low-impact gear, indirectly promoting lower WFs through reduced energy consumption (Jacquet and Pauly, 2007). Transitioning to smart and selective fishing gear is a pivotal strategy for reducing the indirect WF in capturing fisheries.

Traditional deck washing and fish cleaning consume freshwater or seawater, often without recycling. Closed-loop cleaning systems reuse wash water after filtration and disinfection. These systems have been trialed on EU-funded fishing vessels, with water reuse rates exceeding 70% (WWF, 2022). Water-efficient cleaning stations such as high-pressure, low-flow cleaning systems at landing centers can cut freshwater use by over 50%. Portable systems equipped with water-saving nozzles and foot-pedal activators help reduce waste.

1.3. IMPROVED CATCH EFFICIENCY AND STOCK MANAGEMENT

Avoiding overfishing is fundamental to sustainable fisheries and WF reduction. Overfishing depletes stocks, causing reduced "Catch Per Unit Effort (CPUE)" and requiring more fuel-intensive fishing effort (Pauly et al., 2002). This raises the virtual water use due to the water-intensive nature of fuel production. By enforcing science-based quotas and seasonal closures, fisheries can stabilize populations, maintain catch efficiency, and reduce energy and water use (Worm et al., 2009).

Ecosystem-Based Fisheries Management (EBFM) is an integrated strategy that manages fisheries in the context of the entire ecosystem, aiming to maintain healthy fish stocks and preserve ecosystem functions (Pikitch et al., 2004). Its goal is to ensure the long-term sustainability of fisheries by maintaining the resilience and productivity of the entire marine ecosystem. EBFM offers a strategic framework to reduce WF by promoting sustainable stock exploitation and preserving ecosystem functions. EBFM helps maintain or increase CPUE. It means fewer fishing trips are needed per kilogram of fish, less fuel is consumed overall, and the virtual WF embedded in fuel production is reduced. Well-managed fisheries operating under EBFM frameworks have shown a 30-50% reduction

in effort and fuel use CPUE compared to overexploited fisheries (FAO, 2020). EBFM encourages the use of selective fishing gear and methods such as Turtle Excluder Devices (TEDs), Bycatch Reduction Devices (BRDs) and Modified hooks and nets. These measures reduce unnecessary energy expenditure and decrease the WF.

Maximum Sustainable Yield (MSY) that managing fishing effort is essential to maximize catch efficiency. When stocks are at or near MSY, fishers benefit from higher CPUE, which reduces the fuel and time needed per kilogram of fish caught. Higher CPUE leads to lower emissions and reduced WF.

Marine Protected Areas (MPAs) serve as refuges that allow fish populations to recover and habitats to regenerate (Lubchenco and Grorud-Colvert, 2015). Improved stock abundance in and near MPAs enhances CPUE (Roberts et al., 2001).

Bycatch reduction contributes to decrease WFs in fisheries because low bycatch rates decrease fuel consumption.

1.4. POST-HARVEST AND PROCESSING INNOVATIONS

Innovations in post-harvest and processing technologies offer significant opportunities to reduce water footprints in capture fisheries. From smart ice production systems to membrane-based water recycling and automation, these practices not only improve water efficiency but also enhance food quality and operational resilience.

1.4.1. IMPROVED ICE PRODUCTION TECHNOLOGIES

In tropical and coastal fisheries, ice can account for over 60% of direct freshwater use in post-harvest activities. Ice-on-demand machines/technologies reduce evaporative and melt loss during storage, minimize energy and water consumption. They can reduce

water usage by 30-40% compared to conventional ice block production (Bostock et al., 2010). Slurry ice systems can be useful to decrease WFs. Slurry ice consists of micro-crystals suspended in a liquid solution, providing superior chilling efficiency with less total ice volume. This method achieves faster cooling and better fish surface contact (Fernández-Segovia et al., 2011).

1.4.2. LOW-WATER-USE PROCESSING PLANTS

Traditional processing facilities discharge most of this water as wastewater, often untreated, further increasing the grey WF. Membrane filtration systems are a high-efficiency water treatment technique that enables recycling and reuse of process water within the facility. It led to up to 60% water reuse, significantly reducing freshwater intake and grey water output (Pérez-Gálvez et al., 2019). Automation in processing lines by using automated systems have multiple benefits. They standardize water use through controlled spray systems, reducing water losses. Semi-automated fish processing lines use 35% less water per ton of fish processed compared to traditional systems (FAO, 2020).

1.4.3. SMART COLD STORAGE

Cold chain infrastructure is crucial in maintaining the quality, safety, and shelf life of fish products. Phase-change materials such as phase-change refrigerants absorb and release heat at specific temperatures and maintain constant cold conditions. They reduce the WF tied to electricity generation (Love et al., 2015). Solar-powered ice machines produce off-grid ice, offering a renewable alternative to diesel-powered cooling. They can cut fuel use by 40–60%, with a lower WF per kilogram of preserved fish (IRENA, 2015). Improved thermal insulation by using high-efficiency insulation materials reduces the cooling load of iceboxes and minimizing energy and water demands (Love et al., 2015).

1.4.4. REDUCING POST-HARVEST LOSSES

Post-harvest losses in fisheries contribute significantly to the blue, grey, and virtual WFs. When fish spoil after capture, all water-intensive resources used in harvesting are wasted (Mekonnen & Hoekstra, 2012). The main strategies to reduce post-harvest losses are:

- **Digital marketplaces for just-in-time sales:** using digital marketplaces and mobile apps can reduce spoilage rates by 20–30%, especially (Diei-Ouadi et al., 2015).
- **Onboard refrigeration:** technologies decrease WF in fisheries by reducing post-capture spoilage up to 50%. This improves WF per kilogram of consumed fish and reduces energy-related water waste (Love et al., 2015).
- **Mobile processing units:** using mobile and modular processing units offer hygiene, controlled environments and reduce waste rate per landing and minimize grey WF (Turan et al., 2019).

1.5. CIRCULAR SYSTEMS AND WASTE MINIMIZATION

Implementing circular economic principles and waste minimization strategies in fisheries is critical to reducing the WF of the sector. Fish processing involves high blue water consumption, and a significant grey WF due to wastewater and organic effluent discharge.

Water-reuse and recirculation systems in modern processing plants are incorporating membrane filtration and UV disinfection to treat and reuse water. These systems can cut water use by 40–60% (Turan et al., 2019).

By-product utilization indirectly decreases WF in fisheries. Fish processing generates large quantities of by-products. The circular economy promotes the valorization of these materials into

high-value products, which reduces the overall WF by offsetting the demand for water-intensive raw materials elsewhere (Turan et al., 2019). A plant that transforms 30% of its by-products into fishmeal can reduce its WF per unit of edible protein by up to 20% (Pahlow et al., 2015).

Improved cold chain logistics from onboard refrigeration to transportation and storage play a critical role in preserving fish quality and extending shelf life. Cold chain logistics decrease post-harvest losses due to spoilage are a major contributor to resource wastage, including embedded water use (Love et al., 2015).

1.6. DIGITAL AND SMART TECHNOLOGIES

Low-cost technologies, including mobile applications, IoT-based monitoring systems, and solar-powered fishing gear, offer accessible and scalable solutions (Hungevu et al., 2025). The integration of digital technologies is essential for ensuring compliance with sustainability standards and improving socio-economic outcomes for fishing communities (European Commission, 2025). Digital transformation can help support and meet expansion needs of the fisheries/aquaculture industries that include exploiting and harnessing ICT, IoT, Cloud-edge computing, AI, machine learning, immersive technologies and blockchain. The global digital transformation of fishery and aquaculture industry will also meet sustainable development goals of the UN (Rowan, 2023). These technologies enable precise real-time monitoring, data-driven decision-making, and enhanced traceability, all contributing to reductions in the WF of fisheries.

Real-time monitoring technologies, including GPS-based systems, fuel-use loggers, and electronic catch documentation, are critical tools for optimizing fishing operations. Integrated data platforms using oceanographic data allow dynamic rerouting and

adaptive fishing strategies and lead to lower blue and grey WF (FAO, 2020).

Data-driven fisheries and decision making by using recent advancements in big data and artificial intelligence (AI) are revolutionizing fisheries management. Such data-driven approaches enhance stock sustainability and operational efficiency simultaneously, resulting in decreased WF (Piroddi et al., 2021).

IoT-based fish monitoring systems provide real-time data on various environmental parameters, such as water temperature, dissolved oxygen levels, pH, and ammonia concentrations. These systems can alert farmers to changes in environmental conditions (Bachtiar et al., 2022). Furthermore, by optimizing conditions like feeding schedules and water quality, IoT systems can help minimize waste, reduce resource overuse, and prevent unnecessary chemical treatments (Hungevu et al., 2025).

Using digital catch documentation and electronic monitoring systems (e-monitoring) helps maintain healthy stock levels and efficient harvests. By ensuring that fishing operations remain within ecologically safe limits, such systems protect stock levels and maintain high CPUE (Piroddi et al., 2021). Digital documentation is also linked to eco-labeling, traceability requirements, and consumer-driven sustainability certification led to lower WF (Jacquet and Pauly, 2007).

1.7. CERTIFICATION AND ECO-LABELING

Certified fisheries and aquaculture typically meet standards for sustainable stock levels, low-bycatch gear and energy-efficient practices. These contribute to lowering WFs by minimizing inputs and optimizing yields (Jacquet and Pauly, 2007). Eco-labeling and certification schemes target biodiversity conservation and reduce WF of capture fisheries.

The Marine Stewardship Council (MSC) is one of the most widely recognized international eco-labeling organizations for sustainable seafood. Fisheries that seek MSC certification must meet three key principles: 1) Sustainable fish stocks, 2) Minimized environmental impact and 3) Effective fisheries management (MSC, 2021). Though the program does not explicitly measure water use, these criteria indirectly reduce the total WF, especially the blue and grey water components. Some eco-labeling systems, including MSC and Friend of the Sea (FOS) encourage adoption of fuel-efficient engines, route optimization, and better gear management reduces fossil fuel use and reduces virtual water usage (FAO, 2020). Certification offers a market-driven incentive for fishers to comply with sustainability norms. Consumers are increasingly demanding seafood with verified sustainability, reinforcing responsible behavior that coincidentally minimizes WF through reduced environmental inefficiencies.

1.8. SUSTAINABLE SUPPLY CHAIN AND TRACEABILITY SYSTEMS

Reducing the WF in capture fisheries requires a system-wide transformation, extending beyond the act of fishing to encompass processing, transport, and consumption. Transport in fisheries supply chains contributes significantly to the virtual WF.

Local processing and distribution shortening the supply chain through local or regional processing facilities, decentralized distribution hubs and direct-to-consumer sales models (e.g., community-supported fisheries).

Digital traceability systems such as blockchain, QR codes, RFID tags, and cloud-based logistics tools are increasingly being adopted in global fisheries. These systems are particularly valuable for tracking the cumulative WF from harvest to market.

Increasingly, consumer preferences play a vital role in driving down the environmental footprint of seafood. Consumers are demanding products that are locally sourced, eco-labeled and fully traceable. Such choices directly encourage producers and retailers to adopt lower-WF practices.

Integrating supply chain transparency and localization not only benefits water conservation but also reduces carbon and WFs simultaneously (FAO, 2020). Efforts toward green supply chains in fisheries align with the United Nations Sustainable Development Goals (SDGs), particularly SDG 12 and SDG 14, lead to decrease fisheries WFs.

1.9. POLICY AND REGULATORY INNOVATIONS

Sustainable water management in fisheries and aquaculture requires coordinated efforts across the value chain. Policy and regulatory innovations at both national and international levels are fundamental to achieving lower WFs in capture fisheries and aquaculture.

National-level regulatory reforms have demonstrated measurable success in reducing fuel consumption, improving stock health, and decreasing operational inefficiencies. They all contribute to lowering the WF of capture fisheries. For example, Norway anchored in the Individual Transferable Quotas (ITQs) and vessel decommissioning schemes. These policies reduce overcapacity, prevent overfishing, and maintain high CPUE, indirectly decreasing the WF (Asche et al., 2014).

EU Common Fisheries Policy (CFP) integrates ecological and economic sustainability by setting fleet efficiency targets, quota-based management systems and fuel-use monitoring and low-emission incentives. These measures align with reducing the WF by discouraging overfishing and fuel-intensive operations (European

Commission, 2020). In addition to the CFP, the EU has adopted supplementary frameworks and directives to address water and energy use in fisheries more broadly. The Marine Strategy Framework Directive (MSFD) promotes an ecosystem-based approach to fisheries, requiring member states to achieve "Good Environmental Status" in marine waters (European Parliament & Council, 2008). EU's Blue Economy policy encourages sustainable ocean-related industries, including eco-innovation in fisheries. Investment in green port infrastructure, cold chain optimization, and low-emission vessels indirectly lower the WF by reducing waste (European Commission, 2021).

Training programs and participatory extension services can also empower farmers with knowledge and skills to adopt water-saving techniques (Tran et al., 2020). Awareness campaigns and eco-labeling initiatives help link consumer behavior to WF reduction (Richards et al., 2017).

2. INNOVATIVE STRATEGIES TO DECREASE WATER FOOTPRINT IN AQUACULTURE

Aquaculture has become one of the most important sectors in the global food supply, and demand is constantly growing. In recent years, the focus in aquaculture has shifted beyond production volume to sustainable practices that ensure long-term ecological balance (Elric, 2025). In aquaculture, water is used not only for the basic needs of aquatic organisms but also for other sub-sectors such as feed production, waste disposal, temperature control, and processing. WF in aquaculture consists of bluewater, greenwater, and graywater. Because aquaculture relies on clean water, clean water is crucial for reducing the environmental impact of production (Obirikorang et al., 2024).

While fish farming is often touted as a more sustainable alternative to capture fisheries, it is known to have a significant

environmental footprint. Furthermore, the intensive production methods used in fish farming pose a risk of causing a number of environmental problems (Al kahraisat, 2023). Therefore, water consumption and the impacts of the aquaculture sector on water quality have attracted considerable attention in recent years (Symeonidou and Mente, 2024). Technologies and innovations such as Recirculating Aquaculture Systems (RAS), Integrated Multi-Trophic Aquaculture (IMTA), aquaponics, and Biofloc Technology (BFT) improve water use, reduce water quality and waste, and promote sustainability by enhancing biodiversity (Xu, 2024). Feed ingredients such as plant proteins, insect meals, and single-cell protein alternatives to fish meal can reduce feed WF. In addition, technology-driven solutions such as smart production systems, precision aquaculture, and the adoption of sustainable practices will contribute to balancing growth in aquaculture with environmental protection (Mansour, 2025). Consequently, improvements in aquaculture systems, feed, and farming practices can significantly advance more sustainable and responsible aquaculture production (Cortes et al., 2025).

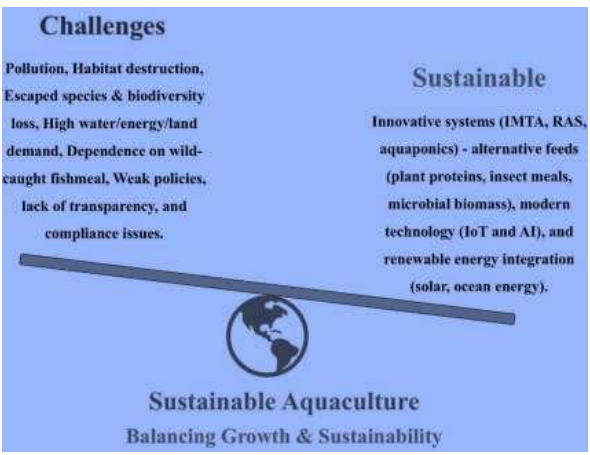


Figure 1. Sustainable aquaculture, challenges, and solutions balance (Source: Mansour, 2025)

2.1. INNOVATIVE WATER-SAVING STRATEGIES IN AQUACULTURE

One of the direct environmental impacts of aquaculture on ecosystems is the pollution of nutrient-rich discharge water (nitrogen, phosphorus, and organic matter) (Grzegorzek et al., 2024). Reducing WF in aquaculture is essential for improving sustainability (Table 1). A few technological and ecological innovations are being developed and implemented in the sector to significantly reduce WF in aquaculture systems. Reducing the water footprint can also be achieved through selective breeding, species diversification, and the implementation of more technologically advanced aquaculture systems (Wróbel et al., 2023). Innovative water-saving strategies such as RAS, IMTA, aquaponics, and BFT are shaping the future of sustainable aquaculture. Each system offers different advantages for reducing water use and WF.

Farming System	**Estimated Water Use (m^3 water/ton of fish)**
Ponds	8,000–15,000
Cages	100–500
RAS	100–300
IMTA	500–1,500
Aquaponics	50–100

Table 1. Estimated water use by fish farming system (m^3/ton of fish) (Verdegem and Bosma, 2009; FAO, 2022)

2.1.1. RECIRCULATING AQUACULTURE SYSTEMS (RAS)

One of the most common methods for reducing water use is RAS. RAS are closed-loop systems that recirculate water rather than continuously pumping freshwater through the farm (Figure 2). This reduces the farm's overall water use and the amount of wastewater discharged into the environment (Al Khraisat, 2023). In this system, most of the water is continuously filtered and recirculated, maintaining optimal water quality and reducing overall water resource use. Freshwater addition is minimal, and more than 90–99% of the water is recycled (Badiola et al., 2012). This system, which protects rivers, lakes, and coastal areas, significantly reduces waste and nutrient discharge. RAS also creates optimal conditions for fish growth by precisely controlling water quality, temperature, and oxygen levels (Zhang, 2024). The efficiency and biosecurity of RAS are attracting the attention of researchers and investors, especially for high-value species such as salmon, trout, and tilapia (Elric, 2025). Moreover, controlled environments such as this reduce the risk of disease, leading to less antibiotic use and better overall fish health (Lin et al., 2018; Dymoke, 2022).



Figure 2. A simplified diagram of a recirculation system in aquaculture (Source: Wrobel et al., 2023; Jena et al., 2017)

2.1.2. INTEGRATED MULTI-TROPHIC AQUACULTURE (IMTA)

IMTA is another progressive approach that has become widespread in recent years. This method combines fish, shellfish, and seaweed to cultivate species from different trophic levels in the same system. Fish waste becomes food for the seaweed and filter feeders, creating a naturally balanced environment. IMTA reduces nutrient pollution, improves water quality, supports healthier species by reducing risks of disease, and increases overall productivity. IMTA reduces the ecological footprint of aquaculture by utilizing waste products (Sukhdhane et al., 2018; Rusco et al., 2024). IMTA also provides economic advantages (Alam et al., 2024) and increases the social acceptability of seafood as environmentally sustainable products by consumers (Hossain et al., 2022). By integrating ecological principles, IMTA reduces water pollution and leads a shift toward more sustainable aquaculture practices (Zhang, 2024).

2.1.3. AQUAPONICS

Aquaponics is a modern food production system that symbiotically combines aquaculture and hydroponics in a balanced circulation environment. In an aquaponics system, fish waste provides nutrients for the plants, while the plants help filter and purify the water, which is then returned to the fish tanks. In an aquaponics system (Figure 3), nutrient-rich water from the fish tanks is used as liquid fertilizer to fertilize the hydroponic production beds. This closed-loop system conserves water and reduces waste. The system's efficient use of water and space makes it a potential technology for addressing both food security and sustainability challenges (Belton et al., 2020). Aquaponics offers the highest sustainability potential compared to traditional aquaculture, with reduced resource consumption and less environmental impact (Colt et al., 2022). Smart aquaponic systems are also being developed

using sensors, actuators, microcontrollers and microprocessors to manage all aquaculture applications (Shafeena, 2016).

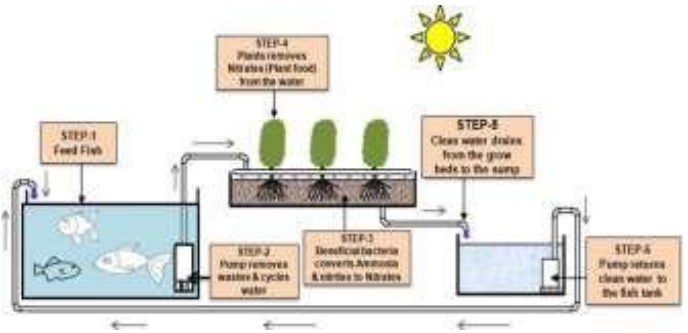


Figure 3. Flow diagrammatic representation of aquaponics system (Source: Jena et al., 2017)

2.1.4. BIOFLOC TECHNOLOGY (BFT)

BFT is a microbial-based aquaculture system that supports the growth of heterotrophic bacteria to convert waste nutrients, primarily nitrogenous compounds, into microbial biomass, or "bioflocs" (Figure 4). These bioflocs provide a supplementary protein-rich feed source for aquatic organisms, particularly tilapia and shrimp. Integrating microbial-based systems such as BFT enables the conversion of waste nutrients into valuable feed ingredients, supporting fish and shrimp production while minimizing resource use (Liu et al., 2025). BFT reduces the need for water exchange, increases feed efficiency, and contributes to the overall health and growth of aquaculture species. It also reduces feed costs by replacing fish meals and fish oil (Akpoilih, 2023; Elric, 2025). BFT assimilates excess nutrients, reducing waste discharge and reducing the risk of eutrophication in the environment. Biofloc technology used in aquaculture can reduce water usage by up to 90%, making it one of the most sustainable aquaculture systems available.

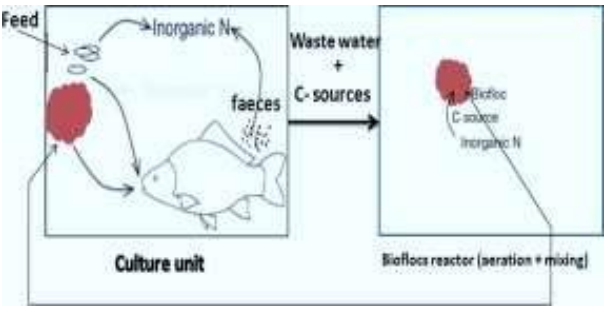


Figure 4. Flow diagram of Bioflocs based aquaculture (Source: Jena et al., 2017)

2.1.5. OFFSHORE AQUACULTURE: EXPANDING INTO DEEPER WATERS

Offshore aquaculture systems are less likely to cause disease outbreaks and water pollution than traditional coastal farms. Furthermore, they provide access to deeper, cleaner waters that may be more suitable for certain species, such as salmon. With the development of floating platforms, advanced monitoring tools, and GPS technology, offshore aquaculture is becoming more feasible. Offshore farming has the potential to increase production while minimizing the environmental impact on coastal ecosystems (Xu, 2024). This system involves establishing farms in deeper, offshore environments far from shore. The adoption of offshore aquaculture is expanding in the Mediterranean, Norway, Australia, and the Americas, demonstrating significant potential for responsible aquaculture growth on a global scale. This system reduces environmental impact and WF on coastal ecosystems while producing healthier aquaculture.

2.2. WATER-EFFICIENT FEED AND NUTRITION MANAGEMENT IN AQUACULTURE

More than 90% of greenhouse gases in aquaculture originate from the fish feed used. Feed production also accounts for a

significant portion of the total WF in aquaculture (Figure 5). The development of alternative foods is a critical area of innovation in sustainable aquaculture management. Aquaculture feeds significantly impacted WF due to virtual water consumption based on the production of product ingredients. In feeds, the use of high levels of fishmeal/soybean meals, ingredients with low water use efficiency and low digestibility, or high nutrient discharge increases WF. Optimizing Feed Conversion Ratio (FCR) is directly related to minimizing water use. Lower FCRs translate into lower feed inputs and, therefore, a smaller virtual WF. Therefore, optimizing feed formulations, feed distribution systems, and feed conversion efficiency is essential to reduce overall water use in aquaculture systems. Advanced feed formulation strategies such as integration of alternative low-WF ingredients into feed, focus on alternative feed ingredients, precision feeding, real-time monitoring systems (Zhang, 2024), nanoscale technology (Ahmad, 2025), and multipurpose and net energy-based diets offer concrete ways to reduce both direct and indirect water use.



Figure 5. WFs of livestock and farmed fish (Source: Yuan et al., 2017)

2.2.1. ALTERNATIVE FEED INGREDIENTS

Traditionally, fish meals and fish oil (FMFO) derived from wild-caught fish have been the primary ingredients of aquaculture

feeds. Innovations in alternative feeds, such as plant-based proteins, insect meals, and microbial biomass (Figure 6), are essential to reduce reliance on wild-caught fish and improve the sector's ecological footprint (Costa-Pierce et al., 2010). Alternative protein and lipid sources, including insect-based proteins, algae, and plant-derived ingredients, are being investigated for their potential to reduce the ecological footprint of aquaculture feeds while supporting optimal growth and health outcomes in fish species.



Figure 6. Alternative feeds for aquaculture (Source: Anonym, 2025)

PLANT PROTEINS

In recent years, aquaculture feed manufacturers have been turning to agricultural products such as soy, corn, and canola instead of FMFO. The use of transgenic seeds, water, pesticides, and fertilizers in the production of these products has a negative impact on environmental sustainability (Demir and Zengin, 2025). Research indicates that various plant protein sources can effectively replace fish meals, either partially or completely, by reducing feed costs, protecting fish health, and reducing environmental impacts (Han et al., 2022; Mugwanya et al., 2023; Akter et al., 2024). However, some pretreatment practices (enzymatic, heat treatments, and fermentation) can be considered to increase the utilization of plant

protein sources and neutralize anti-nutritional factors (Hussain et al., 2024).

INSECT MEALS (ENTOFEEDS)

Insect meals are one of the most promising alternatives to traditional fish meals, offering several advantages in terms of sustainability and efficiency. Insect meals are emerging as a sustainable alternative to traditional fish meals in aquaculture, meeting the increasing protein demand while reducing environmental impacts (Fantatto et al., 2024). Insects, such as black soldier fly larvae (Hermetia illucens), can be reared in organic waste streams with minimal water input. Insect meal derived from black soldier flies, offers a high-protein alternative with an excellent amino acid profile for carnivorous fish (Henry et al., 2015). Furthermore, insect-based feeds have a lower environmental impact than traditional fish feeds (Al khraisat, 2023). Research indicates that insect meals, particularly those of yellow mealworms and black soldier flies, can effectively replace fish meal in aquaculture feeds. Additionally, the carbon footprint and environmental impact of insect meal production are significantly lower (Auzins et al., 2024). Integrating insects into aquaculture feeds as alternative protein sources may offer a promising path toward sustainable and environmentally friendly aquaculture systems (Fantatto et al., 2024). EU legislation has evolved to permit the use of specific insect species in aquaculture feeds, facilitating market access and approval of additional species. Consequently, insect feeds have significant potential to address current sustainability challenges in aquaculture while shaping the future of animal feed (Yadav et al., 2025).

MICROBIAL PROTEINS

Microorganisms including microalgae, seaweed (macroalgae), yeasts, fungi, bacteria and other alternative ingredients have significant potential in aquaculture feeds with

minimal land and water use potential (Demir and Zengin, 2025). Single Cell Proteins (SCPs) produced by bacteria, yeasts and fungi using industrial by-products or wastewater require less land and water and emit less greenhouse gases (Galkanda-Arachchige et al., 2020). Microalgae protein and oil also have the potential to replace FMFO in aquaculture feeds. In recent years, seaweed has gained importance due to its bioremediation capabilities. The crude protein content in microalgae ranges from 50 to 70% (Nagappan et al., 2021; Ma and Hu, 2023). Schizochytrium sp. microalgae and macroalgae such as Ulva are rich in omega-3 fatty acids and essential micronutrients. They can be cultivated using brackish or seawater, thus conserving freshwater resources (Makkar et al., 2016). Yeasts, mostly Saccharomyces cerevisiae, are considered an alternative feed source for aquaculture due to their high crude protein content (Warwas, 2023). Bacteria have the advantage of growing rapidly on organic substrates such as methane, methanol, carbon dioxide, hydrogen, and sugars (Matassa et al., 2020).

Feed Ingredient	**Water Footprint (L/kg)**
Soybean meal	~1,800–2,300
Fishmeal (wild-caught)	~1,000–1,500
Insect meal	~400–800
Algae (marine-sourced)	<200

Table 2. Comparison of WFs of some alternative feeds (Mungkung et al., 2013; Tlusty et al., 2017)

2.2.2. INNOVATIVE FEEDING STRATEGIES

PRECISION FEEDING

Precision feeding involves real-time control and optimization of feeding schedules, feeding quantities, and nutrient profiles using sensors, automated feeders, and data analytics. Smart feeding technologies optimize feed distribution by analyzing fish behavior, biomass, and environmental parameters in real time. Advanced technologies such as underwater cameras and biometric sensors used for precision feeding assess fish appetite and size to adjust feed rates in real time (Martins et al., 2012). Automated feeders minimize labor input and prevent overfeeding, thereby reducing nutrient leaching into the water column (Zhang et al., 2016). Artificial intelligence tools analyze feeding behavioral trends in fish and suggest dynamic adjustments to feeding regimes (Rosa et al., 2021). Precision feeding reduces the need for water changes to maintain quality and limits WF associated with nutrient pollution and wastewater treatment. By combining these transformative technologies, the aquaculture industry can evolve into a system better equipped to lower feed costs and reduce environmental impacts (Solomon et al., 2025).

IMPROVING FEED CONVERSION RATIO (FCR) BY GENETICS NUTRITIONAL MODEL

The feed-to-return ratio (FCR) is a key performance indicator in aquaculture. A lower FCR not only reflects economic efficiency but also reflects a lower environmental footprint, including indirect water use. Technologies that increase digestive efficiency (e.g., probiotics, enzymes) and selecting fish species with higher nutrient utilization capacity contribute to reducing feed input per unit of production (NRC, 2011). Reducing FCR through balanced diets and efficient feeding systems directly reduces both the amount of feed used and the virtual WF contained in these inputs (Table 3).

Species	Typical FCR	Water Footprint (L/kg live weight)
Tilapia	1.6–1.8	2,500–3,000
Shrimp (semi-intensive)	1.5–2.0	3,500–5,000
Salmon (RAS)	1.1–1.3	~1,200

Table 3. FCR and WFs of aquaculture species (Verdegem et al., 2006; Mungkung et al., 2013)

Reducing environmental impact and improving FCR through fish breeding programs by refining genetic nutritional models can also indirectly improve water quality in aquaculture. It has been reported that a 1% improvement in FCR across four species in the EU requires 30,000 tons less feed to produce the same number of fish. Reducing feed use per fish produced translates to a reduction in the water load of approximately 200 tons of phosphorus (P) and 900 tons of nitrogen (N) and lower pressure on the original raw material. Breeding programs targeting disease resistance can lead to healthier fish and improved FCR. The gut microbiota of farmed fish is likely influenced by their diet, probiotics, and the genetic background of the fish. Generally, the more efficiently the fish utilize the feed, the more nutrient-rich the feed is (European Commission, 2025).

MULTIOBJECTIVE (MO) DIET FORMULATION

Currently, feeds are formulated to meet the nutritional requirements of fish while minimizing feed cost and meeting addition limits for specific feed ingredients. Several studies have considered environmental impacts in feed formulation (Mackenzie et al., 2016; Nguyen et al., 2012). Recently, Garcia-Launay et al. (2018) developed a multi-objective (MO) diet formulation model that uses the constraints of the least-cost formulation (protein

content, amino acid balance, lipid levels, water footprint, carbon emissions) and calculates a function that includes both feed cost and environmental impact indicators obtained through life cycle assessment (LCA) (i.e., minimize cost, maximize growth rate and FCR, climate change, non-renewable energy use, P demand, land occupation). These models use linear and non-linear programming to evaluate trade-offs between performance metrics, including water use, and sustainability objectives (Naylor et al., 2021). MO formulation is a useful tool for reducing the environmental footprint of aquaculture production without compromising animal performance or increasing production costs (Wifart et al., 2023). MO diet optimization enables the formulation of eco-efficient feeds using low-WF ingredients while ensuring adequate nutrition and growth.

NET ENERGY (NE)-BASED DIET FORMULATION

The energy units of aquaculture diets are often based on metabolizable energy (ME). Net energy-based diet formulation focuses on the actual energy available for growth and maintenance, as opposed to gross or digestible energy. This approach allows a better match between energy intake and metabolic needs of aquaculture species. NE-based diet formulations improve nutrient utilization efficiency, leading to lower feed waste and better FCR; they reduce the excretion of unused nutrients, reduce nitrogen and phosphorus loads in aquatic systems, and enable precise matching of dietary energy to fish requirements across life stages. By improving the biological efficiency of feed utilization, net energy-based formulation indirectly contributes to lower feed demand and, consequently, less virtual water use in feed production systems.

2.3. WASTEWATER TREATMENT AND REUSE INNOVATIONS

Aquaculture waste, such as uneaten feed and feces, contain organic components that contribute to the degradation of both water bodies and the sediments into which they are released. The primary components of aquaculture wastewater that can cause environmental problems and inhibit fish growth are dissolved and particulate organic matter, total dissolved solids, and nutrients such as phosphate and nitrogen (Lal et al., 2024). These nutrient-rich wastes lead to eutrophication and degradation of water bodies. Innovative strategies for wastewater treatment and reuse offer ways to overcome these challenges while reducing the sector's wastewater removal (WF). Among these, constructed wetlands, phytoremediation, and zero-discharge systems have received significant attention due to their ability to increase water reuse and reduce environmental impact. Some technologies, such as wastewater-integrated algae culture, may offer a sustainable and environmentally friendly solution. Therefore, the adoption of advanced wastewater treatment technologies is vital to supporting the environmental sustainability of aquaculture practices (Kumar et al., 2025).

Some common aquaculture wastewater treatment technologies include:

- **Physical treatment technologies:** include sedimentation, filtration, flotation, and membrane filtration.
- **Chemical treatment technologies:** including coagulation, flocculation, and disinfection.
- **Biological treatment technologies:** including constructed wetlands, biofilters, activated sludge, moving-bed biofilm reactors, IMTA, BFT, aquaponics, and the Upflow Anaerobic Sludge Blanket (UASB) Process (anaerobic digestion technology).

- **Phytoremediation:** a biological process that uses aquatic plants to remove, retain, or degrade contaminants in aquaculture wastewater. Key species for phytoremediation are duckweed (Lemna spp.), water hyacinth (Eichhornia crassipes), and water spinach (Ipomoea aquatica).

Water On, an advanced wastewater treatment and reuse technology, is revolutionizing water management with its cutting-edge smart metering and automatic leak prevention system (Lal et al., 2024).

2.4. SUSTAINABLE POND AND CAGE MANAGEMENT PRACTICES

Sustainable pond and cage management practices offer effective and accessible strategies for reducing WF in aquaculture.

Pond liner involves lining the bottom and sides of aquaculture ponds with impermeable materials, often such as high-density polyethylene (HDPE), geomembranes, clay, or concrete, to minimize water loss due to seepage and infiltration. Seepage can account for up to 30% of total water losses in unlined soil ponds, particularly in sandy or porous soils (Boyd and Tucker, 2012). In India, shrimp farms with HDPE-lined ponds have achieved a 20–30% reduction in water consumption per crop cycle (Devi et al., 2016).

Rainwater harvesting (RWH) involves collecting and storing rainwater for aquaculture. In regions with seasonal rainfall, RWH can supplement or even replace freshwater withdrawals from rivers or aquifers, thus reducing the blue water component of RWH. Integrated RWH systems in rural aquaculture farms have reduced groundwater reliance by up to 40%, improving sustainability and reducing pumping energy use (Rahman et al., 2020).

Water reuse in polyculture systems involves growing multiple species selected to occupy different ecological niches or trophic levels in the same pond or cage. Properly designed polycultures recycle nutrients within the system, reducing the need for frequent water changes and minimizing waste accumulation. Water reuse in polyculture improves water use by nutrient cycling within the system rather than requiring new water inputs. The tilapia-shrimp polyculture system in Southeast Asia achieved a 25% reduction in water exchange and a 15% increase in feed efficiency, both contributing to a significantly lower overall WF per biomass (Kibria et al., 2017).

2.5. TECHNOLOGY-DRIVEN AQUACULTURE WITH SMART MONITORING APPLICATIONS

Optimum conditions can be maintained through automated systems that monitor water oxygen levels, temperature, pH, and waste concentrations in real time. This precise control eliminates the stress factors that fish often experience in natural or open aquaculture environments (Ohia, 2025). This technology allows for timely interventions and supports long-term sustainability by minimizing environmental impact (Jayandan et al., 2024).

The integration of the Internet of Things (IoT), artificial intelligence (AI), and cloud computing in aquaculture increases fish production, biodiversity, and reduces waste production, ultimately supporting sustainable development goals by addressing environmental challenges through innovative digital technologies (Kathuria et al., 2024). Tools such as automated feeding systems, underwater drones, and AI-enabled monitoring software enable real-time data collection and monitor key environmental parameters such as dissolved oxygen, pH, temperature, and turbidity, as well as fish movement, behavior, and management. AI algorithms analyze vast data streams to provide actionable insights, such as predicting

optimal feeding times, identifying health anomalies, or predicting growth rates. By enabling precise feeding and water quality management in fish farming, AI-powered IoT reduces feed waste, improves fish health, delivers higher yields, and lowers operating costs. Automated systems such as robotic feeders and sensor-based water quality monitors also reduce labor costs and allow farmers to manage operations more effectively. As technology continues to evolve, smart aquaculture systems will play an increasingly important role in the sector's shift toward sustainability (Choudhury et al., 2022). Digital technology is further contributing to precision aquaculture and sustainability. Blockchain technology is also being adopted to increase traceability and transparency in the supply chain, ensure food safety, and increase consumer confidence in aquaculture products (Zhang, 2024). Cloud-based platforms and mobile applications also enable proactive decision-making by providing user-friendly interfaces for ubiquitous data access.

3. INNOVATIVE STRATEGIES TO DECREASE WF IN FISH PROCESSING

Fish processing, which encompasses activities such as washing, gutting, filleting, freezing, and packaging, represents a critical link in the seafood value chain. These processes are typically water-intensive, generating significant amounts of wastewater and contributing to the overall water flows of fisheries (Mungkung et al., 2013). While green water plays a minimal role in post-harvest processing, blue and grey water flows are of greater importance and are often insufficiently reported in sustainability assessments. Studies indicate that fish processing facilities may consume between 5 and 15 m^3 of freshwater per ton of processed fish, depending on scale, technology, and hygienic protocols (Mungkung et al., 2013). According to SINTEF (2021), replacing conventional open cleaning systems with closed-loop water reuse systems can reduce the blue

water footprint by 30–50%, highlighting the importance of technological innovation in footprint reduction. Grey water is defined as the amount of freshwater required to assimilate pollutants generated during fish processing, such as blood, offal, tissue residues, biochemicals, oils, greases, cleaning chemicals, and disinfectants (Chen et al., 2019). The grey water footprint can be particularly high in facilities with poor waste segregation or inefficient wastewater treatment systems. Vázquez-Rowe et al. (2012) reported that fish processing stages may account for up to 60% of the total freshwater impact in post-harvest phases. Hoang et al. (2021) found that wastewater treatment capacity significantly influences the grey water footprint, with facilities employing advanced membrane bioreactors showing a 40% lower grey water footprint compared to conventional systems.

Reducing the water footprint in the fish processing sector is a critical strategic objective not only for mitigating environmental impacts but also for lowering operational costs and enhancing competitiveness in global markets. The integration of technological innovations (e.g., membrane bioreactors, closed-loop systems), water-saving equipment, and digital monitoring systems offer substantial improvements in the management of blue and grey water flows. Furthermore, regulatory frameworks developed through collaboration between policymakers and industry stakeholders can promote circular water use, paving the way for a more sustainable fish processing industry. Consequently, water efficiency and wastewater management in fish processing are expected to become key performance indicators within the broader context of sustainable food production.

3.1. PROCESS OPTIMIZATION TECHNOLOGIES

Water is a critical resource in fish processing operations. The fish processing industry is increasingly adopting process

optimization technologies to reduce water use without compromising product quality or food safety. Such technologies provide powerful tools to minimize water footprint (WF) and address both environmental and economic challenges. Water-efficient equipment directly reduces consumption (blue water), while dry processing techniques minimize freshwater demand and lower wastewater loads (grey water). In addition, automation and smart sensor systems enable precise control, reduce waste, and optimize hygiene procedures.

3.1.1. WATER-EFFICIENT EQUIPMENT

The replacement of conventional water systems with high-efficiency equipment can significantly reduce water consumption. Traditional systems often operate at unnecessarily high flow rates or lack control mechanisms, leading to excessive use. In contrast, high-efficiency nozzles, pressurized washing systems, and automated cleaning technologies can lower water use by up to 40% (FAO, 2020). For this purpose, the implementation of low-flow nozzles, high-pressure/low-volume cleaning systems, and sensor- or foot pedal–operated faucets and hoses allow the same level of cleaning performance with 30–40% less water use (Bailone et al., 2022). Furthermore, Cleaning-In-Place (CIP) systems, water recovery and filtration units, closed loop water systems, and particularly cascading applications where the same water is reused across different processes according to its hygiene level enable up to 70–80% recovery of water efficiency (Martins et al., 2010). In fish processing, cooling and freezing are especially critical stages, both in terms of product quality and shelf life, as well as being among the most water- and energy-intensive phases. Compared with traditional methods, the adoption of closed-loop systems, slurry ice machines, and phase change material (PCM) based cooling technologies offers considerable potential for reducing the water footprint (WF).

In addition, several innovative technologies already integrated into other food industries such as dry ice (CO_2) surface cleaning systems, ozonated and electrochemical oxidation (ECA) water treatment units, ultrasonic cleaning systems, and vacuum cooling represent promising solutions for application in fish processing facilities. The adaptation of these technologies would constitute an important step toward reducing the WF in the sector, contributing both to environmental sustainability and operational efficiency.

3.1.2. DRY PROCESSING TECHNIQUES

These are cleaning methods that utilize mechanical or air flow instead of water. In fish processing, they can be applied for scaling, vacuum-assisted gutting, and surface cleaning, particularly in small to medium-sized facilities, achieving 20–50% water savings compared to conventional washing (Jeyasanta et al., 2019). In recent years, the increasing adoption of pneumatic vacuum conveyors and "air knife" technologies have enabled the transport of fish along processing lines using belt conveyors instead of water channels (Fu et al., 2024), effectively eliminating water requirements in this stage. In addition, dry processing not only reduces freshwater demand but also decreases the generation of organic-rich wastewater, thereby lowering the grey water component of the WF.

3.1.3. AUTOMATION AND SENSOR-CONTROLLED WATER FLOW

Sensor-controlled water flow is an intelligent automation system in fish processing lines (such as cleaning, washing, and transport processes) that delivers water only where and when it is needed, in the required amount. By replacing traditional continuously open water valves, it enhances resource efficiency. Although sensor-controlled water flow is not as radical a change as

dry processing, it provides a sustainable and smart intermediate solution for processes where water is still required. This approach can achieve 25–45% water savings in washing and disinfection operations, thereby significantly reducing the blue component of the WF (Sapkota et al., 2022).

3.1.4. WATER REUSE AND RECYCLING SYSTEMS

These systems involve the treatment and reuse of water that becomes contaminated during fish processing operations (such as washing, cleaning, and transport). The primary objectives are to reduce water consumption, decrease wastewater volume, lower operational costs, and enhance environmental sustainability. Closed-loop water cycles, combined with technologies such as membrane filtration, reverse osmosis, UV disinfection, and activated carbon, can achieve up to 80% water reuse (Chen et al., 2019). However, the use of recovered water in processes that come into direct contact with food (e.g., final product washing) is generally not accepted and is restricted by food safety regulations in many countries (FDA, EFSA). In these systems, water quality and safety must be rigorously monitored to ensure compliance and prevent contamination, thereby controlling both blue and grey components of the WF.

3.1.5. ANAEROBIC WASTEWATER TREATMENT

Anaerobic digestion is a biological treatment process in which organic contaminants are broken down by anaerobic bacteria in the absence of oxygen, producing biogas (a mixture of methane – CH_4 – and carbon dioxide – CO_2) and stabilized sludge. This method is particularly suitable as a pre-treatment for high-strength organic wastewater. In the context of fish processing, the highly organic wastewater generated can be effectively treated through anaerobic digestion. The process not only generates biogas as a renewable energy source but also reduces biochemical oxygen demand (BOD)

and chemical oxygen demand (COD) by over 80%, making the reuse of treated water feasible (Nasseri et al., 2020).

Moreover, anaerobic treatment contributes to both environmental and economic sustainability. By integrating anaerobic digesters, fish processing facilities can lower operational costs through energy recovery, reduce the blue and grey components of the WF, and decrease the overall environmental footprint of wastewater management. This approach also supports circular resource use, as the stabilized sludge can be further applied in agricultural or energy applications, and the recovered water can be reused in non-contact processes. Given these benefits, anaerobic digestion is considered a highly effective and recommended technology for treating fish processing wastewater, aligning with both sustainability goals and industry best practices.

3.1.6. WATER CASCADING

Water cascading is a process optimization strategy in which water is reused multiple times in a decreasing order according to hygiene requirements. Fresh water is first applied to the most sensitive stages of processing (e.g., final rinsing of fish fillets), and the resulting lightly used water is then directed to lower-risk processes such as preliminary fish washing, cleaning of external floors or containers, and ice production for transport. This approach effectively maximizes the value of each unit of water by extending its usability before discharge.

Implementation of water cascading in fish processing facilities can achieve 25–30% freshwater savings. The key to success lies in establishing regional water hygiene classifications and applying color-coded piping and storage systems to prevent cross-contamination (Martins et al., 2017). In addition, water cascading reduces wastewater volume and organic load, thereby decreasing the grey component of the WF.

An illustrative example of water cascading in a fish processing plant is as follows:

- **High Hygiene → Medium Hygiene:** Fresh water for final rinsing of fillets and equipment disinfection; the first-stage used water can be reused for initial fish washing or transport channels.
- **Medium Hygiene → Low Hygiene:** Second-stage used water from transport channels can be reused for floor cleaning or truck washing.
- **Low Hygiene → Very Low Hygiene:** Third-stage used water, after appropriate treatment, can serve as reserve water for fire suppression systems or landscape irrigation.

3.2. CLEANER PRODUCTION AND ECO-EFFICIENCY APPROACHES

Beyond technological upgrades, cleaner production and eco-efficiency strategies offer systemic approaches to reducing especially the blue and grey WF.

3.2.1. LEANING PROCESSING

Lean management is a management philosophy focused on reducing waste and increasing efficiency. It is employed to identify and eliminate water use inefficiencies, such as overuse, leaks, and unnecessary flow. In the fish processing sector, lean approaches help pinpoint water inefficiencies in operations such as washing, rinsing, and equipment cleaning. A fundamental lean tool, value stream mapping, can be used to visualize water consumption across each process step and identify areas of excessive use. Implementation of lean tools in processing facilities has been shown to reduce freshwater use by 12-18% without compromising hygiene or operational efficiency, thereby decreasing the blue component of the WF (Valente et al., 2020).

3.2.2. GOOD MANUFACTURING PRACTICES (GMP) AND HAZARD ANALYSIS AND CRITICAL CONTROL POINT (HACCP)

GMP and HACCP systems play a key role in maintaining food safety. When effectively implemented, these systems ensure hygiene without the need for excessive water use for cleaning and disinfection. Strict adherence to GMP principles reduces the need for water-intensive sanitation. For example, one common HACCP practice—isolating high-contamination-risk areas and applying dry-cleaning protocols in low-risk zones—can significantly reduce water consumption (Lindberg and Espejo-Hermes, 2015).

These strategies not only decrease the blue component of the WF but also reduce the grey WF by preventing the overuse of chemical cleaning agents that contribute to wastewater contamination. GMP and HACCP should not be viewed merely as regulatory requirements or commercial certifications. They serve as tools to shift the traditional mindset of "more water is needed for cleaning" toward a philosophy of "optimized water for smart cleaning." Water efficiency is therefore a natural and expected outcome for these systems. In designing a water management strategy for a fish processing facility, GMP and HACCP principles should be central to the approach.

3.2.3. USE OF NATURAL CLEANING AGENTS

Traditional fish processing operations rely heavily on synthetic chemical detergents and disinfectants, which contribute to high grey water loads due to their chemical oxygen demand and toxicity. A shift toward natural cleaning agents such as enzymatic cleaners, citric acid, and plant-based surfactants can reduce the environmental impact of wastewater. Their use can lead to improved compatibility with water recycling systems, lower grey water volumes due to reduced need for dilution and reduced reliance on

intensive water treatment technologies. Replacing chlorine-based cleaners with enzymatic alternatives in seafood operations can decrease wastewater toxicity by 45%. This wastewater can be reused for non-food contact applications (Aalbers et al., 2018).

3.3. DIGITAL AND SMART WATER MANAGEMENT SYSTEMS

Digital and smart water management technologies are reshaping how fish processing industries manage their WF. IoT devices enable precise, real-time monitoring, digital twins and AI offer predictive insights and virtual testing of conservation strategies ensures transparent, traceable water use data.

3.3.1. INTERNET OF THINGS (IOT) INTEGRATION

In fish processing plants, IoT-based flow meters and pressure sensors can monitor water use at critical control points, such as cleaning stations, scalers, chillers, and filtration systems. By providing continuous feedback on flow rates and usage patterns, these systems allow for precise identification of inefficiencies, leaks, or overuse (Domènech et al., 2021). Advanced IoT platforms integrate water data with cloud-based analytics to generate dashboards and performance indicators. Predictive maintenance based on sensor data can also prevent equipment malfunctions that typically lead to water waste (Ahmed et al., 2022). This results in both quantitative reductions in blue WF and qualitative improvements in sustainability reporting.

3.3.2. DIGITAL TWINS AND AI

Digital twins are virtual replicas of physical processing systems. In fish processing, digital twins can model various processing scenarios, identifying combinations of equipment and operating conditions that minimize water consumption without

compromising hygiene or throughput (Papacharalampopoulos and Stavropoulos, 2019). AI models complement digital twins by learning from historical and real-time data to forecast water requirements based on daily processing loads, fish species, or weather conditions. Machine learning algorithms can adjust cleaning schedules dynamically or optimize water-to-fish ratios, thereby reducing waste (Zhang et al., 2021).

When summarizing all these processes, artificial intelligence (AI) enables real-time monitoring of water consumption in fish processing facilities, immediately detecting abnormal usage and leaks. Machine learning algorithms optimize cleaning protocols and process parameters to achieve maximum hygiene with minimal water and energy use. Additionally, predictive maintenance allows potential equipment failures that could cause water leaks to be identified and prevented before production is interrupted, thereby contributing to reductions in both blue and grey components of the WF.

3.3.3. BLOCKCHAIN FOR TRACEABILITY

Blockchain technology is a decentralized, immutable ledger that ensures transparency and traceability in supply chains. In the context of fish processing, blockchain can securely record water usage data from various stages of production, creating verifiable WF reports (Wang et al., 2020). This is particularly important for meeting sustainability criteria in eco-labels and consumer-facing certifications like the ASC or Global G.A.P. by linking IoT and AI-driven water use data to blockchain, companies can provide digital evidence of compliance with environmental standards and resource efficiency targets.

3.4. WASTE MANAGEMENT AND BY-PRODUCT RECOVERY

In fish processing, water is intensively used both as a carrier (to remove waste and for cleaning) and as a separation medium (e.g., for oil-protein separation). When by-products are effectively and properly recovered, both water consumption and wastewater load can be reduced. Specifically, if solid by-products such as fish heads, bones, skins, and internal organs are separated at the source, the formation of bloody and oily wastewater is minimized (Lal et al., 2024). Recovered cleaner process water can then be reused for secondary cleaning or cooling purposes, potentially improving water efficiency by 20–40%, thereby reducing both the blue and grey components of the WF.

3.5. TRAINING, AWARENESS, AND BEHAVIORAL APPROACHES

Increasing water efficiency in fish processing facilities is achievable not only through technological investments and infrastructure improvements but also via human-centered approaches. In this context, employee training, raising awareness, and promoting behavioral changes are considered integral components of water management strategies (Coppola et al., 2021). Beyond training, systematically conducted awareness campaigns are crucial. The use of informative posters and visual materials within the facility, regular sharing of water consumption data with employees, and fostering a savings-oriented competitive environment between shifts are effective methods to enhance awareness. For example, rewarding the shift that achieves the highest water savings strengthens both team spirit and accountability. Additionally, explaining the concept of the water footprint with simple and relatable examples makes the

environmental and economic implications of water use tangible, thereby motivating staff (Simat, 2021).

Behavioral approaches play a critical role in embedding a water efficiency culture. Practices such as using scraping or sweeping methods instead of water during pre-cleaning, opening taps and hoses only when needed, and developing simple habits to prevent water waste are small but effective measures. Shift supervisors and managers modeling these behaviors and encouraging employees to report water wastage incidents further reinforce organizational ownership. When training, awareness, and behavioral approaches are implemented holistically, water savings of 15–30% in fish processing facilities can be achieved, which is expected to reduce operational costs while enhancing environmental sustainability (Ltaief et al., 2025).

3.6. WATER MANAGEMENT IN SMALL-SCALE AND TRADITIONAL FISH PROCESSING

Water management in small-scale and traditional fish processing operations involves different dynamics compared to large industrial facilities. These operations typically face constraints in capital, technology, and infrastructure; nevertheless, effective water management is critical for both product safety and sustainability. While overall water consumption in these facilities is lower than in industrial plants, water use per unit of product is often higher due to manual and uncontrolled processes (Kurniasih and Soemantojo, 2018).

In small-scale and traditional fish processing facilities, water management can be improved through low-cost technologies, behavioral changes, and cooperative-based shared solutions. Such approaches not only enhance product safety but also reduce environmental impacts by optimizing both the blue and grey components of the WF.

3.7. GREEN ENERGY AND COLD CHAIN MANAGEMENT

In fish processing, both energy and water management are critical components of sustainability. Green energy, particularly in energy-intensive processes such as refrigeration and ice production, indirectly contributes to water efficiency. For instance, renewable energy–powered cooling systems and eco-friendly ice production technologies optimize the energy-water cycle, thereby reducing water consumption (Fry et al., 2024). Moreover, marine-based renewable energy systems, such as wave and tidal energy, can be integrated with aquaculture operations to enable more efficient use of water resources (Cao et al., 2025).

Cold chain management is a fundamental element in maintaining fish product quality and safety. When properly planned and integrated with technology, it also enhances water efficiency. High-efficiency refrigeration units, closed-loop ice production systems, and smart temperature sensors not only save energy but also prevent unnecessary water use. Digital monitoring and optimization of the cold chain minimize losses in both water and energy consumption, contributing to sustainable production (Luo et al., 2025).

In conclusion, the integration of green energy applications with effective cold chain management strengthens both water efficiency and energy sustainability in the fish processing sector. This approach not only reduces operational costs but also serves as a strategic measure to improve environmental performance within the industry.

3.8. POLICY AND CERTIFICATION

Effective regulation is foundational for encouraging water efficiency across the fish processing sector. The European Union Water Framework Directive (Directive 2000/60/EC) provides a

comprehensive legislative framework to ensure the sustainable use of water resources. It sets quantitative and qualitative water use limits and mandates integrated river basin management plans. Under this directive, fish processors operating within the EU must comply with effluent discharge limits, adopt water-saving practices, and contribute to achieving “good ecological status” in surrounding water bodies (European Commission, 2021). These standards often include restrictions on BOD, COD, total suspended solids, and freshwater abstraction limits.

Environmental certification and eco-labeling are also powerful tools for promoting water stewardship. ASC and Global G.A.P. incorporate GAP in aquaculture and fish processing. Water use monitoring, source protection, and efficient wastewater handling are mandatory components of its certification audits. Companies that meet these criteria gain access to European and global retail markets that prioritize certified sustainability (Global G.A.P., 2022). Certified water-efficient processors can label their products with eco-labels that appeal to environmentally conscious consumers.

REFERENCES

Aalbers, S., van den Boomen, R., & Blom, H. (2018). The use of natural cleaning agents in food processing: Environmental and operational benefits. Journal of Cleaner Production, 172, 3934–3942. https://doi.org/10.1016/j.jclepro.2017.04.076

Ahmad, I. (2025). Advances in Aquaculture Nutrition: Nanotechnology, Sustainable Feed Innovations and Precision Feeding Strategies. ISBN: 9789358872385

Ahmed, R., Talmoudi, A., & Dammak, A. (2022). Smart water management in the food industry: A review of IoT-enabled monitoring and optimization. Journal of Industrial Information Integration, 28, 100297. https://doi.org/10.1016/j.jii.2022.100297

Akpoilih, B. U. (2023). Microbial-Based Systems and Single-Cell Ingredients: Exploring Their Role in Sustainable Aquaculture Production. In Emerging Sustainable Aquaculture Innovations in Africa (pp. 209-249). Springer. https://doi.org/10.1007/978-981-19-7451_9_9.

Akter, S., Haque, M. A., Sarker, M. A.-A., Atique, U., Iqbal, S., Sarker, P. K., Paray, B. A., Arai, T., & Hossain, M. B. (2024). Efficacy of using plant ingredients as partial substitute of fishmeal in formulated diet for a commercially cultured fish, Labeo rohita. Frontiers in Sustainable Food Systems, 8, 1376112. https://doi.org/10.3389/fsufs.2024.1376112.

Alam, M. M., Jørgensen, N. O., Bass, D., Santi, M., Nielsen, M., Rahman, M. A., Hasan, N. A., Bablee, A. L., Bashar, A., & Hossain, M. I. (2024). Potential of integrated multitrophic aquaculture to make prawn farming sustainable in Bangladesh. Frontiers in Sustainable Food Systems, 8, 1412919. https://doi.org/10.3389/fsufs.2024.1412919.

Al khraisat, A. (2023). Eco-Friendly Practices in Fish Farming: Reducing the Environmental Footprint. Livestock Research Directorate. National Agricultural Research Center. Jordan.

Anonym. (2025). sciencedirect.com; https://shapiroe.com/blog/fish-waste-management/

Asche, F., Guttormsen, A. G., & Tveteras, R. (2014). Future trends in aquaculture: Productivity growth and increased production. Marine Resource Economics, 24(4), 403–424.

Auzins, A., Leimane, I., Reissaar, R., Brobakk, J., Sakelaite, I., Grivins, M., & Zihare, L. (2024). Assessing the socio-economic benefits and costs of insect meal as a fishmeal substitute in livestock and aquaculture. Animals, 14(10), 1461. https://doi.org/10.3390/ani14101461.

Bachtiar, M. I., Hidayat, R., & Anantama, R. (2022). Internet of Things (IoT) based aquaculture monitoring system. In MATEC Web of Conferences (Vol. 372, p. 04009). EDP Sciences.

Badiola, M., Mendiola, D., & Bostock, J. (2012). Recirculating aquaculture systems (RAS) analysis: Main issues on management and future challenges. Aquacultural Engineering, 51, 26–35. https://doi.org/10.1016/j.aquaeng.2012.07.004

Bailone, R. L., Borra, R. C., Fukushima, H. C. S., & Aguiar, L. K. (2022). Water reuse in the food industry. Discover Food, 2(1), 5.

Belton, B., Reardon, T., & Zilberman, D. (2020). Sustainable commoditization of seafood. Nature Sustainability, 3(9), 677–684.

Bostock, J., McAndrew, B., Richards, R., Jauncey, K., Telfer, T., Lorenzen, K., ... & Corner, R. (2010). Aquaculture: global status and trends. Philosophical Transactions of the Royal

Society B: Biological Sciences, 365(1554), 2897–2912. https://doi.org/10.1098/rstb.2010.0170

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

Buchmann, C., Lewandowski, I., & Huppenbauer, C. (2022). Circular economy strategies in fish processing: Integration with energy and food systems. Resources, Conservation and Recycling, 180, 106194. https://doi.org/10.1016/j.resconrec.2022.106194

Cao, J., Liu, J., Liu, X., Zeng, C., Hu, H., & Luo, Y. (2025). A Review of Marine Renewable Energy Utilization Technology and Its Integration with Aquaculture. Energies, 18(9), 2343.

Chen, Y., Zhang, X., & Yang, M. (2019). Closed-loop water recycling systems in fish processing industries. Water Research, 150, 55–67. https://doi.org/10.1016/j.watres.2018.11.063

Choudhury, A., Lepine, C., Witarsa, F., & Good, C. (2022). Anaerobic digestion challenges and resource recovery opportunities from land-based aquaculture waste and seafood processing byproducts: A review. Bioresource Technology, 354, 127144.

Coppola, D., Lauritano, C., Palma Esposito, F., Riccio, G., Rizzo, C., & de Pascale, D. (2021). Fish waste: From problem to valuable resource. Marine Drugs, 19(2), 116.

Cortes, J.R., Benitez, I., Baldoza, B., Pardillo, C., Auxtero, K., Badec, K., & Varela, D. (2025). Climate-smart aquaculture: Innovations and challenges in mitigating climate change impacts on fisheries and coastal agriculture. Aquaculture and Fisheries. https://doi.org/10.1016/j.aaf.2025.08.009

Costa-Pierce, B. A., Bartley, D., Hasan, M., Yusoff, F., Kaushik, S., Rana, K., Lemos, D., Bueno, P., & Yakupitiyage, A. (2010).

Responsible use of resources for sustainable aquaculture. Farming the waters for people and food. Proceedings of the Global Conference on Aquaculture, Roma, Italy.

Colt, J., Schuur, A. M., Weaver, D., & Semmens, K. (2022). Engineering design of aquaponics systems. Fisheries Science & Aquaculture, 30(1), 33-80. https://doi.org/10.1080/23308249.2021.1886240.

Crab, R., Defoirdt, T., Bossier, P., & Verstraete, W. (2012). Biofloc technology in aquaculture: Beneficial effects and future challenges. Aquaculture, 356–357, 351–356. https://doi.org/10.1016/j.aquaculture.2012.04.046

Demir, E., & Zengin, M. (2025). Changes in Feed and Feeding Practices in Aquaculture Due to Global Warming. Aquaculture for a Climate-Resilient Future. Edited by Anzelika Dautarte. ISBN 978-609-467-671-0. https://doi.org/10.7220/9786094676727

Devi, T. S., Ramesh, R., & Bhatt, R. R. (2016). HDPE lining in aquaculture ponds: A practical water-saving solution. Aquaculture Asia Magazine, 21(2), 22–25.

Diei-Ouadi, Y., Mgawe, Y., Savage, J., & Kefi, A. S. (2015). Achieving the global food agenda: Reducing post-harvest losses in fisheries. FAO Fisheries and Aquaculture Circular No. 1091. https://www.fao.org/3/i4545e/i4545e.pdf

Domènech, L., Gómez, J. A., & Oliver-Solà, J. (2021). Smart water technologies for sustainable food processing. Resources, Conservation and Recycling, 170, 105577. https://doi.org/10.1016/j.resconrec.2021.105577

Dutta, A., Ghosh, S., & Roy, M. (2020). Development of solar biomass hybrid fish drying systems. Renewable Energy, 151, 1098–1107. https://doi.org/10.1016/j.renene.2020.01.118

Dymoke, K. (2022). Basic Neurocellular Patterns: Exploring Developmental Movement, Bonnie Bainbridge Cohen (2018). Journal of Dance & Somatic Practices, 14(2).

Elegbede, I. O., Al Jufaili, S. M., Jolaosho, T. L., Tesleem, B., Adekunle, A. F., Modupe, O. O., & Halimat, A. A. (2025). Health-related dimensions of fishers for sustainable commercial fisheries in the Atlantic Gulf of Guinea: Ecological and social assessments. One Health, 20, 100972. https://doi.org/10.1016/j.onehlt.2025.100972

Elric, J. (2025). Innovative Approaches in Sustainable Aquaculture Practices. Journal of Aquaculture Research & Development, 16, 956. DOI: 10.35248/2155-9546.25.16.956

European Commission. (2021). EU Water Framework Directive (2000/60/EC). https://ec.europa.eu/environment/water/water-framework/index_en.html

European Commission. (2025). Research and innovation for sustainable, climate resilient aquaculture and fisheries. CORDIS Results Pack on food from aquatic ecosystems. Publications Office of the European Union. ISBN 978-92-78-44809-7.

European Parliament & Council. (2008). Marine Strategy Framework Directive (2008/56/EC).

FAO. (2016). Energy-smart food for people and climate: Issue paper. Food and Agriculture Organization of the United Nations. https://www.fao.org/3/i5125e/i5125e.pdf

FAO. (2020). The State of World Fisheries and Aquaculture 2020: Sustainability in action. Food and Agriculture Organization of the United Nations. https://doi.org/10.4060/ca9229en

FAO. (2022). The State of World Fisheries and Aquaculture 2022: Towards Blue Transformation. Food and Agriculture

Organization of the United Nations. https://www.fao.org/publications/sofia/2022

Fantatto, R.R., Guilgur, L.G., Mota, J., Ligeiro, J., Santos, M., & Murta, D. (2024). Exploring sustainable alternatives in aquaculture feeding: The role of insects. Aquaculture Reports, 37, 102228. https://doi.org/10.1016/j.aqrep.2024.102228

Fernández-Segovia, I., Escriche, I., Martínez, A., & Fuentes, A. (2011). Effect of different preservation treatments on quality attributes of chilled cuttlefish. LWT - Food Science and Technology, 44(5), 1153–1160. https://doi.org/10.1016/j.lwt.2010.10.002

Fry, J. P., Scroggins, R. E., Garlock, T. M., Love, D. C., Asche, F., Brown, M. T., ... & Neff, R. A. (2024). Application of the food-energy-water nexus to six seafood supply chains: hearing from wild and farmed seafood supply chain actors in the United States, Norway, and Vietnam. Frontiers in Sustainable Food Systems, 7, 1269026.

Fu, J., He, Y., & Cheng, F. (2024). Intelligent cutting in fish processing: efficient, high-quality, and safe production of fish products. Food and Bioprocess Technology, 17(4), 828-849.

Galkanda-Arachchige, H. S. C., Rajapaksha, R. P. V. J., Vithanage, M., & Sarmah, A. K. (2020). Single cell protein: A sustainable protein source for the future aquaculture industry. Aquaculture Reports, 17, 100372. https://doi.org/10.1016/j.aqrep.2020.100372

Garcia-Launay, F., Dusart, L., Espagnol, S., Laisse-Redoux, S., Gaudre, D., & Meda, B., Wilfart, A. (2018). Multiobjective formulation is an effective method to reduce environmental

impacts of livestock feeds. British Journal of Nutrition, 120, 1298-1309. https://doi.org/10.1017/s0007114518002672.

Gasco, L., Finke, M., & Van Huis, A. (2020). Can diets containing insect meal have a positive effect on fish welfare? A review. Aquaculture, 512, 734258. https://doi.org/10.1016/j.aquaculture.2019.734258

Global GAP. (2022). Aquaculture certification: Good Agricultural Practices (GAP). https://www.globalgap.org/uk_en/for-producers/globalg.a.p.-certification/aquaculture/

Grzegorzek, M., Wartalska, K., & Kowalik, R. (2024). Occurrence and sources of hormones in water resources—Environmental and health impact. Environmental Science and Pollution Research, 31(26), 37907-37922. https://doi.org/10.1007/s11356-024-33713-z.

Han, Y.-K., Xu, Y.-C., Luo, Z., Zhao, T., Zheng, H., & Tan, X.-Y. (2022). Fish meal replacement by mixed plant protein in the diets for juvenile yellow catfish Pelteobagrus fulvidraco: effects on growth performance and health status. Aquaculture Nutrition, 2022(1), 2677885. https://doi.org/10.1155/2022/2677885

Henry, M., Gasco, L., Piccolo, G., & Fountoulaki, E. (2015). Review on the use of insects in the diet of farmed fish: Past and future. Animal Feed Science and Technology, 203, 1-22. https://doi.org/10.1016/j.anifeedsci.2015.03.001

Hoang, T. D., Le, H. P., & Nguyen, M. A. (2021). Membrane bioreactors for water reuse in fish processing: Case study in Vietnam. Journal of Environmental Management, 287, 112311. https://doi.org/10.1016/j.jenvman.2021.112311

Hoekstra, A. Y., Chapagain, A. K., Aldaya, M. M., & Mekonnen, M. M. (2011). The water footprint assessment manual: Setting the global standard. Earthscan.

Hossain, A., Senff, P., & Glaser, M. (2022). Lessons for coastal applications of IMTA as a way towards sustainable development: A review. Applied Sciences, 12(23), 11920. https://doi.org/10.3390/app122311920.

Hungevu, R., Ademola, T., Yinusa, S., Titiloye, T.A., Lasisi, R., & Okunola, M. (2025). The impact of low-cost technological innovations on sustainable fisheries for economic development in developing countries. World Journal of Advanced Research and Reviews, 25(02), 1170-1184. https://doi.org/10.30574/wjarr.2025.25.2.0463

Hussain, S. M., Bano, A. A., Ali, S., Rizwan, M., Adrees, M., Zahoor, A. F., Sarker, P. K., Hussain, M., Arsalan, M. Z.-u.-H., & Yong, J. W. H. (2024). Substitution of fishmeal: Highlights of potential plant protein sources for aquaculture sustainability. Heliyon, 10(4), e26573. https://doi.org/10.1016/j.heliyon.2024.e26573.

IRENA. (2015). Renewable energy in the water, energy and food nexus. International Renewable Energy Agency. https://www.irena.org/publications

Jacquet, J., & Pauly, D. (2007). The rise of seafood awareness campaigns in an era of collapsing fisheries. Marine Policy, 31(3), 308–313. https://doi.org/10.1016/j.marpol.2006.09.003

Jayandan, S., Prathibanandhi, K., Sahana, A., Agilesh, M., & Chethan, K. (2024). Smart Systems for Sustainable Aquaculture: A Focus on Water Quality. International Conference on Power, Energy, Control and Transmission Systems (ICPECTS). https://doi.org/10.1109/ICPECTS62210.2024.10780341.

Jena, A.K., Biswas, P., & Saha, H. (2017). Advanced Farming Systems In Aquaculture: Strategies to Enhance the Production. Innovative Farming, 1(1), 84-89.

Jeyasanta, K. I., Patterson, J., & Kingsley, H. J. (2019). Innovations in dry fish processing to reduce water use. Indian Journal of Fisheries, 66(3), 13–21.

Kathuria, S., Rawat, P., Kumar, G. R., Singh, B., & Taneja, A. (2024). Amalgamation of Technologies for Smart Monitoring of Sustainable Aquaculture. 2023 International Conference on Smart Devices (ICSD), Dehradun, India. https://doi.org/10.1109/ICSD60021.2024.10751351.

Kibria, G., Nugegoda, D., & Haroon, Y. (2017). Sustainability of aquaculture in Asia with special reference to polyculture. Asian Journal of Water, Environment and Pollution, 14(4), 45–53. https://doi.org/10.3233/AJW170006

Kumar, G., Solomon, J., Priyadharshini, Raman, S., Behere, G.S., Misra, T., & Bhautik, S. (2025). Advanced technologies for effluent water treatment in aquaculture: Advancing environmental sustainability and pollution mitigation. In Aquaculture Reimagined: Modern Approaches to Sustainable Fish Farming (pp. 152-162). Biotica Publications. https://doi.org/10.54083/978-81-980121-3-5_12.

Kurniasih, S. D., Soesilo, T. E. B., & Soemantojo, R. W. (2018). Water resources management at the fish processing industry using waste minimization approach. E3S Web of Conferences, 74, 06004.

Lal, J., Vaishnav, A., Kumar, D., Jana, A., Jayaswal, R., Chakraborty, A., Kumar, S., Devati, Pavankalyan, M., & Sahil. (2024). Emerging Innovations in Aquaculture: Navigating towards Sustainable Solutions. International Journal of Environment

and Climate Change, 14(7), 83-96. https://doi.org/10.9734/ijecc/2024/v14i74254.

Lin, X.X., Nieder, A., & Jacob, S.N. (2018). The neurocellular implementation of representational geometry in primate prefrontal cortex. bioRxiv.

Lindberg, M., & Espejo-Hermes, J. (2015). GMP and HACCP for water use reduction in fish processing. Aquaculture International, 23(3), 553–565.

Liu, G., Verdegem, M., Ye, Z., Zhao, J., Xiao, J., Liu, X., Liang, Q., Xiang, K., & Zhu, S. (2025). Advancing Aquaculture Sustainability: A Comprehensive Review of Biofloc Technology Trends, Innovative Research Approaches, and Future Prospects. Reviews in Aquaculture, 17(1), e12970. https://doi.org/10.1111/raq.12970.

Ltaief, A. B., El-Boudy, T., Horchani-Naifer, K., & Mouelhi, M. (2025). Protein recovery from shrimp processing wastewater using ultrafiltration-diafiltration: A circular economy approach. Foods, 14(12), 2044.

Lubchenco, J., & Grorud-Colvert, K. (2015). Making waves: The science and politics of ocean protection. Science, 350(6259), 382–383. https://doi.org/10.1126/science.aad5443

Lucchetti, A., Melli, V., & Brčić, J. (2023). Editorial: Innovations in fishing technology aimed at achieving sustainable fishing. Frontiers in Marine Science, 10, 1310318. https://doi.org/10.3389/fmars.2023.1310318

Luo, Y., Zhang, M., Yu, Q., Mujumdar, A. S., & Rui, L. (2025). Intelligent control for improving the quality of fresh meat products with rich lipid in cold chain logistics: research status, challenge, and potential applications. Critical Reviews in Food Science and Nutrition, 1-28.

Love, D. C., Fry, J. P., Milli, M. C., & Neff, R. A. (2015). Wasted seafood in the United States: Quantifying loss from production to consumption and moving toward solutions. Global Environmental Change, 35, 116–124.

Ma, M., & Hu, Q. (2024). Microalgae as feed sources and feed additives for sustainable aquaculture: prospects and challenges. Reviews in Aquaculture, 16(2), 818–835. https://doi.org/10.1111/raq.12869

Mackenzie, S.G., Leinonen, I., Ferguson, N., & Kyriazakis, I. (2016). Towards a methodology to formulate sustainable diets for livestock: accounting for environmental impact in diet formulation. British Journal of Nutrition, 115, 1860-1874. https://doi.org/10.1017/s0007114516000763.

Makkar, H. P. S., Tran, G., Heuzé, V., & Ankers, P. (2016). State-of-the-art on use of insects as animal feed. Animal Feed Science and Technology, 197, 1–33. https://doi.org/10.1016/j.anifeedsci.2014.07.008

Mansour, A.T. (2025). Challenges and innovative solutions in sustainable aquaculture: How can it contribute to food security and environmental protection. Animal Reports, 1, 1-13.

Martins, C. I. M., Eding, E. H., Verdegem, M. C. J., Heinsbroek, L. T. N., Schneider, O., Blancheton, J. P., ... & Verreth, J. A. J. (2010). New developments in recirculating aquaculture systems in Europe: A perspective on environmental sustainability. Aquacultural Engineering, 43(3), 83–93. https://doi.org/10.1016/j.aquaeng.2010.09.002

Martins, C. I. M., Eding, E. H., & Verreth, J. A. J. (2012). The effect of recirculating aquaculture systems on the welfare of rainbow trout. Aquacultural Engineering, 46(1), 1–7. https://doi.org/10.1016/j.aquaeng.2011.11.001

Martins, M., Ramos, A., & Quintas, C. (2017). Cascading water use strategies in fish processing plants. Water Science and Technology, 75(4), 1023–1031. https://doi.org/10.2166/wst.2016.562

Matassa, S., Papirio, S., Pikaar, I., Hülsen, T., Leijenhorst, E., Esposito, G., ... & Verstraete, W. (2020). Upcycling of biowaste carbon and nutrients in line with consumer confidence: the “full gas” route to single cell protein. Green Chemistry, 22(15), 4912–4929. https://doi.org/10.1039/D0GC01382J

Mekonnen, M. M., & Hoekstra, A. Y. (2012). A global assessment of the water footprint of farm animal products. Ecosystems, 15(3), 401–415. https://doi.org/10.1007/s10021-011-9517-8

Mills, E., Gengnagel, T., & Wollburg, P. (2014). Solar-LED alternatives to fuel-based lighting for night fishing. Energy for Sustainable Development, 21, 30–41. https://doi.org/10.1016/j.esd.2014.04.006

MSC. (2021). Peruvian anchoveta fishery profile. https://www.msc.org

Mugwanya, M., Dawood, M. A., Kimera, F., & Sewilam, H. (2023). Replacement of fish meal with fermented plant proteins in the aquafeed industry: A systematic review and meta analysis. Reviews in Aquaculture, 15(1), 62-88. https://doi.org/10.1111/raq.12701.

Mungkung, R., Aubin, J., Prihadi, T. H., Slembrouck, J., van der Werf, H. M., & Legendre, M. (2013). Life cycle assessment for environmentally sustainable aquaculture management: A case study of combined aquaculture systems for carp and tilapia. Journal of Cleaner Production, 57, 249–256. https://doi.org/10.1016/j.jclepro.2013.06.024

Nagappan, S., Das, M., Thaher, M., Khan, S., Mahata, C., Aljabri, H., Vatland, AK., & Kumar, G. (2021). Potential of microalgae as a sustainable feed ingredient for aquaculture. Journal of Biotechnology, 341. https://doi.org/10.1016/j.jbiotec.2021.09.003.

Nasseri, S., Yaghmaeian, K., & Khorsandi, H. (2020). Anaerobic digestion for fish processing wastewater treatment and biogas recovery. Environmental Technology & Innovation, 20, 101156. https://doi.org/10.1016/j.eti.2020.101156

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. https://doi.org/10.1038/s41586-021-03308-6

Nguyen, T.T.H., Bouvarel, I., Ponchant, P., & van der Werf, H.M.G. (2012). Using environmental constraints to formulate low-impact poultry feeds. Journal of Cleaner Production, 28, 215-224. https://doi.org/10.1016/j.jclepro.2011.06.029.

Obirikorang, K.A., Quagrainie, K., Kassah, J.E., & Von Ahnen, M. (2024). Editorial: Sustainable aquaculture production for improved food security. Frontiers in Sustainable Food Systems, 8, 1485956. https://doi.org/10.3389/fsufs.2024.1485956

Ohia, C. (2025). Aquaculture Technologies and Practices: Balancing Innovation, Environment and Economy for Sustainability. In Food Security, Nutrition and Sustainability Through Aquaculture Technologies (pp. 417-424). Springer. https://doi.org/10.1007/978-3-031-75830-0_23.

Pahlow, M., Van Oel, P. R., Mekonnen, M. M., & Hoekstra, A. Y. (2015). Increasing pressure on freshwater resources due to terrestrial feed ingredients for aquaculture production.

Science of the Total Environment, 536, 847–857. https://doi.org/10.1016/j.scitotenv.2015.07.124

Papacharalampopoulos, A., & Stavropoulos, P. (2019). A digital twin-based approach for smart manufacturing: Simulation and optimization of fish processing operations. Procedia Manufacturing, 28, 515–520. https://doi.org/10.1016/j.promfg.2019.11.072

Parker, R., & Tyedmers, P. (2014). Fuel consumption of global fishing fleets: Current understanding and knowledge gaps. Fish and Fisheries, 16. https://doi.org/10.1111/faf.12087.

Pauly, D., Christensen, V., Guénette, S., Pitcher, T.J., Sumaila, U.R., Walters, C.J., Watson, R., & Zeller, D. (2002). Toward sustainability in world fisheries. Nature, 418, 689-695.

Pérez-Gálvez, R., Moral, A., & Fidalgo, L. (2019). Membrane technologies for water reuse in seafood processing plants: Towards zero discharge. Journal of Environmental Management, 240, 263–272. https://doi.org/10.1016/j.jenvman.2019.03.094

Pikitch, E. K., Santora, C., Babcock, E. A., Bakun, A., Bonfil, R., Conover, D. O., ... & Sainsbury, K. J. (2004). Ecosystem-based fishery management. Science, 305(5682), 346–347. https://doi.org/10.1126/science.1098222

Piroddi, C., Coll, M., Steenbeek, J., Moy, D. M., & Christensen, V. (2021). Modelling the Mediterranean marine ecosystem to support fisheries management: Current achievements and future directions. Ecological Modelling, 442, 109437.

Rahman, M. H., Hossain, M. M., & Ahmed, S. (2020). Rainwater harvesting in aquaculture: Experience from smallholder farms in Bangladesh. Aquaculture Reports, 18, 100489. https://doi.org/10.1016/j.aqrep.2020.100489

Richards, T., Jensen, O., & Olesen, P. (2017). Eco-labeling and consumer behavior: The case of sustainable seafood. Marine Policy, 76, 110–117. https://doi.org/10.1016/j.marpol.2016.11.010

Roberts, C. M., Bohnsack, J. A., Gell, F., Hawkins, J. P., & Goodridge, R. (2001). Effects of marine reserves on adjacent fisheries. Science, 294(5548), 1920–1923. https://doi.org/10.1126/science.1060281

Roberts, C., Béné, C., Bennett, N., Boon, J.S., Cheung, W.W.L., Cury, F., Defeo, O., ... & O'Leary, B.C. (2024). Rethinking sustainability of marine fisheries for a fast-changing planet. Ocean Sustainability, 3(41), 1-11. https://doi.org/10.1038/s44183-024-00078-2

Rosa, R., Fernandes, J. M. O., & Guerreiro, P. M. (2021). Artificial intelligence and machine learning in aquaculture: A review. Aquaculture Reports, 21, 100876. https://doi.org/10.1016/j.aqrep.2021.100876

Rowan, N.J. (2023). The role of digital technologies in supporting and improving fishery and aquaculture across the supply chain – Quo Vadis? Aquaculture and Fisheries, 8, 365–374. https://doi.org/10.1016/j.aaf.2022.06.003

Rusco, G., Roncarati, A., Di Iorio, M., Cariglia, M., Longo, C., & Iaffaldano, N. (2024). Can IMTA System improve the productivity and quality traits of aquatic organisms produced at different trophic levels? The benefits of IMTA—Not only for the ecosystem. Biology, 13(11), 946. https://doi.org/10.3390/biology13110946.

Sala, S., Bianchi, A., Bligny, J.C., Bouraoui, F., Castellani, V., De Camillis, C., Mubareka, S., Vandecasteele, I., & Wolf, M.A. (2013). Water footprint in the context of sustainability

assessment. European Commission, Joint Research Centre. EUR 25781EN

Sapkota, S., Ahmed, M., & Mikalsen, R. (2022). Smart flow control in water use for seafood processing. Sustainability, 14(3), 1810. https://doi.org/10.3390/su14031810

Shafeena, T. (2016). Smart aquaponics system: Challenges and opportunities. European Journal of Advances in Engineering and Technology, 3(2), 52-55. https://doi.org/10.1016/j.egypro.2017.12.694

SINTEF. (2021). Reducing water footprint in Norwegian salmon processing. SINTEF Reports. https://www.sintef.no/

Simat, V. (2021). Valorization of seafood processing by-products. In Valorization of agri-food wastes and by-products (pp. 515-536). Academic Press.

Sukhdhane, K. S., Kripa, V., Divu, D., Vase, V. K., & Mojjada, S. K. (2018). Integrated multi-trophic aquaculture systems: A solution for sustainability. Aquaculture Asia, 22(4), 26-29.

Solomon, J., Kumar, G., Asgolkar, P., Veeramaruthu, B., & Varghese, T. (2025). Emerging Technologies and Innovations in Aquaculture Nutrition. In Aquaculture: Enhancing Food Security and Nutrition. Springer. https://doi.org/10.1007/978-3-031-92858-1_9

Smith, L. C., Chuenpagdee, R., & Sumaila, U. R. (2020). Evaluating hybrid-electric propulsion in marine capture fisheries. Marine Policy, 119, 104055. https://doi.org/10.1016/j.marpol.2020.104055

Symeonidou, S., & Mente, E. (2024). Water Consumption and the Water Footprint in Aquaculture: A Review. Water, 16, 3376. https://doi.org/10.3390/w16233376

Tlusty, M., Rhyne, A. L., Herrnkind, W., & Lotze, H. K. (2017). Marine aquaculture: Trends in water use and wastewater

generation. Water Research, 119, 139–150. https://doi.org/10.1016/j.watres.2017.04.005

Tran, N.L.D., Rañola, R.F., Ole Sander, B., et al. (2020). Determinants of adoption of climate-smart agriculture technologies in rice production in Vietnam. International Journal of Climate Change Strategies and Management, 12, 238–256. https://doi.org/10.1108/IJCCSM-01-2019-0003

Turan, K., Sönmez, H., Yildiz, H., & Aydın, I. (2019). Cleaner fish processing technologies: Water reuse, waste valorization and resource optimization. Journal of Cleaner Production, 234, 383–392. https://doi.org/10.1016/j.jclepro.2019.06.167

Turchini, G. M., Torstensen, B. E., & Ng, W. K. (2009). Fish oil replacement in finfish nutrition. Reviews in Aquaculture, 1(1), 10–57. https://doi.org/10.1111/j.1753-5131.2008.01003.x

Valente, C., Ferreira, V., & Correia, J. (2020). Lean tools for sustainable fish processing: Reducing water footprint and waste. Sustainability, 12(16), 6543. https://doi.org/10.3390/su12166543

Vázquez-Rowe, I., Villanueva-Rey, P., Moreira, M. T., & Feijoo, G. (2012). Environmental analysis of Galician fishing activities: A case study of the hake fishing fleet. Marine Policy, 36(1), 180–188. https://doi.org/10.1016/j.marpol.2011.05.005

Verdegem, M. C. J., & Bosma, R. H. (2009). Water withdrawal for brackish and inland aquaculture, and options to reduce water use. Water Policy, 11(S1), 52–68. https://doi.org/10.2166/wp.2009.003

Warwas, N. (2023). Novel Marine Ingredients for Aquaculture - Fish Nutrition, Physiology and Intestinal Health. Doctoral thesis, University of Gothenburg. ISBN 978-91-8069-513-8.

Wang, Y., Han, J., & Beynon-Davies, P. (2020). Understanding blockchain technology for future supply chains: A systematic literature review and research agenda. Supply Chain Management: An International Journal, 25(2), 124–146. https://doi.org/10.1108/SCM-03-2019-0096

Wilfart, A., Garcia-Launay, F., Terrier, F., Soude, E., Aguirre, P., & Skibba-Cassy, S. (2023). A step towards sustainable aquaculture: Multiobjective feed formulation reduces environmental impacts at feed and farm levels for rainbow trout. Aquaculture. https://doi.org/10.1016/j.aquaculture.2022.738826

Worm, B., Hilborn, R., Baum, J. K., Branch, T. A., Collie, J. S., Costello, C., ... & Zeller, D. (2009). Rebuilding global fisheries. Science, 325(5940), 578–585.

Wróbel, J., Gałczyńska, M., Tański, A., Korzelecka-Orkisz, A., & Formicki, K. (2023). The challenges of aquaculture in protecting the aquatic ecosystems in the context of climate changes. Journal of Water and Land Development, 57, 231–241. https://doi.org/10.24425/jwld.2023.145354.

WWF. (2022). Water-smart fisheries: Innovations to reduce water use in seafood production. World Wide Fund for Nature. https://www.worldwildlife.org

Xu, C. (2024). Innovations in Aquaculture Systems: Preparing for Sustainable Seafood Production. Fish and Aquaculture Journal, 15, 365. https://doi.org/10.35248/2150-3508.24.15.365

Yadav, N.K., Deepti, M., Patel, A.B., Kumar, P., Angom, J., Debbarma, S., Singh, S.K., Deb, S., Lal, J., & Vaishnav, A. (2025). Dissecting insects as sustainable protein bioresource in fish feed for aquaculture sustainability. Discover Food, 5, 47. https://doi.org/10.1007/s44187-025-00318-5

Yuan, Q., Song, G., Palmer, P.R., Wang, Y., Semakula, H.M., Mekonnen, M.M., & Zhang, S. (2017). Water footprint of feed required by farmed fish in China based on a Monte Carlo-supported von Bertalanffy growth model: A policy implication. Journal of Cleaner Production, 153(1), 41-50.

Yue, K., & Shen, Y. (2022). An overview of disruptive technologies for aquaculture. Aquaculture and Fisheries, 7, 111–120. https://doi.org/10.1016/j.aaf.2021.04.009

Zhang, D., Li, K., Zhao, Y., & Lv, X. (2016). Application of precision feeding techniques in aquaculture: A review. Aquaculture International, 24(6), 1441–1460. https://doi.org/10.1007/s10499-016-0005-4

Zhang, Y., Liu, C., & Zhao, H. (2021). Machine learning for water footprint prediction in seafood processing: A case study using artificial neural networks. Environmental Modelling & Software, 145, 105191. https://doi.org/10.1016/j.envsoft.2021.105191

Zhang, D. (2024). Aquaculture Innovations for Global Food Security. Poultry, Fisheries & Wildlife Sciences, 12, 288.

GLOSSARY AND ABBREVIATIONS

AI – Artificial Intelligence
Computer-based systems capable of analysing data, identifying patterns and supporting automated or predictive decisions. In fisheries and aquaculture, AI can help optimise feeding, monitor water quality and forecast water requirements.
Source: Papacharalampopoulos and Stavropoulos (2019).

Aquaculture
The farming of aquatic organisms, including fish, molluscs, crustaceans and aquatic plants, under controlled or semi-controlled conditions.
Source: FAO (2022).

Aquaponics
A production system that combines aquaculture with soilless plant cultivation. Nutrients from fish waste are used by plants, while treated water is recirculated to the aquatic system.
Source: FAO (2022).

BFT – Biofloc Technology
An aquaculture method in which microorganisms convert dissolved nutrients and nitrogenous waste into microbial biomass. This helps maintain water quality, reduces water exchange and may provide an additional food source for cultured species.
Source: Avnimelech (2009); Crab et al. (2012).

Blue Water Footprint
The volume of surface water and groundwater consumed during the production of a product or service. In fisheries and aquaculture, this may include water used for rearing, washing, cleaning, ice production and processing.
Source: Hoekstra et al. (2011).

Capture Fisheries
The harvesting of naturally occurring aquatic organisms from marine or inland waters, rather than their production through farming.
Source: FAO (2022).

Circular Economy
An approach that seeks to reduce waste and keep materials and resources in use for as long as possible through prevention, reuse, recycling, recovery and valorisation. In the seafood sector, this may include recovering proteins, oils, nutrients or energy from processing by-products and wastewater.
Source: FAO (2022).

Consumptive Water Use
Water withdrawn from a source that is not returned to the same catchment because it has evaporated, been incorporated into a product or become otherwise unavailable for immediate reuse.
Source: Hoekstra et al. (2011); Symeonidou and Mente (2024).

Digital Twin
A virtual representation of a physical system, process or facility that uses real or simulated data to test operating scenarios. In fish processing, it can help identify ways to reduce water consumption without compromising hygiene, quality or production capacity.
Source: Papacharalampopoulos and Stavropoulos (2019).

Direct Water Use
Water used directly during fishing, aquaculture or processing operations. Examples include water for fish rearing, cleaning equipment, washing catches, producing ice and maintaining hygiene.
Source: Symeonidou and Mente (2024).

Effluent
Liquid waste discharged from an aquaculture facility or fish-processing plant. It may contain organic matter, nutrients, suspended solids, cleaning products or other pollutants.
Source: Mungkung et al. (2013).

Eutrophication
The excessive enrichment of water with nutrients, particularly nitrogen and phosphorus. It can cause algal blooms, oxygen depletion and deterioration of aquatic ecosystems.
Source: Mungkung et al. (2013).

FCR – Feed Conversion Ratio
A measure of feed efficiency expressed as the amount of feed required to produce a given amount of animal biomass. A lower FCR generally indicates more efficient feed use and may reduce the indirect water footprint associated with feed production.
Source: Pahlow et al. (2015).

Green Water Footprint
The volume of rainwater stored in the soil and used during production. In aquaculture, it is mainly associated with the agricultural crops used to manufacture fish feed.
Source: Hoekstra et al. (2011); Pahlow et al. (2015).

Grey Water Footprint
An indicator of water pollution expressed as the volume of freshwater required to assimilate a pollutant load while meeting

applicable water-quality standards.
Source: Hoekstra et al. (2011).

IMTA – Integrated Multi-Trophic Aquaculture
An aquaculture system in which species from different trophic levels are cultivated together. Waste or nutrients generated by one species are used as resources by others, such as shellfish or seaweed.
Source: Chopin et al. (2001).

Indirect Water Use
Freshwater consumed outside the immediate fishing, aquaculture or processing operation but embedded in the production of inputs such as feed, fuel, energy, vessels, equipment, packaging and infrastructure.
Source: Hoekstra et al. (2011).

IoT – Internet of Things
A network of connected sensors and devices that collect and exchange data. In aquaculture and fish processing, IoT systems can monitor water flow, temperature, dissolved oxygen, pH and other parameters in real time.
Source: Ebeling and Timmons (2010).

LCA – Life Cycle Assessment
A method for evaluating the environmental impacts associated with the different stages of a product, process or system, from the extraction of raw materials to production, use and end-of-life management.
Source: Bohnes et al. (2019).

Non-Consumptive Water Use
Water that is withdrawn and used temporarily before being returned to the environment without a substantial reduction in quantity,

although its quality or temperature may have changed.
Source: FAO (2024).

Precision Feeding
The use of data, monitoring and automated technologies to provide the appropriate quantity and composition of feed at the right time. It can improve feed efficiency and reduce nutrient waste and the indirect water footprint of aquaculture.
Source: Pahlow et al. (2015).

RAS – Recirculating Aquaculture System
A land-based aquaculture system in which water is treated and reused through mechanical, biological or chemical filtration. RAS can significantly reduce water withdrawal and wastewater discharge compared with flow-through systems.
Source: Badiola et al. (2012); Martins et al. (2010).

Virtual Water
The freshwater used throughout the production of a product or service and embedded in it through its supply chain. In fisheries and aquaculture, it includes water used to produce feed, energy, equipment, vessels and packaging.
Source: Hoekstra (2002); Hoekstra et al. (2011).

Wastewater Treatment
The application of physical, chemical or biological processes to remove pollutants from used water before its discharge or reuse.
Source: Mungkung et al. (2013).

Water Footprint
An indicator of freshwater use that accounts for both direct and indirect water consumption and pollution across the value chain of a product, process, organisation or activity.
Source: Hoekstra et al. (2011).

Water Reuse
The use of treated wastewater or process water for another purpose instead of discharging it after a single use. In aquaculture and fish processing, reused water may support cleaning, cooling or production processes when hygiene and quality requirements are met.
Source: Badiola et al. (2012).

Water Scarcity
A situation in which available freshwater resources are insufficient to meet demand, or where access is constrained by water quality, infrastructure, environmental requirements or economic conditions.
Source: FAO (2022); Hoekstra et al. (2011).

Water Stewardship
The responsible and collaborative management of water resources to achieve environmentally sustainable, socially equitable and economically beneficial outcomes. In fisheries and aquaculture, it includes monitoring water use, protecting water sources and managing wastewater responsibly.
Source: GlobalG.A.P. (2022).

References

Avnimelech, Y. (2009). Biofloc technology: A practical guide book. World Aquaculture Society.

Badiola, M., Mendiola, D., & Bostock, J. (2012). Recirculating aquaculture systems analysis: Main issues on management and future challenges. *Aquacultural Engineering, 51*, 26–35. https://doi.org/10.1016/j.aquaeng.2012.07.004

Bohnes, F. A., Hauschild, M. Z., & Schluep, M. (2019). Life cycle assessment of aquaculture systems: A critical review. *Reviews in Aquaculture, 11*(4), 1061–1079.

Chopin, T., Buschmann, A. H., Halling, C., Troell, M., Kautsky, N., Neori, A., Kraemer, G. P., Zertuche-González, J. A., Yarish, C., & Neefus, C. (2001). Integrating seaweeds into marine aquaculture systems: A key toward sustainability. *Journal of Phycology, 37*(6), 975–986.

Crab, R., Defoirdt, T., Bossier, P., & Verstraete, W. (2012). Biofloc technology in aquaculture: Beneficial effects and future challenges. *Aquaculture, 356–357*, 351–356. https://doi.org/10.1016/j.aquaculture.2012.04.046

Ebeling, J. M., & Timmons, M. B. (2010). *Recirculating aquaculture*. Cayuga Aqua Ventures.

Food and Agriculture Organization of the United Nations. (2022). *The State of World Fisheries and Aquaculture 2022: Towards Blue Transformation*. https://www.fao.org/publications/sofia/2022

Food and Agriculture Organization of the United Nations. (2024). *The State of World Fisheries and Aquaculture 2024: Blue Transformation in Action*.

GlobalG.A.P. (2022). *Aquaculture certification: Good Agricultural Practices*. https://www.globalgap.org/uk_en/for-producers/globalg.a.p.- certification/aquaculture/

Hoekstra, A. Y. (2002). *Virtual water trade: Proceedings of the International Expert Meeting on Virtual Water Trade*. UNESCO-IHE.

Hoekstra, A. Y., Chapagain, A. K., Aldaya, M. M., & Mekonnen, M. M. (2011). *The water footprint assessment manual: Setting the global standard*. Earthscan.

Martins, C. I. M., Eding, E. H., Verdegem, M. C. J., Heinsbroek, L. T. N., Schneider, O., Blancheton, J. P., … Verreth, J. A. J. (2010). New developments in recirculating aquaculture systems in Europe: A perspective on environmental sustainability. *Aquacultural Engineering, 43*(3), 83–93. https://doi.org/10.1016/j.aquaeng.2010.09.002

Mungkung, R., Aubin, J., Prihadi, T. H., Slembrouck, J., van der Werf, H. M. G., & Legendre, M. (2013). Life cycle assessment for environmentally sustainable aquaculture management: A case study of combined aquaculture systems for carp and tilapia. *Journal of Cleaner Production, 57*, 249–256. https://doi.org/10.1016/j.jclepro.2013.06.024

Pahlow, M., van Oel, P. R., Mekonnen, M. M., & Hoekstra, A. Y. (2015). Increasing pressure on freshwater resources due to terrestrial feed ingredients for aquaculture production. *Science of the Total Environment, 536*, 847–857. https://doi.org/10.1016/j.scitotenv.2015.07.124

Papacharalampopoulos, A., & Stavropoulos, P. (2019). A digital twin-based approach for smart manufacturing: Simulation and optimization of fish processing operations. *Procedia*

Manufacturing, 28, 515–520. https://doi.org/10.1016/j.promfg.2019.11.072

Symeonidou, S., & Mente, E. (2024). Water consumption and the water footprint in aquaculture: A review. *Water, 16*(23), 3376. https://doi.org/10.3390/w16233376