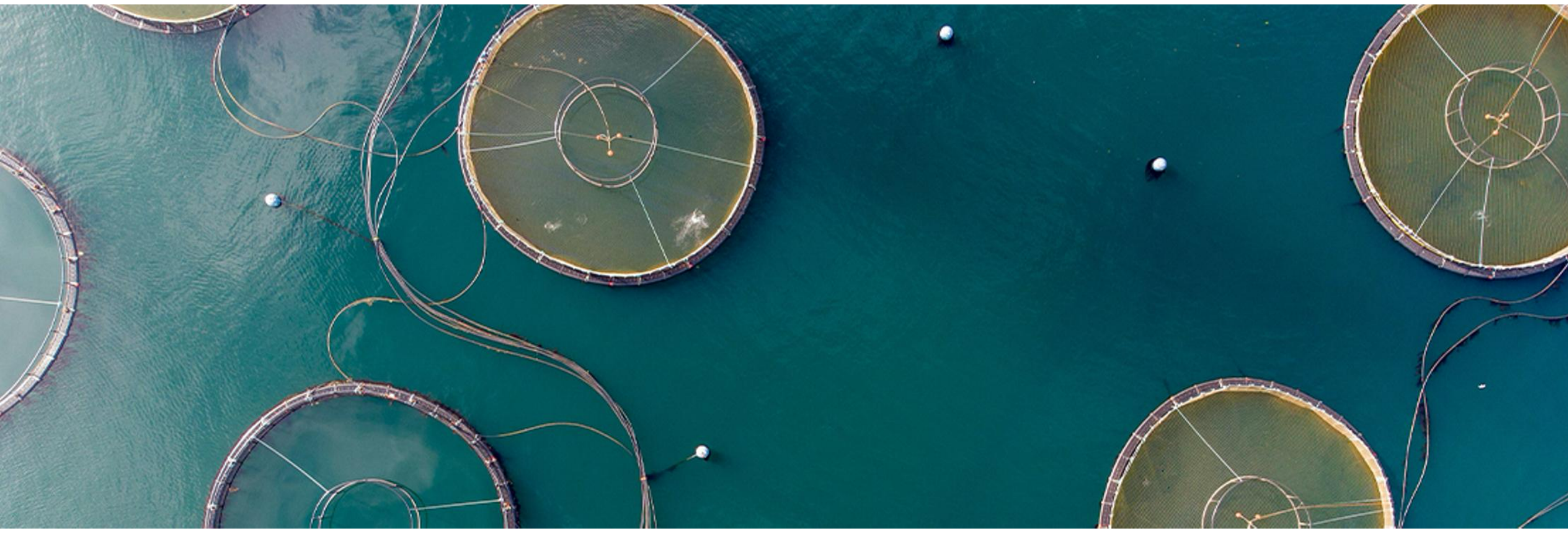

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Guide with circular aquaculture business practices and opportunities

TRANSITIONING TO CIRCULAR AQUACULTURE

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Abbreviations

ABPs	Animal by-products
ASC	Aquaculture stewardship council
BFT	Biofloc Technology
C-AZA	Allocated Zones for Circular Aquaculture
CAGR	Compound annual growth rate
CAPEX	Capital expenditure
CF	Carbon footprint
EIA	Environmental impact assessments
EF	Environmental footprint
EMFAF	European Maritime, Fisheries and Aquaculture Fund
ESG	Environmental, Social, and Governance
FCRs	Food conversion rates
FS	Fed species
GES	Good environmental status
IES	Inorganic extractive species
IMRAS	IMTA coupled to RAS
IMTA	Multi-trophic aquaculture
LCA	Life cycle assessment
MSP	Maritime spatial planning
OEF	Organisation environmental footprint
OES	Organic extractive species
PEF	Product environmental footprint
PEFCR	Product environmental footprint category rules
PPs	Project partners
PUFAs	Polyunsaturated fatty acids
RAS	Recirculating aquaculture systems
SMEs	Small and medium-sized enterprises

USD US dollar

WF Water footprint

Executive Summary

This guide provides a comprehensive framework to support the transition of the European aquaculture sector toward circular, resource-efficient, and environmentally sustainable production models. Developed for application across eight participating territories, it combines scientific knowledge, regulatory analysis, business practices, and market perspectives into a practical reference for policymakers, aquaculture operators, investors, and new entrepreneurs.

The introduction sets the context by outlining the **current state of aquaculture worldwide and Europe**, highlighting its strategic importance for food security, coastal economies, and the Blue Economy. A general overview of the aquaculture sector and priorities by country was shown emphasizing why circular aquaculture is essential to address structural challenges such as resource inefficiency, environmental pressures, regulatory complexity, and market volatility. The **key five principles** that govern transition toward circular aquaculture are introduced as the foundation of the guide.

The second section builds a shared understanding of circular aquaculture by defining core concepts and describing the paradigm shift from linear to circular production systems. It details the **main circular production models** currently available, including Integrated Multi-Trophic Aquaculture (IMTA), Recirculating Aquaculture Systems (RAS), Biofloc Technology (BFT), and aquaponics. These models are analysed in terms of technological requirements, environmental performance, and scalability. The section also reviews the regional and national regulatory frameworks that enable or constrain circular aquaculture as well as sustainability and environmental considerations such as water use, nutrient management, biodiversity, and climate resilience.

Section three focuses on practice and implementation, presenting successful circular aquaculture business models, case studies, and examples of eco-design, eco-innovation, and industrial symbiosis. It demonstrates how circular principles can be translated into viable **circular production models** indicating case studies in different environments under different approaches and business models. Moreover, associated business to valorisation of aquaculture biomass after reuse and recycles of wastewater and by-products as well as **downstream biorefinery and bioeconomy applications** are shown. As horizontal element for competitive aquaculture solutions based on **eco-design and eco-innovation** are presented. The potential of industrial symbiosis to sustain circular aquaculture ecosystem is discussed.

Section four **provides practical guidelines for transitioning to circular aquaculture**, tailored separately for existing businesses and new entrepreneurs. It outlines step-by-step approaches to system redesign, technology adoption,

business planning, partnership building, and performance monitoring, supporting both incremental transitions and novel circular projects.

Section five explores **emerging business opportunities** linked to circular aquaculture, identifying market gaps, high-potential value chains, and demand trends. It reviews **funding and financing instruments**, with particular emphasis on the European Maritime, Fisheries and Aquaculture Fund (EMFAF), as well as complementary public and private financing options, mentoring schemes, and training programmes.

Section six addresses the **main challenges** hindering circular aquaculture adoption, economic, environmental, technical, market, regulatory, and social, and presents practical, evidence-based solutions to overcome them. The guide concludes by identifying remaining **gaps and future directions**, and by issuing a clear call to action for coordinated efforts among industry, policymakers, researchers, and financiers to scale up circular aquaculture across Europe.

1. Introduction

1.1 Purpose of the Guide

This guide has been designed to **facilitate an inclusive transition and promote the development of circular aquaculture business** across the eight territories participating in the AZA4ICE project. The methodological approach developed for the preparation of these guidelines was based on desktop research, partner contribution and sectorial interviews during LiRRIE events in each territory for a transition towards more circular and sustainable models. All project partners (PPs) have participated in the preparation of these guidelines through established business networks and platforms, ensuring the reliability, quality, and traceability of the information and data provided.

The final document aims to serve as a **practical and strategic resource** to support existing and new aquaculture enterprises **in adopting circular approaches** while also stimulating the **creation of new circular business initiatives**. The guide will include:

- Identification of robust circular aquaculture practices and main principles
- Documented successful practices and models of circular aquaculture businesses
- Identification of market opportunities and existing gaps
- Information on available funding and financing mechanisms
- Access to mentoring and support services for business development

1.2 Overview of Aquaculture in Europe

Aquaculture is rapidly growing worldwide becoming an essential activity for food security, socio-economic resilience and sustainable blue growth. According to *The State of World Fisheries and Aquaculture 2024* – Blue *Transformation in Action* (FAO 2024), total fisheries and aquaculture production reached an unprecedented 223.2 million tonnes (Tn) in 2022, of which 185.4 million Tn corresponded to aquatic animals and 37.8 million Tn to algae.

Aquaculture achieved a record production of **130.9 million tonnes**, accounting for 59% of total aquatic output. For the first time, **aquaculture output surpassed that of capture fisheries** in terms of aquatic animal production, contributing 51% of the global total and 57% of all aquatic foods intended for human consumption.

This expansion of aquaculture occurs at a moment when the **global demand for nutrient-rich aquatic foods is accelerating faster than population growth**. In

2022, **89% of aquatic animal production** was consumed directly as **food**, corresponding to **20.7 kg per capita**. Aquatic foods provided **15% of animal-derived proteins and 6% of total proteins worldwide**, as well as essential micronutrients such as omega-3 fatty acids, minerals and vitamins. These figures reinforce the role of aquaculture as a strategic component in diversifying diets ad supporting food security in low- and middle-income regions.

Aquaculture in Europe represents a **strategic pillar of the EU Blue Economy**, supplying high-quality aquatic proteins while contributing to rural and coastal communities, food security and value-chain diversification. **The sector is highly diverse** (**Supplementary Table** and **Figure 1**), influenced by geography, range of species and regulatory measures. Marine finfish and mollusc production is predominantly concentrated in the Mediterranean and Atlantic regions, whereas northern and eastern European countries continue to maintain robust freshwater aquaculture practices. Although **overall production within the EU has plateaued** and competition from non-EU exporters (particularly Turkey in seabass and seabream) has intensified, Europe retains leading expertise in hatchery technologies, selective breeding, animal welfare regulation, and certification standards. Strategic initiatives such as the *European Green Deal, Mission Ocean, EMFAF* actively support the transition toward low-impact systems, eco-intensive technologies, and enhanced market transparency, thus affirming aquaculture's role as an essential economic sector that significantly advances climate neutrality and circular nutrient management.

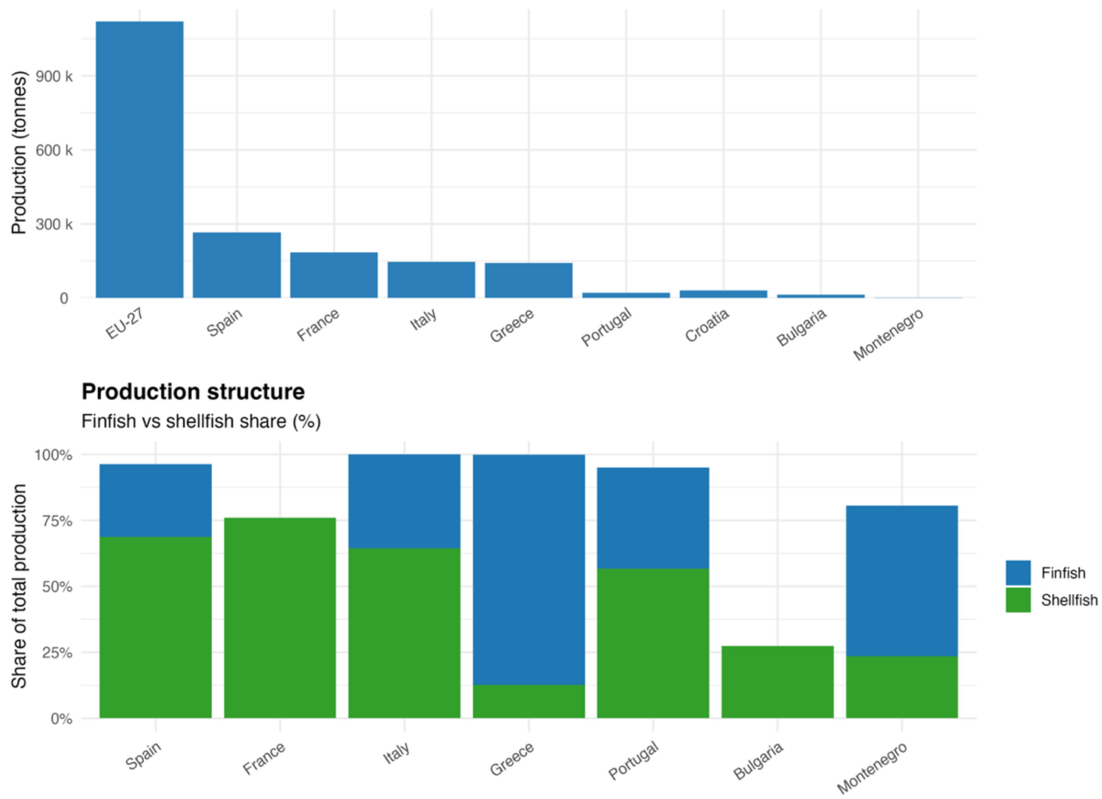

Figure 1. *Main figures of aquaculture production (Top) and by species group (bottom) in Europe*

In this context, each country's aquaculture sector showcases unique ecological features and market advantages (**Table 1**). **Bulgaria** maintains modest volumes centred on freshwater carp systems and Danube basin resources. **Croatia** is a major Mediterranean finfish producer with competitive seabass and seabream exports, supported by coastal grow-out capacity. **France** combines a robust mollusc sector (particularly oysters and mussels) as well as marine and freshwater finfish production with high domestic seafood demand and stringent coastal zoning. **Greece** remains one of Europe's top seabass and seabream producers, with advanced hatchery capacity and export-driven markets. **Italy** is an important producer for seabass and seabream balancing clam and mussel aquaculture in the Adriatic with expanding low-trophic diversification. **Montenegro** leverages small but expanding marine cage farming and niche coastal production. **Portugal** integrates Atlantic mussels, seabass, seabream and macroalgae, advancing IMTA demonstration sites. **Spain**, the EU's leading producer by volume, dominates mussel production and maintains high-value sectors including seabass, seabream, flatfish (turbot and sole) and tuna, combining industrial capacity with strong hatchery output and consolidated coastal zones.

Table 1. *Country highlights for aquaculture sector*

Bulgaria	Predominantly freshwater aquaculture centred on carp and trout species; expanding investments in diversification and improved pond-based management; continuous expansion of black mussel farms
Croatia	Competitive Mediterranean cage farming of seabass and seabream with strong export positioning; dynamic growth supported by clear maritime spatial planning and high-quality branding.
France	One of Europe's strongest mollusc sectors, especially oysters and mussels, reinforced by a large domestic consumer base and advanced coastal licensing frameworks.
Greece	Leading European producer of seabass and seabream, driven by consolidated hatchery capacity, export-oriented markets, and technological leadership in marine grow-out systems.
Italy	Significant Mediterranean producer of Manila clams and rainbow trout, with additional production of sea bass and sea bream from a limited number of marine farms. Strong tradition in lagoon-based aquaculture and ongoing innovation in low-impact, circular and restoration-oriented farming models.

Montenegro	Small but strategically expanding marine aquaculture footprint, improving licensing agility and coastal infrastructure to support seabass and seabream growth.
Portugal	Atlantic-driven production of seabass, seabream, carpet shell and mussels reinforced by promising IMTA demonstration platforms and emerging macroalgae valorisation chains.
Spain	Top EU producer by volume, dominating mussel production and maintaining high-value segments including seabass, seabream, tuna, sole and turbot; strong national hatchery output and consolidated spatial planning with stable growth and export capacity.

LiRRIE events organised within the AZA4ICE project have served as a valuable platform for identifying the **main priorities** expressed by quadruple-helix stakeholders. The outcomes provide valuable insights into the current state of the aquaculture sector, including **levels of acceptance**, **strategic priorities**, and **perceived barriers** to the transition from conventional linear production models towards more circular and sustainable aquaculture approaches. The principal priorities are outlined in **Table 2**.

Table 2. *Stakeholder priorities as identified in LiRRIEs hold in each country.*

Bulgaria	Policymakers emphasize the need to reinforce local aquaculture communities, while placing strong focus on marketing, value addition, and processing as key levers to enhance competitiveness and long-term sustainability of the sector. Local aquaculture businesses prioritise boosting demand and consumption of locally produced aquaculture products, strengthening food security, improving professional skills, and adopting new technologies, alongside a clear commitment to more environmentally friendly production practices.
Croatia	Local policymakers aim to balance environmental protection and socio-economic development by safeguarding Natura 2000 areas and promoting environmentally friendly practices. They also emphasize improving administrative efficiency, particularly in concession and licensing procedures. Local businesses prioritise the financial sustainability of their operations, facing high production costs for feed and energy and the

	need for stable market prices. There is also growing interest in adopting new technologies and eco-efficient practices to enhance productivity and reduce costs, while addressing environmental pressures through practical solutions and targeted support.
France	Shellfish farmers in the Thau Lagoon face multiple challenges, including water quality issues, disease outbreaks, climate variability (with rising temperatures – for example, the lagoon reached 27°C in June 2025), as well as competition for space, regulatory constraints, and complex management systems. At present, circular economy is not considered a top priority by local producers. However, there are some promising practices worth highlighting, such as the valorisation of oyster shells. The concept of co-culture is also gaining interest, with local stakeholders showing strong enthusiasm. Projects involving the co-culture of algae and oysters have already been tested in other regions of France, such as Brittany, and could serve as inspiration for future initiatives in Thau.
Greece	It is essential to maintain the Good Environmental Status (GES) of the waters, as failure to do so leads to strong opposition from citizens and consumers towards aquaculture.
Italy	Main priority is to continue their activities in ways similar to traditional practices, ensuring stability of income and livelihoods. Policymakers, on the other hand, place greater emphasis on adapting governance and management to current challenges and awareness, aligning regulations and planning tools with sustainability, environmental protection, and EU policy frameworks.
Montenegro	Reducing the national seafood trade deficit is a shared objective, pursued alongside strong commitments to ecological sustainability, EIA-based aquaculture licensing, and the integration of aquaculture development with biodiversity protection. Stakeholders also emphasize tourism–aquaculture synergies as an opportunity to diversify local economies and raise consumer awareness. They also indicate that call for vocational training programmed is required as well as clearer and more efficient permitting procedures, as well as improved coordination among ministries, to unlock investments and support offshore aquaculture development. Policymakers and processors identify circular practices as key priorities, including the valorisation of fish waste and shell by-products, organic certification schemes, and the recycling of nets, ropes, and packaging, with several pilot initiatives focused on producing biofertilizers and

	compost from aquaculture residues promoting stronger academia–industry partnerships to accelerate innovation uptake.
Portugal	The Strategic Plan for Portuguese Aquaculture 2021–2030, aligned with the Recovery and Resilience Plan, aims to increase and diversify aquaculture production based on sustainability, social cohesion, animal welfare, quality, and food safety. Priorities include promoting native species to boost productivity and local economies, encouraging local branding of sustainably farmed products, and fostering best practices that support the circular economy
Spain	Companies ranked environmental sustainability, regulatory clarity, and economic feasibility as the most critical factors for implementing circular aquaculture. Also, stakeholders identified to strengthen local community engagement and participatory governance as key elements to support circularity with an active involvement of civil society via workshops, open days, and guided visits. Another key aspect is the strengthen of knowledge transfer and capacity building to clearly communicate the environmental and socio-economic benefits of circular aquaculture; greater use of demonstration activities and real, visitable pilot cases to showcase technical feasibility and economic performance; and enhanced participatory governance, calling for the inclusion of local actors in regulatory development and ensuring access to project results to support informed co-creation of circular aquaculture policies.

1.3 Importance of Circular Aquaculture

With the global population projected to exceed 9 billion by 2050 (Ahmad 2001), seafood will continue to play a critical role in ensuring food and nutrition security as a key source high-quality protein and micronutrients. However, currently most of the conventional linear aquaculture systems still rely on resource-intensive models, characterized by significant nutrient-rich effluent discharges, dependence on wild forage fish for feed, spatial footprint expansion, and elevated water and energy demands. In this context, **circular aquaculture** has emerged as a **strategic pillar to boost the European Union's Blue Economy**[1] aligned with core European policy frameworks including the EU Green Deal, Biodiversity Strategy 2030, Farm-to-Fork Strategy, *Strategic Guidelines for Sustainable Aquaculture (2021–2030)* [2], and

[1] A new approach for a sustainable blue economy in the EU Transforming the EU's Blue Economy for a Sustainable Future (COM/2021/240 final); https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A52021DC0240
[2] Strategic guidelines for a more sustainable and competitive EU aquaculture for the period 2021 to 2030 (COM/2021/236 final); https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=COM:2021:236:FIN

Mission Ocean and positioning circular aquaculture as a necessary transition pathway toward climate neutrality and zero-pollution targets (Oyeboade & Olagoke-Komolafe 2024b).

This is defined as **the application of resource efficiency, waste valorisation, and system integration to minimize environmental impacts while enhancing economic and social value** (Verreth et al. 2023; Chary et al. 2024; Jasrotia et al. 2024).

The **circular paradigm** directly addresses main constraints at the core of linear models **by closing nutrient, water, and energy loop** and **integrating extractive low-trophic species** (e.g., macroalgae, bivalves, halophytes, detritivores). This evolution from conventional monoculture systems towards integrated and circular models is mostly represented by four productive models (irrespective of the stocking density) and combinations (Lothmann & Sewilam 2023; Chary et al. 2024; Lal et al. 2024), which aim to maximize resource use while reduce waste:

- **Integrated Multi-Trophic Aquaculture (IMTA)**
- **Recirculating aquaculture systems (RAS),**
- **Aquaponics**
- **Biofloc (BFT)**

Technological innovation is considered as a fundamental **driver** for the successful transition toward circular aquaculture. A better understanding of species life cycles, seed production, automation and mechanisation technologies, use of novel ingredients for aquafeeds 3.0, and implementation of advanced solutions for high-value products and waste management are critical **enablers**. Additionally, digitalisation, smart process control, and the integration of renewable energy into RAS, IMTA, and aquaponic modules are transforming both efficiency and profitability within these systems. Such advancements facilitate the **scalable and practical transition** from pilot phases to full industrial operations, thereby strengthening operational autonomy while reducing production costs and environmental impacts.

A **core component** of circularity is the *prevention, recovery, valorisation and upcycling of side stream outputs*. Nutrient-rich effluents, sludge, and biological by-products are **not considered final waste streams but essential resources** that can be converted in valuable biomass and transformed through **biorefinery approaches** into biofertilizers, biostimulants, immunomodulatory feed additives, biogas, bioplastics, and marine-derived biomaterials (Chary *et al.* 2024). These symbiotic conversions support the establishment of **blue biorefineries and industrial symbiosis clusters**, making feasible the cross-sector circulation of nutrients and biomass, logistics, and technological innovation between aquaculture, agro-production, and biotechnology sectors. A joint development of these sectors around the circular aquaculture will support the EU's shift toward regenerative production models, cross-sectorial integration and a sharing-economy principles in which nutrients, biomass, and knowledge circulate across sectors. However, the transition toward circularity **extends beyond the biological or technological advances and system design**. It requires **governance innovation** and **harmonised policy** to address fragmented regulations, poor cross-sector coordination, and unclear circular indicators (Masi *et al.* 2026).

Despite recent advances in this field, the sector still **faces structural barriers to adoption and upscaling of circular solutions**. Significant **knowledge gaps persist** regarding economic viability, equity impacts, and context-specific outcomes, especially across diverse regions and environments (Masi *et al.* 2024; Olagoke-Komolafe & Oyeboade 2025; Silva *et al.* 2025). *Producers* typically prioritise energy stability and feed cost reduction, *policymakers* emphasise emissions, nutrient discharge, and licensing risk, while *citizens* value transparency, origin, and ecological responsibility. These differentiated priorities underscore persistent socio-technical and perception challenges that must be mediated through inclusive governance, stakeholder co-creation, and knowledge exchange protocols (Aitken *et al.* 2025).

Addressing these gaps in governance mechanisms requires a **multi-actor governance approach** to ensure sustainable and equitable expansion of circular aquaculture. Additionally, barriers such as limited technical expertise, weak industrial partnerships, conflicting stakeholder objectives, insufficient integration between research and practice, inconsistent regulations, and market volatility must be effectively addressed (Gregg *et al.* 2019; Vu & Chi 2024).

1.4 Principles of Circular Aquaculture

Circular aquaculture brings circular economy principles to aquatic food production by aiming to eliminate waste, maximize resource efficiency, and restore natural systems. Based on frameworks proposed by Muscat *et al.*, (2021) and Chary *et al.*, (2024), **five principles** (**Figure 2**) guide a robust, ecologically focused **roadmap** to tackle **environmental, economic, and social sustainability challenges**. These are discussed below.

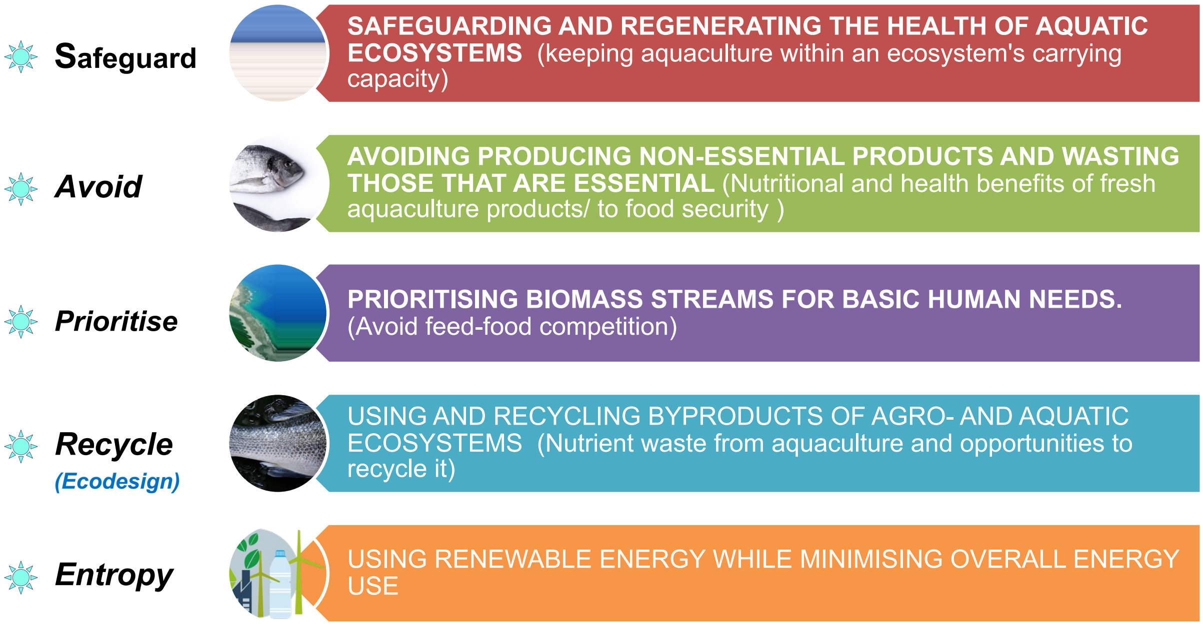

Figure 2. *Five principles of circular aquaculture by Chary et al (2024).*

1. Safeguard: *Protection and Regeneration of Aquatic Ecosystems Within Ecological Carrying Capacity*

The safeguard principle emphasizes maintaining aquaculture operations within the **ecological limits of aquatic ecosystems**. In aquaculture, this principle requires a balance between production and the **ecological carrying capacity** minimising impact of major output stressors including nutrient discharges from uneaten feed and faeces, chemical runoff, habitat alteration and disease transmission to wild populations.

Fed systems, such as intensive finfish and crustacean farming, often exert higher pressure due to reliance on formulated feeds, leading to eutrophication and biodiversity loss. In contrast, unfed or extractive species such as bivalve or seaweed farming can provide positive effects, such as nutrient removal and habitat creation. Under this performance two type of circular aquaculture can be differentiated: a) **regenerative aquaculture** defined as *a farming approach that uses aquatic ecosystem conservation as the entry point to regenerate and contribute to provisioning, regulating, and supporting ecosystem services* (including fed species); and b) **restorative aquaculture** *or extractive aquaculture (combining extractive species such as algae and shellfish) that generate net positive environmental outcomes.* This latter particularly interesting in areas of high environmental protection. While these terms are sometimes used interchangeably, incorporating extractive species in IMTA is considered regenerative if it aims to improve the environment; however, if done solely to reduce finfish farming waste without producing net positive effects, it does not qualify as restorative aquaculture (Alleway *et al.* 2021).

2. Avoid: *Waste Reduction and Resource Efficiency – Minimize Non-Essential Production and Food Loss/Waste*

The avoid principle aims to resource use and waste in aquaculture by focusing on essential production and minimizing losses. Up to half of aquaculture output (29–50%) is lost, mainly due to disease, overfeeding, poor management, spoilage, and inefficient processing or distribution. of production is lost from farm to consumer. Circular practices, such as converting by-products into biogas, fertilizer, compost or feedstuff are encouraged to support this principle.

Moreover, species that maximize nutritional output per resource input, **avoiding luxury niche items** should be prioritised. **Resource efficiency** involves optimizing feed conversion ratios (FCRs) and water use; for example, RAS and aquaponics recycles 99% of water, reducing freshwater depletion. **Waste reduction strategies** include precision feeding to reduce uneaten feed (1–6% in well-managed systems) and biosecurity measures to reduce mortality.

3. Prioritise: *Allocate Biomass for Basic Human Needs, Avoiding Feed-Food Competition*

This principle emphasizes prioritizing biomass for **basic human needs**, and food security rather than non-essential uses like biofuels or ornamentals. In aquaculture, this also means **avoiding feed-food competition**, where edible crops or fish are used as feed instead of direct human consumption. Currently, about 49% of aquafeed ingredients compete with human food, including soy, maize, and forage fish, exacerbating land and water pressures.

Important species such as carp, tilapia, and bivalves (affordable, accessible commodities) should be prioritised for their high nutritional value (e.g., omega-3s, proteins) and low environmental footprints. These omnivorous or extractive species efficiently convert non-competing by-products (e.g., rice bran, agricultural waste) into food, yielding net gains in protein. In contrast, carnivorous species (e.g. salmon) require animal-based feeds, potentially creating deficits in edible yields.

To reduce competition, animal feeding should be based on ***Aquafeed 3.0*** formulations that use byproducts, insects, algae, and single-cell proteins unsuitable for human consumption. This approach promotes equity, directs biomass to those in need, and could boost global calories by 10–16% if widely implemented.

4. Recycle: *Closing Loops Through Nutrient Recycling and By-Product Valorisation*

The recycling principle closes material loops by keeping materials in use and turning by-products and nutrients into valuable resources rather than waste. In aquaculture, wastes like sludge, uneaten feed, dissolved nitrogen, and processing leftovers (which can account for 35–70% of fish biomass) can be reused productively.

This is the main advantage of IMTA systems able to maximize nutrients recycling on farms reducing emissions by 40–75%.

Beyond dissolved nutrients, pond sludge is used to fertilize crops, and processing by-products such as fish heads and skins are repurposed for food (like soups), animal feed, or even materials (such as leather from fish skins). To maximize both economic and social benefits, recycling should first focus on producing human food, then animal feed, followed by fertilizers and biogas, with landfills being the last choice.

5. Entropy: *Minimize Energy Use and Shift to Renewable Sources*

The entropy principle minimizes overall energy demand while transitioning to **renewables**, countering aquaculture's energy hotspots: feed production (up to 90% in some systems), on-farm operations (aeration, pumping), and transport. Intensive RAS consume high energy for water recirculation and heating, while cages rely on diesel generators.

Species and systems influence efficiency: low-trophic extractives use minimal energy, carnivores more due to feed. Solutions include optimizing FCRs, site selection for natural conditions (e.g., avoiding heating tropical species in cold climates), and renewables such as solar-powered aerators or waste-heat symbiosis.

6. Horizontal principle: *Sharing: Knowledge and Industrial Collaboration*

While not one of the original five principles identified by Chary et al. (2024), knowledge exchange and industrial collaboration support circular aquaculture by fostering **innovation ecosystem and scalability**. This involves cross-disciplinary partnerships, open data on best practices, and supply-chain collaborations for by-product reuse.

In practice, **industrial symbiosis** (e.g., aquaculture with agriculture, cosmetic, food industry or energy sectors) shares resources around aquatic biomass (e.g. algae) creating adequate niche for different business. Moreover, knowledge platforms, and research networks accelerate adoption of circular techniques. By promoting sharing, aquaculture can build resilient communities, drive technological advances, and ensure equitable benefits, aligning with broader circular economy goals for sustainable development.

2. Understanding Circular Aquaculture

2.1 Definition and Core Concepts:

Circular economy, as indicated in section 1, represents a **transformative shift** in how industries operate, moving away from the traditional linear model ("take-make-dispose") towards a more sustainable framework characterized by ***Reduce-Reuse-Recycle***. In the context of aquaculture, this transition is essential for the sector to properly tackle the **environmental challenges** associated with fish farming and marine resource management. But not only, this approach also **promotes economic resilience** and **create new niche and opportunities** within the aquaculture sector and blue economy by fostering innovative practices and efficient resource utilisation (Emerenciano *et al.* 2025).

2.1.1. Shifting Paradigms

For decades, **conventional aquaculture practices** have been based on **linear production models** in which resources are extracted, used, and discharged. High feed input, water use, and energy consumption combined with low nutrient recovery and sludge discard usually resulted in high use of water, heavy reliance on fishmeal and fish oil, eutrophication and ecosystem degradation.

The shift toward circular economy principles reframes aquaculture as a **regenerative and restorative production system**, where waste is valorised and reused, and ecological carrying capacities are actively preserved. This presents a **transformative approach** that shifts production from a model of throughput and disposal to one of regeneration, nutrient recovery, and closed-loop management. Circular aquaculture is therefore not merely an incremental improvement but a **structural transformation** toward systems in which:

- Waste and by-products are transformed in a new resource
- **Recover** nutrients are principles **for biomass production**
- Valorisation of biomass is included within bioeconomy principles
- **Ecosystem services** are integrated in the production model
- **Decarbonisation** is part of the production cycle
- Secure long-term **food resilience**

Achieving this transformation demands a **coordinated innovation** (**Figure 3**) to fulfil the five circular principles prioritizing:

a) Transition toward Aquafeed 3.0. Aquafeeds is a major input in aquaculture. To eliminate dependency on wild forage resources, **circular aquafeeds** should be based on *microbial proteins, insect meals, macroalgae, fermented biomass, and processing by-products*.

b) Closing Nutrient Loops and high value biorecovery. Circular aquaculture systems **recover essential dissolved nutrients** from wastewater such as nitrogen, phosphorus, carbon and organic particulates and transform them into **secondary biomass** suitable as:

- fertilisers and compost
- protein biomass
- macroalgal and halophyte-based feed ingredients
- bioactive extracts and high-added value products

c) Water and carbon efficiency at industrial scale. Regenerative and restorative aquaculture systems should contribute drastically to reduce fresh and marine water extraction. Circular models such as RAS/IMRAS/Aquaponics/BFT often by more than 90% while allowing for precise control over energy consumption. When integrated with renewable energy sources and digital water-quality control, operational emissions are highly reduced minimizing carbon footprints and moving beyond compliance to climate-positive operation.

d) Designing bio-based value chains. Circular aquaculture should convert side stream by-products into **market commodities** to support **blue biorefineries and industrial symbiosis**. This valorisation strategy not only turns waste into economic opportunity but also diversifies revenue streams and strengthens industrial symbiosis within the aquaculture sector. Through dedicated bioprocessing routes, these biological streams are upgraded into **biopolymers and bioplastics**, **food-grade ingredients** such as protein hydrolysates, gelatine, marine oils and antioxidant extracts, as well as **aquafeed components** proteins, DHA-rich extracts, hydrolysates and immunostimulant additives. In parallel, effluents and biosolids can be transformed into **organic fertilisers**, biostimulants, composted digestates, fish emulsions and nitrogen-rich liquid soil amendments, reducing dependency on finite mined nutrients such as phosphorus and potassium and closing elemental cycles between aquatic and terrestrial sectors. More advanced valorisation pathways allow for the extraction of **high-added-value compounds** including omega-3 fatty acids, collagen, chitin, chitosan, bioactive peptides and biopolymers for nutraceutical, cosmetic, pharmaceutical and biomaterial applications. At the **energy interface**, anaerobic digestion, hydrothermal conversion and sludge-to-energy systems enable the production of biogas, biomethane and bio-oil, directly contributing to low-carbon aquaculture operations (Cooney *et al.* 2023).

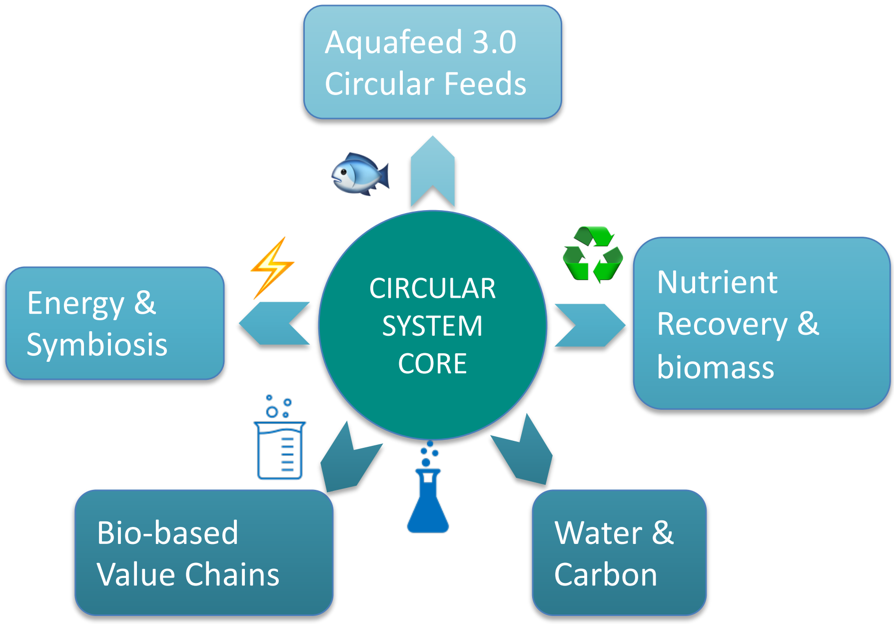

Figure 3. *Key innovations required for a transition toward circular aquaculture*

This transition is not merely an environmental correction but an **economic and technological upgrade** that:

- Enhances productivity through nutrient upcycling
- Generates new revenue flows from secondary biomass
- Strengthens climate resilience and reduce food-feed competence
- Reduces exposure to resource volatility (water, energy, fishmeal markets)
- Ensures compliance with the evolving EU Taxonomy for Sustainable Finance

2.1.2 Core Concepts of Circular Economy and Aquaculture

In addition to the **five guiding principles** that underpin circular aquaculture, five **operational concepts** (**Figure 4**) must be embedded across aquaculture production models to ensure resource circularity, nutrient retention, and systemic efficiency.

1- Reduce. Reducing inputs and emissions is the first operational priority in circular aquaculture. This comprises the a) reduction of feed losses through precision feeding; b) improving feed conversion; c) limiting water exchange via recirculating systems; and d) minimizing energy demand through optimized system design. By limiting nutrient leakage, reducing dependence on external raw materials, and reducing effluent release, aquaculture lessens its environmental footprint and reinforces its contribution to ecological resilience and circular economy targets.

2. Reuse. Reuse deals with extending lifespan of **biological and material resources** within the system. By-products, low-trophic biomass, microbial consortia, macroalgae, and halophyte outputs are redirected into secondary biomass suitable for aquafeeds, composts, bioenergy substrates, among others. This internal recirculation of matter not only diminishes disposal volumes but also supports multi-trophic integration, strengthens industrial symbiosis, and increases the economic value captured per unit of biomass produced.

3. Recycle. Recycling focuses on **recovering critical nutrients** and converting them back into productive inputs. Nitrogen, phosphorus, carbon, and organic solids are captured and reprocessed through technologies such as anaerobic digestion, composting, nitrification–denitrification, halophyte-based filtration, and algal /halophyte nutrient uptake. These pathways enable the transformation of effluents and sludge into biofertilizers, biostimulants, biomethane, or nutraceuticals establishing true closed-loop resource cycles while opening new economic channels for valorisation.

4. Recover. Recovering value from residual streams goes beyond mere recycling by extracting strategic compounds, bioactive, and high-value molecules for secondary market sectors. Recovery transforms aquaculture residues into high-value biochemical assets, positioning circular aquaculture as a feeder system for blue biorefineries, nutraceutical development, and advanced feed formulations.

5. Restore. Regeneration and restoration advances beyond efficiency to actively repair, restore, and **enhance ecological functions**. This involves:

- *Ecosystem service reinforcement,* such as nutrient depuration, carbon sequestration, and habitat structuring via seaweeds, bivalves, and halophytes.
- *Saltmarsh and wetland recovery* through controlled effluent reuse and halophyte cultivation.
- *Biodiversity reinforcement* in lagoon, estuarine, and coastal systems through IMTA-associated ecological buffers.
- Circular aquaculture as a *net-positive actor*, where nutrient surplus becomes biomass input, and effluent reuse drives plant–algal growth, sediment stabilisation, and increased carbon burial.

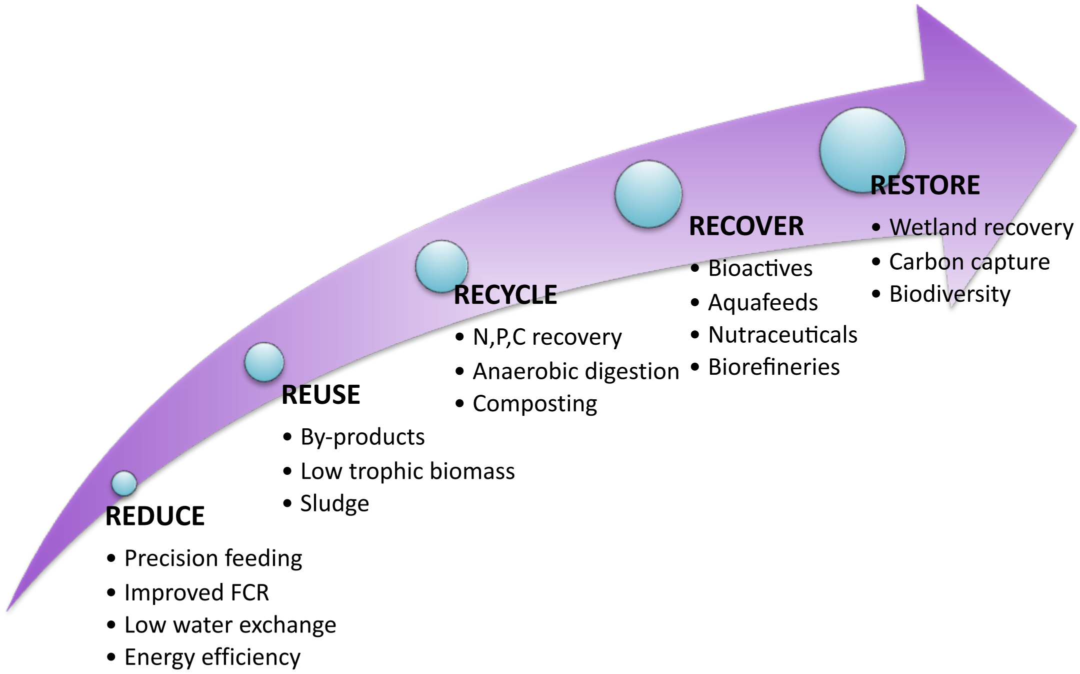

Figure 4. *Conceptual framework of circular aquaculture operations.*

The model illustrates a progressive pathway from input efficiency (Reduce) to ecosystem restoration (Restore). Each "R" stage integrates specific management actions, valorisation routes and outputs, forming a closed-loop system where resource efficiency, nutrient recovery and ecosystem services are mutually reinforced through adaptive feedback mechanisms.

2.1.3 Sustainable feed formulations using non-food-competing ingredients

A key eco-innovation for circular aquaculture is the design and validation of **sustainable feed formulations.** Traditionally, feeds have been reliant on the use of marine ingredient resources (proteins and oils, mainly from fisheries, also known as **Aquafeed 1.0**. Subsequent reformulations incorporating terrestrial crops and animal by-products (**Aquafeed 2.0**) reduced pressure on wild fish stocks but simultaneously displaced a substantial share of aquaculture's environmental impacts onto terrestrial and freshwater ecosystems. This transition has intensified land-use change and freshwater competence raising concerns about the long-term sustainability of current feed sourcing strategies. In response, circular aquafeeds (**Aquafeed 3.0**) have emerged as a new paradigm, integrating circular economy and blue bioeconomy principles to support regenerative, resource-efficient and resilient aquaculture production systems (Eroldoğan *et al.* 2023).

Aquafeed 3.0 is not defined by a single ingredient class, but by a system-level approach that valorise by-products from other sectors or even remediate nutrient discharges (Colombo & Turchini 2021). A central concept in Aquafeed 3.0 is the *prioritisation of non-food-competing ingredients*. Novel feed resources currently under investigation include *insects (larval stages), polychaetes, microbial biomass (microalgae, yeasts, bacterial and fungal-like protists), large plankton, small crustaceans and macroalgae* (Chary *et al.* 2024).

Connected with biomass production of circular aquaculture we have the following commodities suitable for aquafeeds 3.0:

a) Single-Cell ingredients in circular aquafeeds. Microorganisms, including microalgae, yeasts, bacteria and protists, represent a cornerstone of circular aquafeed strategies. These single-cell ingredients (SCI) are characterized by short generation times, high areal productivity and the ability to utilize nutrients from aquaculture effluents, industrial by-products and other residual streams. Connected to SCI and beyond their direct use, **macroalgae constitute a reliable and scalable substrate for microbial biotransformation**. Compared with heterogeneous food wastes, **macroalgal biomass** offers greater compositional consistency, predictable supply and lower contamination risk, while remaining non-food-competing in many regions. Several studies have demonstrated that **microbial fermentation of macroalgae** via submerged or solid-state processes can reduce high dietary fibre and anti-nutritional factor content, Increase protein availability and digestibility and Improve overall nutritional balance of the biomass (Ang *et al.* 2021). However, the fermentation of macroalgae for aquafeed applications **remains at an earlier development stage**. Additional research is required to achieve **nutritional profiles comparable to FM and to assess palatability, physiological responses and growth performance** in target aquaculture species prior to industrial-scale application (Ang *et al.* 2021).

b) Macroinvertebrates. They are key components in IMTA, and they are gaining interest within **Aquafeed 3.0** due to their capacity to convert low-value organic matter and aquaculture waste streams into high-quality biomass positions them as key organisms at the interface between circular economy, IMTA systems and feed innovation. Among macroinvertebrates, **copepods, amphipods (mainly caprellids), and polychaetes** stand out due to their nutritional quality, functional properties and ecological roles.

Copepods, isopods and amphipods are detritivores species, and recent studies demonstrate that amphipod-derived biomass exhibits a nutritional profile highly suitable for aquafeed applications. Amphipod-based products show crude protein levels comparable to conventional alternative protein sources (e.g. maize, meat and bone meal, poultry by-product meal), balanced amino acid profiles, high mineral content, and particularly elevated levels of n-3 polyunsaturated fatty acids (PUFA), comparable to fish oil. This combination makes amphipods especially valuable as natural ingredients capable of partially replacing fishmeal and fish oil in aquafeeds (Guerra-García *et al.* 2016; Fernandez-Gonzalez *et al.* 2018).

Similarly, **polychaetes** are increasingly recognised as core circular aquaculture organisms, owing to their capacity to thrive on aquaculture sludge and organic side streams (Wang *et al.* 2019). When cultured along gradients of aquaculture-derived solids, polychaetes efficiently convert waste nutrients into biomass with high nutritional value, directly linking waste management with feed production (Jerónimo *et al.* 2021). Polychaete biomass is characterized by high crude protein content, significant concentrations of n-3 long-chain PUFA, balanced lipid profiles essential for fish and crustacean nutrition These attributes underpin their widespread use as maturation diets for shrimp broodstock, where LC-PUFA play a pivotal role in enhancing reproductive performance in shrimps (Wang *et al.* 2019; Pombo *et al.* 2020; Yang *et al.* 2022). Beyond basic nutrition, several polychaete species (e.g. Alitta virens) have been shown to produce bioactive peptides with antioxidant, antimicrobial and immunomodulatory activity *in vitro*. Additionally, polychaetes synthesise chitin associated with antimicrobial and anti-inflammatory effects and microbiota modulation (Monteiro *et al.* 2025).

2.2 Circular production models

Circular economy principles and aquaculture-specific operational concepts are the core of circular production systems (**Figure 5**) including **IMTA, RAS, BFT, and aquaponics**, offering a unified framework for advancement and innovation, as outlined below.

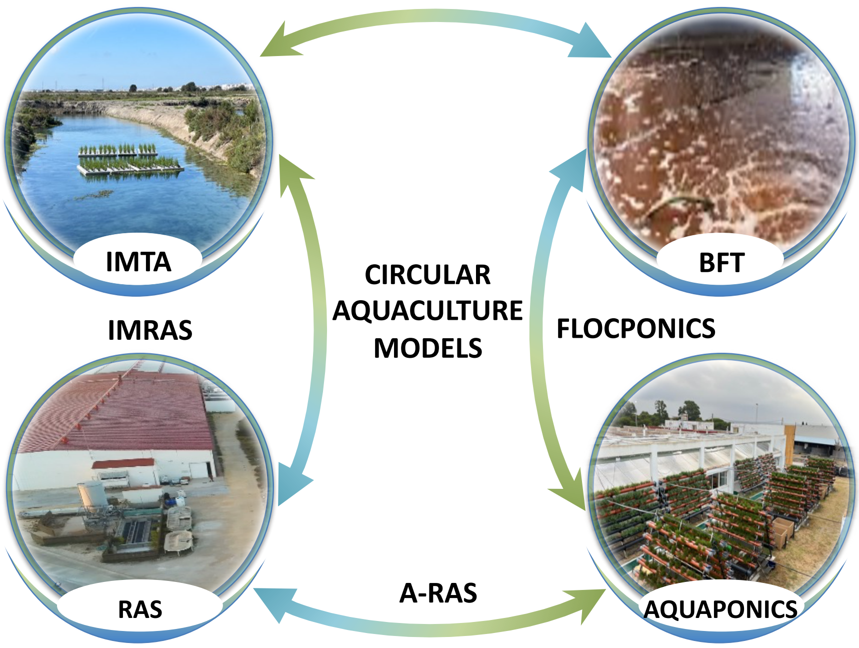

Figure 5. *Circular production model and their hybrids.*

2.2.1 Integrated Multi-Trophic Aquaculture (IMTA)

Basic Concepts and Fundamentals

According to FAO, (2014), IMTA is defined as "*a practice in which the by-products (wastes) from one species are recycled to become inputs for another*". This concept represents a fundamental shift away from conventional linear aquaculture models toward circular, regenerative production systems. At its core, IMTA tries to **recreate natural trophic networks** by **combining species from different levels** in a single, functionally **connected system**. **Fed species** such as finfish or shrimp generate organic and inorganic waste through metabolism and uneaten feed. Instead of being released into the environment, these residual nutrients are supplied to **inorganic extractive species** that absorb *dissolved nutrients* (aquatic plants or seaweeds) or **organic extractive species**, including *suspension feeders* (mainly bivalves that filter the small organic particles) or deposit feeders (sea cucumbers or worms that feed from large particles at the bottom) (Troell et al. 2009; Alexander et al. 2015). In this way, waste with nutrients is transformed into valuable biomass. Contrarily to polycultures, where all species belong to the same trophic level or they are not necessarily connected trophically, IMTAs provide a balanced system recycling and recovering all nutrients in the wastewater. Hence, IMTA is considered as an **ecosystem-based approach to aquaculture** that mimics natural ecological processes by co-culturing species from different trophic levels in a synergistic manner.

The concept of IMTA is **extremely flexible** and it can be applied to most aquaculture production systems (open-sea ponds and even integrated in hybrid models with land-based RAS). However, to be considered as a "suitable IMTA model", a system should meet all the following minimum criteria according to the INTEGRATE Interreg project:

a) Species must be principally aquatic. The core of species included in the IMTA must be aquatic (marine, brackish, or freshwater). Terrestrial components (e.g., halophytes in coastal systems) can be included, but the system's primary trophic network should remain aquatic.

b) There must be a demonstrated flow of nutrients (connectivity). Mere polyculture is not IMTA. Functional groups must be trophically connected through a real pathway of waste/nutrients (particulate and/or dissolved) moving from the fed component to extractive components and being assimilated into biomass.

c) IMTA must include at least two different trophic functional groups among:

- Fed species (FS)
- Organic extractive species (OES): deposit feeders and/or suspension feeders
- Inorganic extractive species (IES): photosynthetic nutrient absorbers

A "complete" IMTA commonly integrates three trophic functions (FS + OES + IES), but the minimum is two connected groups.

d) IMTA must be a productive model, not mere bioremediation The system must be designed to produce marketable biomass at multiple trophic levels. A key mechanism for balance is harvesting, which removes part of the biomass and nutrients from the system, helping to maintain stability and turning nutrient recovery into economic output. Since IMTA is a flexible concept, many species combinations across various environments are possible, leading to diverse IMTA designs. Therefore, production strategies should be carefully evaluated to establish a clear IMTA approach (Nissar *et al.* 2023) prioritizing:

- **Complementarity**: species must use the waste produced
- **Preference for native well-known species** reduces ecological risk and improves acceptance
- Consider the **type and consistency of waste materials** present in the selected farm site.
- **Prioritise growth/extractive potential**: absorption efficiency and harvest potential
- **Prioritise species with high market value and value chain**: product must be sellable (food, feed, bioactives, other)
- **Avoid commercialisation barriers**: food safety, processing limits, consumer acceptance
- **Socio-ecological and political acceptance**: licensing, spatial planning, MPA constraints, public perception

All the aspects described for IMTA (minimum criteria, trophic connectivity, species selection, nutrient pathways, environmental features, operational feasibility, harvesting strategy, biosecurity, and governance) should be explicitly integrated into maritime spatial planning (MSP) assessments and used as decision criteria when defining Circular Allocated Zones for Aquaculture (C-AZA). Within the eight pilot sites in AZA4ICE, we selected, the species with the highest potential to be exploited in IMTA. They are shown in **Error! Reference source not found.** - **Error! Reference source not found.** by trophic group.

Table 3. *List of fed-species identified in eight countries. SP, Spain, POR, Portugal; IT, Italy; FR, France; CR, Croatia; GR, Greece; BU, Bulgaria; MO, Montenegro. Selected species are shaded.*

	SP	POR	IT	FR	CR	GR	BU	MO
Sparus aurata								
Dicentrarchus labrax								
Solea senegalensis								
Seriola dumerili								
Penaeus japonicus								

Argyrosomus regius								
Oncorhynchus mykiss								
Scophthalmus maximus								
Cyprinus carpio								

Table 4. *List of organic extractive-species (filter feeders) identified in eight countries. SP, Spain, POR, Portugal; IT, Italy; FR, France; CR, Croatia; GR, Greece; BU, Bulgaria; MO, Montenegro. Selected species are shaded.*

	SP	POR	IT	FR	CR	GR	BU	MO
Mytilus galloprovincialis								
Magallana / Crassostrea gigas								
Crassostrea angulata								
Ostrea edulis								
Ruditapes decussatus								
Venerupis corrugata								
Pecten jacobeus								

Table 5. *List of organic extractive-species (deposit feeders) identified in eight countries. SP, Spain, POR, Portugal; IT, Italy; FR, France; CR, Croatia; GR, Greece; BU, Bulgaria; MO, Montenegro. Selected species are shaded.*

	SP	POR	IT	FR	CR	GR	BU	MON
Holothuria poli								
Holothuria tubulosa								
Holothuria arguinensis								
Hediste diversicolor								
Nereis virens/								
Marphysa sanguínea								
Mugil cephalus								
Liza ramada								
Liza aurata								
Paracentrotus lividus								

Table 6. *List of inorganic extractive-species (deposit feeders) identified in eight countries. SP, Spain, POR, Portugal; IT, Italy; FR, France; CR, Croatia; GR, Greece; BU, Bulgaria; MO, Montenegro. Selected species are shaded.*

	SP	POR	IT	FR	CR	GR	BU	MON
Ulva sp								
Chaetomorpha linum								
Salicornia ramossisima								
Salicornia fruticosa								
Gracilaria sp.								
Codium sp.								
Porphyra sp.								
Cystoseira sp								
Nymphaea alba								
Phragmites australis								

IMTA is widely recognized as the most important circular production model and is increasingly adopted worldwide (Nederlof et al. 2022; Chary et al. 2024) as an important strategy for sustainable growth in marine and coastal aquaculture due to:

1. **Support of species diversification**. IMTA requires the integration of species from different trophic levels, such as primary producers (e.g., seaweeds), filter feeders (e.g., molluscs), and carnivorous fed animals. This diversity allows for a more balanced ecosystem and enhanced biomass productivity.

2. **Nutrient cycling**: By using species that use different nutrients, IMTA promotes efficient nutrient cycling. Nutrient-retention efficiency ranges between 40–75% in a four-species system (i.e., salmon, kelp, mussels and polychaetes)

3. **Enhancement of environmental benefits**: IMTA systems reduce the environmental impacts minimizing nutrient pollution and improving water quality. The presence of filter feeders and seaweeds acts as regenerative aquaculture absorbing excess nutrients, leading to healthier aquatic environments.

4. **Promote economic efficiency**: By diversifying production, IMTA enhances economic resilience for farmers. The integration of multiple species maximizes feed use reducing mean costs and increased profitability through the sale of various products.

5. **Versatility**: IMTA systems can be tailored to local ecological and economic contexts, making them versatile and adaptable to different environments.

6. **Support food security**: IMTA enhances productivity improving food security in aquaculture-dependent communities, contributing to local economies and global food supply.

2.2.2 Recirculation Aquaculture systems (RAS)

Basic Concepts and Fundamentals

RAS systems are land-based aquaculture production systems in which water is continuously treated and reused within a closed or semi-closed loop. Typically, 90–99% of the total system water is recirculated, with only a small fraction replaced daily to regulate salinity, nutrient accumulation, remove solids and overall system stability. The defining characteristic of RAS is the decoupling of aquaculture production from the surrounding natural environment, achieved through engineered water treatment processes (mechanical and biological filters and disinfection mechanisms) that maintain optimal and stable conditions for aquatic organisms.

This production model is suitable for multiple species but preferably: i) **robust and fast-growing fed species**; ii) **species tolerant to crowding stress**; iii) **full knowledge of life-cycle requirements** and iv) **high market demands**. Some examples of freshwater species cultivated in RAS are tilapia, catfish, salmon, trout and carp. With respect to marine water, snapper, rabbit fish, yellow perch, flatfish and marine shrimp (Lal *et al.* 2024).

RAS combine biological, mechanical, chemical, and physical treatments to remove animal waste (mainly solids, ammonia, and carbon dioxide) while keeping water quality parameters including oxygen, temperature, and pH within optimal ranges for each species. **RAS can be seamlessly integrated with hybrid systems such as IMTA (IMRAS) and aquaponics.** These systems also show high efficiencies to sludge and by-products recycling and food conversion rates bases in and highly optimized protocols in feeding intensity.

Key aspects of RAS circularity are the following:

1) **Efficient use and closed-loop water management**. Closed-loop approach minimizes freshwater or seawater consumption, reduces effluent discharge to the environment, enables precise and consistent control of rearing conditions

2) **High control of waste**. Cultivated animals generate wastes primarily through metabolic and feeding processes, including uneaten feed and faeces, contributing to particulate solids, nitrogenous excretion, mainly in the form of ammonia (NH_3/NH_4^+) and respiratory by-products, particularly carbon dioxide (CO_2). *Sludge* can be easily managed to agricultural applications while dissolved nutrients can be upcycled if coupled in IMRAS or Aquaponics.

3) **Removal of toxic metabolites through bacterial nitrification**. A cornerstone of RAS operation is biological filtration; whereby specialized microbial communities convert toxic ammonia into less harmful nitrogen compounds through a two-step nitrification process.

4. Stable environmental (temperature, salinity and pH) conditions with high standards of biosecurity. RAS function as engineered ecosystems that depend on stable, steady-state operation for feeding regimes, temperature, biomass, or water chemistry.

5. **Easily to integrate in hybrids circular models.** RAS can be integrated easily with aquaponics and IMTA.

2.2.3. Biofloc Technology (BFT)

Basic Concepts and Fundamentals

BFT is a circular model that tries to minimize water use and effluent output, reducing reliance on formulated feeds, and improving biosecurity in intensive production (Raza *et al.* 2024). In BFT, heterotrophic bacteria assimilate nitrogenous wastes, mainly ammonia, converting these by-products into **microbial biomass that serves as a supplemental food source.** BFT operates as a symbiotic and self-regulating ecosystem, in which coexist cultured aquatic organisms and flocs that are heterogeneous aggregates composed of approximately 60–70% organic matter, including bacteria, algae, fungi, protozoa, and rotifers, and 30–40% inorganic components such as organic polymers, colloids, and dead cells (El-Sayed 2021).

BFT is best suited for **omnivorous or detritivores** species with a **high tolerance both to high stocking densities**, and ablet to live in **microbial-rich environments**, and using biofloc particles as a nutritional supplement. **Shrimp**, particularly the Pacific white shrimp (*Litopenaeus vannamei*), and **Nile tilapia** (*Oreochromis niloticus*) are the preferred species for BFT. Other species are catfish species, such as African catfish (*Clarias gariepinus*) and channel catfish *(Ictalurus punctatus*), carps and other detritivores or omnivorous species (e.g., mullets) but their use is less widespread compared to shrimp and tilapia. Carnivorous species, such as barramundi (*Lates calcarifer*), can be produced in BFT only under carefully controlled conditions and are generally less efficient users of biofloc-derived nutrients.

Some key aspects of BFT circularity are the following:

1) Water reuse and minimal effluent discharge. BFT operates under limited or zero water exchange. This significantly reduces freshwater or seawater consumption and minimizes nutrient-rich effluent discharge to the surrounding environment.

2) Nutrient recycling and waste valorisation. The core circular mechanism of BFT is the conversion of nitrogenous wastes (mainly ammonia and nitrite) into microbial biomass through manipulation of the carbon-to-nitrogen ratio. Metabolic wastes and uneaten feed are assimilated by heterotrophic bacteria and transformed into flocs, which are subsequently reused as a natural feed resource for cultured species.

3) Feed circularity and reduced dependence on external Inputs. Flocs function as an *in situ* protein source rich in microbial biomass, vitamins, fatty acids, and bioactive compounds. This internal feed loop reduces reliance on formulated feeds, lowers feed conversion ratios, and decreases the demand for fishmeal and other finite resources.

4. Compatibility with IMTA Systems Excess biofloc biomass and nutrient-rich water can be coupled with IMTA (Gonçalves *et al.* 2024) and aquaponics (FLOCponics) (Pinho *et al.* 2022) enabling cross-system valorisation of residual nutrients and strengthening circular production chains.

2.2.4. Aquaponics

Basic Concepts and Fundamentals

Aquaponics is an integrated food-production system that couples **recirculating aquaculture** (fish or other aquatic animals) with **soilless plant cultivation** (*hydroponics*) in a shared water loop (Lopchan Lama *et al.* 2025). An aquaponic system comprises three core components: a) the *fish-rearing unit*; b) *Filtration unit* typically includes mechanical solids removal (e.g., settling tanks) and a biological filter for nitrification; c) the *hydroponic grow bed* that largely determines the system type.

Aquaponics are usually classified into three main categories: i) media-filled systems, ii) nutrient film technique (NFT), and iii) floating-raft systems. The *Media-filled systems* incorporate solid substrates within the grow bed that function simultaneously as mechanical and biological filters, often eliminating the need for a separate biofilter. Common media include gravel, pumice, clay stones, and lightweight expanded clay aggregate which provide high surface area for microbial colonisation and physical support for plant roots. The other two systems, *NFT and floating-raft systems* generally rely on separate solids removal and biofiltration units. NFT systems circulate a shallow film of nutrient-rich water through narrow channels, enhancing root aeration and oxygen availability suitable for fast-growing leafy vegetables. The floating-raft systems offer an alternative configuration with lower maintenance demands, greater root–water contact, and broader crop flexibility, including leafy greens, herbs, and some fruiting plants. The selection of each type depends on the plant growth and roots. Normally, floating rafts often experience high oxygen demand and require supplemental aeration or advanced oxygenation technologies such as micro- and nanobubbles

Special attention deserves **marine aquaponics** that integrates hydroponic cultivation of **halophytes** (*salt-tolerant plants*). These systems are quite novel opening new opportunities for the expansion of new business. By enabling land-based production with efficient nutrient recycling and reduced environmental discharge, saline and marine aquaponics provide viable alternatives that can alleviate spatial conflicts and environmental pressures in coastal areas (Nair *et al.* 2025). Although several freshwater vegetables can be cultivated under aquaponics, the marine aquaponics can only use some halophyte species such as **Salicornia spp, Suaeda spp, Atriplex sppm, Crithmum spp or Sarcocornia spp among other**s. all new species to produce high-added biomass in aquaponics

Some relevant aspects of aquaponics circularity are the following:

1. **Integration of aquaculture and hydroponics**: Aquaponics combines traditional aquaculture with hydroponics (growing plants in water without soil) in a symbiotic environment.

2. Nutrient cycling: In an aquaponics system, fish produce waste that contains ammonia, which is toxic to them but serves as a nutrient for plants. Beneficial bacteria in the system convert this ammonia into nitrites and then nitrates, which are utilized by the plants for growth. This process creates a closed-loop system that efficiently recycles nutrients.

3. Water reuse and conservation: Aquaponics systems use significantly less water than traditional soil-based agriculture. The water in the system is continuously recirculated, reducing the overall water usage and making it an ideal solution for areas facing water scarcity.

4. Environmental sustainability: By minimizing the need for chemical fertilizers and pesticides, aquaponics promotes environmentally friendly practices.

5. Versatility to be integrated with other circular systems. In marine aquaponics, BFT and RAS can be integrated to recycle and upcycle dissolved nutrients

6. Space efficiency: Aquaponics can be implemented in various settings, including urban environments and small spaces, making it a versatile option for local food production. Vertical farming techniques can further optimize space utilisation.

We should note that **hybrid models** in circular aquaculture refer to the integration of various aquaculture practices and technologies to **create synergistic systems** that optimize resource use, enhance productivity, and promote sustainability. Some examples are:

1. IMRAS

IMTA coupled to RAS. In this form, fish/shrimps are cultivated in RAS, where their waste is utilized as a nutrient source for seaweeds, filter feeders and deposit feeders. This synergy not only enhances the overall productivity of the system but also minimizes waste. The RAS provides a controlled environment that ensures high water quality for the fish with high levels of nutrients, while the IMTA component helps absorb excess nutrients, improving the ecological balance of the system.

2. RAS and aquaponics

RAS can be combined with aquaponics to create compact systems that utilize limited space efficiently. Fish are raised in RAS, and their nutrient-rich water is directed to grow vegetables in aquaponics setups. This model not only promotes local food production but also reduces the carbon footprint associated with food transport, making it ideal for urban sustainability initiatives or protected areas with limited space availability.

3. FLOCponic

FLOCponics is defined as the integration of BFT-based aquaculture with hydroponics. Thus, this system is an alternative type of aquaponics system where RAS is replaced by BFT. From an application perspective, FLOCponics is most likely to be adopted in the short term by producers already operating BFT systems, by modifying existing infrastructure to incorporate plant production. Rather than enhancing animal growth performance, FLOCponics primarily increases the sustainability of BFT-based monocultures by recovering nutrients, diversifying outputs, and aligning production with circular economy principles, potentially strengthening social acceptance and farm resilience. However, broader commercial positioning will require robust datasets generated under conditions comparable to commercial-scale operations, alongside comprehensive evaluations of economic, environmental, and social impacts, particularly in urban and peri-urban contexts. Currently, 62% of FLOCponics evaluated reported superior plant growth including halophytes and glycophytes indicating a big effort is still necessary for system design improvements to fully exploit its potential, despite reporting comparable or higher yields (Poli *et al.* 2019; Pinho *et al.* 2022).

Overall, the transition to circular practices using these new production models offer new niches to stimulate job creation in emerging sectors such as bio-waste management and aquaculture technology development, which are vital for rural economies (Masi et al. 2024). However, the successful implementation of these models hinges on overcoming regulatory challenges and ensuring stakeholder collaboration, which can significantly influence their scalability and effectiveness. Thus, while the environmental benefits of circular aquaculture are substantial, the social implications must also be carefully navigated to achieve holistic sustainability in the sector.

A comparison of the four circular production models is shown in **Table 7**.

Table 7. *Comparison of main features of four circular production models by circular principle*

Princ.	IMTA	RAS	BFT	Aquaponics
Safeguard	Extractive species reduce nutrients leakage, recover in biomass and regenerate	Closed hydraulic and microbial conversion loop reduce effluent discharge, recover sludge and by-products	Low effluent discharge. maintains water quality via microbial conversion of toxic N to biomass	Plants reduce discharge by absorbing N, P and residual solids and recycle in biomass
Avoid	Avoids nutrient spill by assimilating waste into market biomass	Avoids uncontrolled feed losses through looped recirculation	Avoids nutrient surplus via controlled C:N ratio & floc uptake	Avoids fertiliser inputs by replacing them with fish effluents
Prioritise	Reuses uneaten feed & waste as food/energy for algae, filter feeders	Maximum efficiency in feeding increasing FCR and water reuse	Reuses microbial biomass as feed, reducing external protein sourcing	Reuses fish effluent as fertiliser for plants
Recycle	Nutrients recycled into algae biopolymers, pigments, feeds	Sludge recycled into biogas, digestate, fertilisers via anaerobic digestion	Continuous microbial N & recycling protein formation	Nutrients recycled into plant biomass with nitrate polishing
Entropy	Low-entropy trophic guiding: P & N recaptured in species hierarchy	Digital/engineering efficiency retains energy & nutrient flow. Renewable energies	Low-entropy conversion: N retained as biomass, Renewable energies	Water–nutrient–plant loop prevents energy/nutrient scatter. Renewable energies

2.3 Regional and National Regulatory Frameworks Supporting Circular Aquaculture:

The transition toward circular and resource-efficient aquaculture in Europe is guided primarily by the **EU Strategic Guidelines for Smart and Sustainable Aquaculture (2021)[3]. and Strategic Framework for a Competitive and Sustainable EU Bioeconomy (2025)[4]**. These guidelines represent the most comprehensive European policy framework directly linking aquaculture with circular economy principles, including nutrient recovery, low-trophic and biomass production and valorisation, waste minimisation, eco-certification, digital monitoring, and the integration of renewable energy. As such, they provide the policy backbone for the development of circular business models across the EU.

The Guidelines are explicitly aligned with the **United Nations Sustainable Development Goals (SDGs)**, particularly SDG 2 (Zero Hunger), SDG 12 (Responsible Consumption and Production), SDG 13 (Climate Action), and SDG 14 (Life Below Water), by encouraging regenerative production systems, ecosystem protection, and low-carbon innovation. Together with other EU frameworks (the Water Framework Directive, the Marine Strategy Framework Directive, the Circular Economy Action Plan and the European Green Deal), they form a coherent regulatory base that shapes the European transition toward climate-neutral and circular aquaculture. **Table 8** summarises the main EU-level regulations, directives and policy instruments that connect aquaculture with circular economy principles

Table 8. *EU-level policies linking aquaculture with circular economy*

Policy / Directive / Strategy	Scope & Relevance for Aquaculture	Circular Economy Dimension
European Green Deal (2019) [5]	High-level EU strategy for climate-neutral production systems and biodiversity protection. Establishes the basis for all sustainability legislation.	Supports climate-neutral aquaculture, circular resource use, zero pollution and integration of renewables.

[3] *https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM:2021:236:FIN*
[4] *https://environment.ec.europa.eu/document/download/dbf8d2ba-9332-4f7a-b336-f356fa4b7236_en?filename=COM_2025_960_1_EN_ACT_part1_v10_0.pdf*
[5] *https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en*

Farm to Fork Strategy (2020) [6]	Part of the Green Deal. Aims to create a fair, healthy and environmentally friendly food system.	Promotes sustainable feeds, reduced antibiotics, traceability, and circularity of biomass flows.
Strategic guidelines for a more sustainable and competitive EU aquaculture for the period 2021 to 2030 [7]	Main EU framework guiding sustainable, resilient and low-impact aquaculture. Provides recommendations on planning, environmental performance, animal health, digitalisation and market organisation.	Promotes nutrient recycling, low-trophic species, IMTA, water and energy efficiency, eco-design of farms, and digital monitoring. Strong alignment with SDGs.
Strategic Framework for a Competitive and Sustainable EU Bioeconomy[8]	Promote circularity and enhancing the value of secondary biomass – such as agricultural residues, by-products, and organic waste	Commission will set up initiatives rewarding farmers and foresters who protect soils, enhance carbon sinks and support sustainable biomass use.
EU fertilising products (EU 2019/1009) [9]	Includes new product categories, such as biostimulants and fertilizers made from recycled raw materials, in line with the Circular Economy objectives.	Promotes recovery from fishery and aquaculture waste and by-products. Sludge is not included.
Animal by-products and derived products not intended for human consumption (EU 1069/2009) [10]	Categorizes animal by-products in three categories, allowing for Category 3 to be used for the manufacturing of feed for farmed animals.	Promotes valorisation of by-products but does not classify fish excreta as manure, further complicating sludge recycling for agricultural use.

[6] *https://food.ec.europa.eu/system/files/2020-05/f2f_action-plan_2020_strategy-info_en.pd*f
[7] *https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM:2021:236:FIN*
[8] *https://environment.ec.europa.eu/document/download/1b42ec76-984d-4de1-a66c-f8b062058ad6_en?filename=SWD_2025_895_1_EN_rapport_de_synthese_part1_v4.pdf*
[9] *https://eur-lex.europa.eu/eli/reg/2019/1009/oj/eng*
[10] *https://eur-lex.europa.eu/eli/reg/2009/1069/oj/eng*

EU Circular Economy Action Plan – CEAP 2020 [11]	EU roadmap to accelerate circularity across all sectors, including food systems.	Encourages waste minimisation, valorisation of by-products, resource-efficient production and eco-design in aquaculture.
Marine Strategy Framework Directive (2008/56/EC) [12]	Requires Member States to achieve Good Environmental Status (GES) in marine waters.	Controls eutrophication, seabed integrity, marine litter and biodiversity—all essential for siting of sustainable and circular farms.
Water Framework Directive – WFD (2000/60/EC) [13]	Protects inland and coastal water quality. Requires that aquaculture does not deteriorate ecological status.	Enforces nutrient management, discharge limits, and closed-loop systems that reduce environmental impact.
Biodiversity Strategy for 2030 [14]	EU commitment to protect and restore marine and coastal ecosystems.	Encourages low-impact aquaculture, integration with nature restoration and circular nutrient use.
New approach for a sustainable blue economy in the EU Transforming the EU's Blue Economy for a Sustainable Future (2021) [15]	EU framework for sustainable marine economic development.	Promotes blue bioeconomy, marine biomass valorisation, waste reduction and innovation in circular aquaculture.
EU Climate Law (2021) [16]	Makes climate neutrality by 2050 legally binding.	Drives energy-efficient aquaculture, low-carbon production systems and renewable integration.

[11] https://docs.wbcsd.org/2020/11/WBCSD_Circular_Economy_Action_Plan_2020–Summary_for_business.pdf
[12] https://eur-lex.europa.eu/eli/dir/2008/56/oj/eng
[13] https://eur-lex.europa.eu/eli/dir/2000/60/oj/eng
[14] https://environment.ec.europa.eu/strategy/biodiversity-strategy-2030_en
[15] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:52021DC0240
[16] https://climate.ec.europa.eu/eu-action/european-climate-law_en

Marine Spatial Planning Directive (2014/89/EU) [17]	Requires Member States to plan maritime space sustainably.	Supports allocation of zones (AZAs) for circular aquaculture, including IMTA and ecosystem-based siting.
EU Ecolabel Regulation (indirect relevance) [18]	Framework for eco-design, life-cycle assessment and environmental labelling.	Inspires MS to develop national eco-labels for aquaculture and circular products (e.g., Montenegro's planned scheme).

At national level, Member States translate these EU Guidelines into **local strategies, spatial planning measures, certification schemes and operational standards**. **Table 9** presents some **country-specific frameworks**, related to circular aquaculture are effectively transposed into local regulatory and strategic documents.

Table 9. *Country-specific regulatory frameworks and strategic documents.*

COUNTRY	**NATIONAL / REGIONAL POLICIES AND STRATEGIC DOCUMENTS**	**RELEVANCE FOR CIRCULAR AQUACULTURE**
Bulgaria[19]	• Maritime and Fisheries Programme 2021–2027 (national implementation of EU rules) • National Strategic Plan for Aquaculture (aligned with EU guidelines) • Marine Spatial Plan 2021 – 2035 • Strategic Action Plan for Environmental Protection	Introduces sustainability requirements, promotes efficient resource use, supports environmentally sound aquaculture siting, and integrates circular principles into national aquaculture planning.

[17] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:52021DC0240
[18] https://eur-lex.europa.eu/EN/legal-content/summary/ecolabel.html
[19] https://www.mrrb.bg/bg/morski-prostranstven-plan-na-republika-bulgariya-2021-2035-g/, https://www.eufunds.bg/sites/default/files/uploads/pmdr/docs/2020-08/Aquaculture%20Multi%20Annual%20Plan-rev-2_0.pdf,https://www.eufunds.bg/sites/default/files/uploads/pmdr/docs/2024-11/sfc2021-PRG-2021BG14MFPR001-1.1.pdf, https://faolex.fao.org/docs/pdf/bul222503.pdf

	and Restoration of the Black Sea	
Croatia	• National Aquaculture Development Plan (NPRA) 2021–2027 [20] • Spatial Planning Regulations for Aquaculture Zones[21] • Environmental Monitoring Rules for Marine Farms[22] • EU structural funds (EMFAF) 23	Emphasises low-impact farming, IMTA feasibility, water quality protection and waste management. Emphasizing change adaptation and mitigation using innovative technologies that contribute to a low-carbon economy. Spatial zoning and national monitoring reinforce circularity and nutrient control.
France	• The National Ecological Planning Strategy (*Planification écologique*) [24] • "Aquacultures d'avenir" Plan (2021–2027)[25] • Regional Marine Aquaculture Development schemes in Occitanie and Sud-PACA (Schémas régionaux *de développement de l'aquaculture marine* – SRDAM) [26] • National algae roadmap (2025) [27] • European Maritime, Fisheries and Aquaculture Fund (EMFAF) at national	The policy framework promotes sustainable and resource-efficient production models, including aquaculture. It sets out a national vision for the development of sustainable aquaculture, explicitly incorporating circular approaches. Since 2024, IMTA is promoted to identify, adapt and promote best circular practices across different environments, including offshore systems, coastal lagoons and salt ponds.

[20] *https://ribarstvo.mps.hr/UserDocsImages/akvakultura/NPRA/NPRA%202027_fin_10112022.pdf*
[21] *https://narodne-novine.nn.hr/clanci/sluzbeni/2018_11_106_2070.html*
[22] *https://narodne-novine.nn.hr/clanci/sluzbeni/2022_07_87_1352.html; https://narodne-novine.nn.hr/clanci/sluzbeni/full/2021_03_22_507.html*
[23] *https://euribarstvo.hr/*
[24] *https://www.info.gouv.fr/grand-dossier/france-nation-verte*
[25] *https://agriculture.gouv.fr/presentation-du-plan-aquacultures-davenir-2021-2027*
[26] *https://www.dirm.mediterranee.developpement-durable.gouv.fr/IMG/pdf/SRDAM_LR_valide.pdf; https://www.dirm.mediterranee.developpement-durable.gouv.fr/schema-regional-de-developpement-de-l-aquaculture-a1695.html?lang=fr*
[27] *https://www.mer.gouv.fr/feuille-de-route-nationale-pour-le-developpement-des-filieres-algales-francaises*

	and regional (Occitanie and Sud-PACA) levels[28]	
Greece[29]	• Aquaculture development and other provisions (Law 4282/2014) • Strengthening standard animal husbandry, fisheries and aquaculture provisions (2024) • National Spatial Framework for Aquaculture • European Maritime, Fisheries and Aquaculture Fund (EMFAF) 2021-2027. Greece	No targeted national or regional policy supporting circular aquaculture. However, regulations support improving environmental standards, food safety, possibly waste regulation and supportive for circularity, priorities including increasing innovation, productivity of existing units. Moreover, planning/zoning rules were established reduce conflicts, ensures aquaculture in suitable areas, and support scale-up of better practices
Italy[30]	• Strategic Aquaculture Plan 2014-2020 (PSA, MiPAAF 2015) • Regional Aquaculture Plans (e.g., Sardinia AZA planning) • Marine Spatial Planning • National Strategy for the Circular Economy	National policy promotes IMTA, nutrient recycling, low-trophic species and eco-innovation. Sardinia's AZA planning includes environmental assessment and supports circular systems. Development of fiscal incentives to support the use of secondary raw materials. Strengthening regulatory tools for resource traceability; Promoting product reuse, repair and eco-design; Supporting industrial symbiosis; Setting measurable targets towards climate neutrality.

[28] https://www.europe-en-france.gouv.fr/fr/programmes-europeens/programme-national-feampa-2021-2027; https://www.europe-en-occitanie.eu/-FEAMPA- https://europe.maregionsud.fr/programmes/programmes-europeens/detail/feampa-regional-2021-2027
[29] http://www.alieia.minagric.gr/sites/default/files/basicPageFiles/%CE%A6%CE%95%CE%9A%20182%20%CE%91%20%CE%BD4282%20_2014.pdf; https://leap.unep.org/en/countries/gr/national-legislation/law-no-5087-2024-strengthening-standard-animal-husbandry; https://maritime-spatial-planning.ec.europa.eu/practices/special-framework-spatial-planning-and-sustainable-development-aquaculture
[30] https://leap.unep.org/en/countries/it/national-legislation/national-strategy-circular-economy
https://www.fao.org/faolex/results/details/en/c/LEX-FAOC198073
https://eur-lex.europa.eu/IT/legal-content/summary/maritime-spatial-planning-for-the-sustainable-development-and-growth-of-europe-s-maritime-areas.html

Montenegro	• National Strategy for Fisheries and Aquaculture Development 2024–2029[31] • Draft Regulation on Aquaculture Waste and By-products (EPA, planned 2026)[32] • Spatial Planning for Aquaculture Zones (coastal and inland)[33] • Draft National Strategy for Circular Transition to 2030 (with Action Plan 2023–2024)[34] • Strategy for the Development of the Maritime Economy 2020–2030[35] • Roadmap for Circular Economy (2022)[36]	The framework supports circular economy principles by promoting nutrient recovery, waste valorisation, low-trophic species and IMTA. It fosters cross-sector integration across aquaculture, fisheries and food systems, encouraging the reuse of by-products, energy efficiency, eco-design, traceability and digital monitoring of resources. At the same time, it supports the sustainable expansion and modernisation of aquaculture with environmentally responsible technologies, strengthens circular value chains
Portugal[37]	• Strategic Plan for Aquaculture 2021–2030 • National Marine Spatial Plan (PSOEM) • FITEC (Innovation, Technology and Circular Economy Fund) • The National Ocean Strategy (ENM) 2021-2030	Promotes low-carbon aquaculture by encouraging IMTA, supporting the circular use of marine resources, and integrating aquaculture into marine spatial planning frameworks, while contributing to climate change mitigation, pollution reduction, ecosystem restoration, job creation, and the development of a circular and sustainable blue economy.

[31] https://wapi.gov.me/download-preview/5a618ac2-668e-4b20-9490-2babf13dd46e?version=1.0
[32] https://www.gov.me/dokumenta/42efaf18-72b0-4ccb-b3c9-632422f435cb
[33] https://www.gov.me/dokumenta/42efaf18-72b0-4ccb-b3c9-632422f435cb
[34] https://www.gov.me/dokumenta/c33a4bb6-253d-4e9c-a1e6-6ac2f14ac9e8
[35] https://www.gov.me/en/documents/452e9a0d-305d-41a4-bd57-e5d8c0ae869d
[36] https://circulareconomy.europa.eu/platform/sites/default/files/roadmap_to_circular_economy_-_web_-_single_0.pdf
[37] https://aquaculture.ec.europa.eu/system/files/2023-03/AAM_MNSP_PORTUGAL_0.pdf
https://www.dgrm.pt/en/as-pem-psoem
https://www.eea.europa.eu/en/topics/in-depth/circular-economy/country-profiles-on-circular-economy/circular-economy-country-profiles-2024/portugal_2024-ce-country-profile_final.pdf/@@download/file
https://stip.oecd.org/stip/interactive-dashboards/policy-initiatives/2023%2Fdata%2FpolicyInitiatives%2F99993317

Spain[38]	• Spanish strategy for Aquaculture 2021-2030 • Regional regulatory frameworks (E.g. Andalusian region) • Regional strategy for blue economy (Eg. Andalusian Region) • National strategy of circular Economy • Regional strategy for circular bioeconomy (Eg. Andalusian Region)	Regional and National frameworks support maritime planning, integration of sustainable practices and innovation. All strategies identify the relevance of circularity, and some laws identifies the IMTA as a targeted production model. Moreover, specific regulations to create symbiosis and create synergies with blue sectors to promote cultural heritage is available

*European aquaculture uses a combination of **international certification schemes, organic standards, and national or regional eco-labels**. These schemes reward good environmental management, strengthen traceability, structure internal monitoring systems, and support circular principles such as reduced waste, efficient feed use, and improved water quality. Below is an integrated overview covering Europe (*

Table 10) and some country-specific examples (**Table 11**).

Table 10. *EU-level eco-certification*

Certification	Focus / Key Criteria	Circular Aquaculture Relevance
ASC (Aquaculture Stewardship Council)	Efficient feed use, reduced feed waste, strict water-quality criteria, ecosystem protection, social responsibility, traceability	Promotes nutrient efficiency, lower emissions, ecosystem protection, improved water quality

[38] https://www.mapa.gob.es/es/pesca/temas/acuicultura/plan-estrategico/estrategia-2021-2030
Decree 58/2017, of April 18, regulating marine aquaculture in Andalusia:
https://www.juntadeandalucia.es/boja/2017/76/6
https://www.juntadeandalucia.es/boja/2021/63/2
https://juntadeandalucia.es/organismos/agriculturapescaaguaydesarrollorural/consejeria/transparencia/planificacion-evaluacion-estadistica/planes/detalle/579553.html
https://www.miteco.gob.es/es/calidad-y-evaluacion-ambiental/temas/economia-circular/estrategia.html
https://juntadeandalucia.es/organismos/transparencia/planificacion-evaluacion-estadistica/planes/detalle/155202.html

Global G.A.P. Aquaculture	Food safety, animal health & welfare, environmental management, efficient water & energy use, traceability	Supports responsible production, resource efficiency, traceability
Friend of the Sea	Habitat protection, seabed impact reduction, responsible gear management, reduced marine litter, nutrient monitoring	Encourages low-impact aquaculture and environmental stewardship
EU Organic Aquaculture	Low stocking densities, natural disease prevention, limits on synthetic inputs, sustainable feeds, extensive/semi-extensive production	Promotes sustainable feed use, water quality, and low-impact production

Table 11. *Regional-level eco-certification*

Country	**Label / Scheme**	**Focus / Key Criteria**	**Circular Aquaculture Relevance**
Croatia	EU Organic (Eco-product) "Izvorno Hrvatsko"	Regional co-certified products typically default to the EU Organic logo. In case of Izvorno Hrvatsko, thi is primarily a quality and origin brand although it is often paired with sustainability claims.	Differentiates national seafood, encourages responsible practices
Greece	Fish from Greece	Fish health & welfare, environmental management, feed & veterinary control, social responsibility, traceability	Differentiates national seafood, encourages responsible practices

France	PGI & Regional Labels	Protected Geographical Indications, regional sustainability criteria (water quality, ecosystem stewardship)	Rewards environmental standards in sensitive coastal areas
Italy (incl. Sardinia)	SQN – Acquacoltura Sostenibile; PGI (e.g. Cozza di Olbia IGP); Regional Quality Labels (e.g. Qualità Garantita dalla Regione Sardegna)	National quality scheme and EU geographical indications combined with regional quality labels; focus on product quality, traceability, food safety, animal welfare, defined production areas, and compliance with environmental requirements linked to specific territories.	Differentiates Italian aquaculture products, supports responsible production practices, and reinforces environmental standards in coastal and lagoon systems.
Spain	Regional Labels.	Protected brand "Parque Natural de Andalucía"	Certifies that products originate from protected natural areas supporting biodiversity conservation and local socio-economic development.

Montenegro	Blue Montenegro Certified (national eco-label)[39] + ASC/GlobalG.A.P., Circular Mussel, Organic, Digital traceability	Environmental monitoring, feed efficiency, waste management, nutrient control, digital traceability	Promotes nutrient recycling, low-trophic production, premium eco-certified positioning
Bulgaria	EU Organic (Regulation (EU) 2018/848) Aquaculture Stewardship Council (ASC) Organic mussel farming	Environmental impact, organic feed, animal welfare, restricted chemicals	Promotes low-impact production, nutrient efficiency
Portugal	While Portugal applies international and European certifications for aquaculture products, no dedicated regional eco-label for the sector is currently in place.		

2.4 Sustainability and Environmental Considerations

Circular Economy is gaining increasingly more attention worldwide as a way to advance efficiently towards sustainable consumption and production patterns. The current global interest in this field opens an opportunity to make society's consumption and production patterns more resource efficient and sustainable. However, such growing interest calls for precaution as well, as there is yet no harmonised method to assess whether a specific circular economy strategy contributes towards sustainable consumption and production (Peña *et al.* 2021). In this context, **Life Cycle Assessment (LCA)** is a science-based methodology very well suited to assess the sustainability impacts of circular strategies.

[39] *https://www.gov.me/mpsv*

LCA is a tool used to understand how sustainable an activity, product or service is by evaluating its potential environmental, economic and social impacts throughout its life cycle, from the acquisition of raw materials through production, transport, use, treatment, recycling, to its final disposal (ISO 14040/44, 2006). Many LCA studies of fed aquaculture systems indicate that feed production uses the most energy, mainly associated with the harvest, process, and transport raw ingredients and process them into complete feed. LCA is a crucial assessment methodology to inform and improve CE strategies by comparing them in terms of sustainable performance (Peña *et al.* 2021).

LCA is essential to calculate footprints (carbon, water and environmental) of products and services. The **Carbon Footprint (CF)** assesses a single environmental impact, specifically climate change; the **Water Footprint (WF)** assesses the environmental impact associated with water, both in terms of quantity and quality (e.g., eutrophication, acidification, water scarcity). Meanwhile, the **Environmental Footprint (EF)** assesses 16 categories of environmental impact, including those related to water, climate change, and other impacts (e.g., consumption of raw materials and energy resources). use of the Environmental Footprint methods to measure and communicate the life cycle environmental performance of products and organisations.

3. Successful Circular Aquaculture Business Practices and Models

Aquaculture industry is still at the infancy of a transformation toward circular practices, a phenomenon that will advance rapidly catalysed by the imperative for sustainable practices suitable for environmental restoration while enhancing economic resilience. This section shows some **successful circular aquaculture business practices and models** that not only confront challenges such as resource scarcity and ecological impact but also unlock new avenues for value creation. These practices share the generation of new biomass, reduction of food-feed competition and the valorisation of side streams with the potential to convert waste into.

In this guide, we classified **business opportunities** in three categories:

1) System redesign from lineal to circular models

Most operational costs and environmental impacts, in aquaculture are focused **at the design stage**. Consequently, both new business and the transforming of existing ones need to integrate **circularity by design** (see Section 2), rather than relying on incremental or add-on solutions. This requires an effort to select the most appropriate system design and targeted species compatible with local environmental conditions, regulatory context, and market positioning.

There is **no single or simple optimal solution** applicable to all contexts. Instead, each aquaculture enterprise should conduct a site-specific, model evaluation and factor-driven assessment to determine how circular-by-design configurations, such as RAS, BFT, IMTA, and aquaponics (including saline and marine aquaponics), best fit to the territory and business objectives. The selected configuration should be able to control risk, minimize impacts, ensure regulatory compliance, and access capital, considering as **business capability drivers** the following:

- *Risk management.* While restorative and regenerative aquaculture are targeted objectives, circular systems should carefully control water quality, nutrient flows, and biosecurity.
- *Resource efficiency and cost structure.* The business model should be efficient in valorising waste streams (e.g. nutrients, solids, heat, CO_2) and reducing water, feed, and energy inputs.
- *Species–system–site adaptation*. The biological requirements of cultured species must be compatible with the selected production model and local conditions (salinity, temperature, water availability, land use constraints).
- *Regulatory and social license*. Facilities designed must comply with environmental regulations, nutrient discharge limits, and spatial planning requirements. At the same time, they improve social acceptance and reduce conflicts with other coastal and inland water users, lowering non-technical business risks.

- *Business upside and financing*. From an investor perspective, circular aquaculture systems should provide a clear long-term viable operating business with strong alignment with regulatory criteria. A clear configuration enhances bankability, facilitates access to green and sustainability-linked finance, and improves the overall competitiveness and scalability of the business

A key aspect that should be carefully considered in this transition toward circularity is **feeding**. Feed is typically the largest operating cost in aquaculture, accounting for 40–60% of total costs, and a major source of environmental impact and price volatility. According to the circular principle *3. Prioritise to avoid feed-food competition*, *Aquafeeds 3.0* based on raw materials based on by-products, insects, algae, and single-cell proteins that humans cannot consume should be a priority. Although a challenge, this transition opens a new niche reducing dependence on global commodity markets for fishmeal, fish oil, soy, and cereals. In this way, **local and regional sourcing** of circular feed ingredients increases **strategic autonomy, shortens supply chains, and reduces logistics costs and import dependencies.**

Although aquafeeds 3.0 are important, technology to integrate of precision feeding technologies, such as smart feeders, real-time sensors, and AI-based biomass estimation, to improve FCR and reduce overfeeding are high relevant. This directly reduces feed costs while minimizing waste generation and compliance risks related to nutrient discharges. This strategy has a clear **market differentiation and capital access.** Demonstrating circular feed sourcing and efficient feed use strengthens sustainability requirements and supports compliance with eco-labels.

2) Valorisation of side streams: from cost resources to revenue-generating assets

In conventional aquaculture models, side streams such as sludge and nutrient-rich effluents are primarily treated as costs as their management incurs additional expenses to meet regulatory requirements. Circular approaches reframe these streams enabling the business to convert unavoidable effluents and by-products into additional revenue sources in alignment with EU bioeconomy and blue economy strategies. Two main pathways in valorisation exists:

- *Effluent valorisation through biomass production.* The recovery of dissolved or particulate nutrients to produce seaweeds, bivalves, halophytes, or other extractive species creates potential new marketable biomass. This builds niches for biomass as commodity and aquaculture products without increasing feed inputs.
- *By-product valorisation*. This includes the use of transformation of any product considered as "residue" in the lineal model in a commodity integrated in the production cycle. This includes the sludge, dead fish or any other element of organisms produced.

EU regulations open an opportunity to improve the circularity and economic sustainability of aquaculture by enabling the transformation of aquaculture by-products into legally recognised, marketable outputs. In particular, the **EU fertilising products regulation** (EU) 2019/1009 establishes a harmonised framework for placing circular-marked fertilisers on the EU market, explicitly promoting the **use of secondary raw materials and recovered nutrients**. Moreover, they reuse of animal by-products (ABPs) and their derivative is currently governed by Regulation (EC) No 1069/2009. Within this context, main aquaculture side-streams **include: a) sludge** from production systems and **b) ABPs** generated during fish and shellfish processing. **Fish sludge**, consisting mainly of faeces and uneaten feed collected in land-based aquaculture systems (e.g. RAS/IMRAS), represents a **nutrient-rich by-product with demonstrated agronomic potential**. Its use as fertilizer is already authorized in certain non-EU countries, such as Norway. However, within the EU, its valorisation remains constrained by regulatory gaps. Fish sludge is currently excluded from the scope of Regulation (EU) 2019/1009, and fish excreta are not classified as manure under Regulation (EC) No 1069/2009. As a result, aquaculture operators face **regulatory fragmentation and must rely on national authorisation schemes** or **mutual recognition procedures under Regulation (EU) 2019/515** (Cooney *et al.* 2023). From an operational perspective, the viability of fish sludge as a fertilizer product depends technically on its physicochemical and agronomic properties, including storage stability, odour control, and nutrient balance. However, updating the regulatory framework in line with scientific evidence, EFSA risk assessments, and policy priorities are considered by advisory bodies as a key enabler for unlocking this valorisation route (Aquaculture Advisory Council (AAC) 2024)

ABPs generated within aquaculture and fisheries value chains constitute an additional strategic resource for nutrient recovery and circular bioeconomy applications. Under Regulation (EC) No 1069/2009, ABPs are categorized according to risk, with Categories 2 and 3 being eligible for use in fertilizers and soil amendments under defined conditions. **Category 2** materials include higher-risk by-products such as farm mortalities and contaminated processing residues, which may be valorised following appropriate treatments (e.g. pressure sterilisation, composting, ensiling, or anaerobic digestion) and permanent marking prior to market placement. **Category 3** materials are considered low-risk and include by-products originally fit for human consumption, such as fish processing residues, eggs, and shellfish by-products. These materials may be used for fertiliser production, but they are under strict biosecurity measures and prohibitions on intra-species recycling, for animal and aquaculture feed.

Shellfish shells with remaining organic matter are classified as Category 3 ABPs and may be valorised under conditions. Once organic material is removed, shells are considered inert residues and can be reused in non-food applications such as construction materials or industrial processes, following appropriate pre-treatment.

While these pathways contribute to waste reduction, they generally represent lower value recovery options. From a value-chain perspective, the **highest added value of ABPs is achieved by maintaining or recovering food-grade status for Category 3**, making feasible their use for human consumption or the production of high-value ingredients (e.g. collagen, protein hydrolysates, oils, and bioactive compounds). Use in other industries such as pharmaceutical, veterinary, or medical applications is also possible, if manufacturing processes comply with the relevant regulatory frameworks.

A subsequent level of valorisation involves the use of Category 3 aquaculture ABPs to generate **feed ingredients** (e.g. fishmeal, fish oil, and other marine-derived inputs) for non-ruminant livestock, aquaculture species (excluding intra-species feeding), and crustaceans, in accordance with Regulation (EC) No 1096/2009. The use of these materials in ruminant feed remains largely prohibited under the TSE Regulation (EC) No 999/2001, except for fishmeal authorized for milk replacers for weaning animals. This feed-related pathway represents a technically mature and scalable option, contributing directly to nutrient recycling, reduced reliance on imported feed ingredients, and increased resilience of EU aquaculture and livestock systems.

3) Sustainability accounting as a market enabler and regional clustering

Sustainability accounting is increasingly recognized **as a critical enabler** for the successful scaling of circular business models in aquaculture. Beyond compliance, **robust sustainability metrics** provide the evidence base required to demonstrate environmental performance and support market differentiation

From a market perspective, investors, retailers, and public funding bodies are **placing growing emphasis on the availability of credible, transparent, and comparable sustainability indicators**. Environmental foot printing approaches, such as LCA and the Product Environmental Footprint Category Rules (PEFCR), are key methodologies for a harmonised evaluation of environmental impacts across value chains. In addition, **sustainability metrics** contribute directly to **brand positioning** and **market communication**. For aquaculture businesses targeting premium, regional, or environmentally conscious consumer segments, circularity indicators provide a robust foundation for sustainability narratives, reinforcing trust and transparency. All this makes that sustainability accounting **plays a decisive role in improving access to finance**. Clear and verifiable sustainability performance data **support eligibility for green loans, public grants, and ESG-linked financial instruments**.

Another element key element in supporting circular aquaculture is the capacity to articulate ***regional symbiosis and clustering***. Shared infrastructure, such as anaerobic digesters, biomass management units, or processing hubs, allows multiple producers to distribute capital expenditure, reduce unit costs, and accelerate adoption of valorisation technologies. This strengthens regional competitiveness and reduces individual investment risk.

Following this structure about business related to circular aquaculture, we have structured next section in case studies based on primary production models and eco-innovation, those related with biomass valorisation and the industrial symbiosis.

3.1 Case Studies of Successful circular primary production models

This section presents successful businesses using circular production models, categorized by model type.

1. Circular Aquaponics Business Model

Eauzons! (https://www.eauzons.fr/) represents a technically mature circular aquaculture based on aquaponics in France, demonstrating how integrated system design can translate environmental efficiency into business success.

The company was established in late 2019 with the development of its first pilot farm in Gers (France), conceived as a proof of concept to validate the technical, biological, and economic performance of a closed-loop aquaponic production system. The facility combines **recirculating aquaculture with hydroponic plant cultivation in a 1,600 m² greenhouse.** From a technical and environmental perspective, the Eauzons! produces salmon, trout and shrimps that supply plant-available nutrients through controlled biofiltration processes to different vegetables. This configuration within a single water loop significantly reduces water consumption and eliminates **the need for chemical fertilizers and pesticides** achieving **a low environmental footprint.**

Eauzons!

From an **economic standpoint**, Eauzons! has developed a robust business model based on dual production streams. The simultaneous commercialisation of fish and fresh horticultural products reduces dependency on a single market and improves revenue stability. The company has deliberately focused on short supply chains, supplying local consumers, restaurants, and businesses with high-quality, fresh products. This **proximity-based market strategy** supports premium pricing, enhances traceability, and strengthens customer trust.

By producing food locally and sustainably, the company contributes to regional food sovereignty and reduces dependence on external supply chains. **Employment generated by the farm is inherently local and non-relocatable**, reinforcing rural and peri-urban economic resilience. In addition, the visibility and accessibility of the aquaponics system provide opportunities for education, awareness raising, and positive engagement with the local community, further strengthening social acceptance.

The transition from pilot to expansion phase confirms the **scalability** of the Eauzons! model. A second production site is currently under construction in the Pyrénées-Atlantiques region, with commercial production of fish and leafy vegetables expected to begin in early autumn 2025. This expansion benefits from a modular design that can be adapted to different territorial contexts, particularly in urban and peri-urban settings.

2. Circular Marine regenerative land-based IMTA Business Model

Les 4 Marais (https://les4marais.com/index.php) represents an innovative and relevant example of circular aquaculture based on IMTA principles, developed in Atlantic coastal salt marshes of France.

The production system is implemented in traditional marsh water bodies known as *claires*, where multiple trophic levels are deliberately combined to recreate a self-regulating aquatic food web. Species such as marsh shrimp, mysids, oysters, clams, salicornia, marsh pepper and the green macroalga Ulva are cultivated under IMTA principles maximizing biomass production.

From an **environmental perspective,** Les 4 Marais delivers multiple benefits aligned with circular aquaculture and nature-based solutions. The use of local species enhances ecosystem resilience and biodiversity while reducing biosecurity risks associated with non-native organisms. This approach has demonstrated exceptional resource-use efficiency. Laboratory trials indicate that **1 kg of external feed can generate up to 5 kg of total biomass**, a ratio that improves further under real marsh conditions due to the near elimination of external inputs. Importantly, this restorative aquaculture model demonstrates how aquaculture can function as a tool for wetland regeneration. By reactivating abandoned or underutilized salt marshes, the system contributes to habitat conservation, carbon sequestration, and coastal protection. These ecosystem services extend the value proposition of the business beyond food production, positioning it as a contributor to broader environmental and climate objectives.

Economically, the Les 4 Marais model is based on low-input, low-tech design reducing capital and operating expenditures. Infrastructure relies largely on existing and repurposed materials. **The system is particularly well suited to marginal coastal landscapes, such as abandoned salt marshes, where conventional agriculture or aquaculture is not economically viable**. In France alone, thousands of hectares of such areas are potentially available, representing a substantial opportunity for cost-effective expansion.

Socially, Les 4 Marais promotes aquaculture as an accessible and intuitive activity, described by its proponents as "*permaquaculture*." The model emphasizes learning-by-doing, local ecological knowledge, and adaptive management, making it particularly suitable for small-scale operators, cooperatives, and community-led initiatives. By reconnecting production with natural processes, the system also improves public perception of aquaculture. Its compatibility with traditional landscapes and cultural heritage opens opportunities for education, training, and eco-tourism.

3. Circular Marine land-based IMTA Business Model

The Ferme Marine de Douhet (https://fermesmarinesdusoleil.com) is a pilot project designed to reuse nutrients from wastewater generated by a gilthead seabream hatchery, using lagoon-based macroalgae cultivation as a nature-based treatment and valorisation system.

The system treats a very significant hydraulic load, exceeding 3,670 m^3 per day (approximately 225 m^3/h operating continuously) and the effluents are directed into a 5.5-hectare lagoon system, where the green macroalga Ulva is cultivated to assimilate dissolved nutrients. The singularity of this model is in the integration of an existing hatchery infrastructure with seaweed production in the lagoon. Regenerative practices will require more technology for upscale seaweed production. Moreover, nitrogen losses through denitrification reduce biomass recovery efficiency and limit the full valorisation potential of nutrients. Seasonal variability in algal growth requires adaptive dredging and biomass management strategies to maintain performance throughout the year. The system produces approximately **10 tonnes of dried Ulva annually**, corresponding to an estimated revenue of around **€50,000 per year**. While this income alone does not offset all operational costs, it significantly reduces the net cost of effluent treatment, transforming a regulatory obligation into a partially self-financing activity.

From an **environmental perspective**, the system has demonstrated measurable and quantifiable treatment efficiency at pilot scale. The lagooning–macroalgae system achieves approximately 40% removal of total nitrogen, around 6% removal of phosphorus, and a significant reduction in suspended solids. When combined with periodic dredging of accumulated sediments, phosphorus removal efficiency can reach up to 29%, highlighting the importance of integrated solid-phase management. Its performance is sufficiently robust that the hatchery has demonstrated the capacity to operate in a fully closed-loop mode for one week.

From a **social perspective**, the project has maintained stable employment while improving the environmental performance and social acceptability of the hatchery. The Ferme Marine de Douhet pilot can be used as a model for **coastal hatcheries and land-based marine aquaculture facilities** with similar effluent profiles. The system has proven effective at treating large daily volumes although yield in low-trophic biomass production still require further technological development to become an effective regenerative aquaculture.

4. Circular land-based IMRAS Business Model

CUPIMAR (https://solee-gourmet.com/) located in South Spain is baed on a circular land-based Integrated Multi-Trophic Recirculating Aquaculture System (IMRAS) centred on the production of the flatfish Senegalese sole (*Solea senegalensis*), combined with low trophic species production in ponds including oysters, macroalgae, worms and halophyte-based aquaponics (Salicornia spp.). The system is designed to maximise water reuse, recover nutrients generated by intensive flatfish production, and transform residual streams into additional biomass and value, fully aligned with circular aquaculture and blue bioeconomy principles.

Figure 6. *CUPIMAR IMRAS facilities. Top left, RAS for soles and sludge recovery station. Top right, ponds for worm production. Bottom left, halophyte platforms; Bottom right, oyster bags.*

The core of the system consists of a RAS unit optimised for sole production under controlled conditions (Max 500 Tn), ensuring high biosecurity and stable production performance. Effluents generated within the RAS are sequentially routed through multitrophic units that act simultaneously as treatment, production, and buffering components. Particulate organic matter is partially intercepted and assimilated by worm and oysters, which contribute to marketable shellfish biomass (10 Tn) and seabaits. Dissolved inorganic nutrients are subsequently assimilated by macroalgae and halophytes (~2,000 Tn), which function as biological nutrient sinks while producing biomass suitable for food, feed, or bio-based applications.

A central component of the CUPIMAR model is the recovery and valorisation of **aquaculture sludge** generated within the RAS. Solid wastes are collected and managed as a resource rather than a disposal burden, with pathways identified for their use in fertilisers, subject to regulatory conditions. Moreover, energy efficiency and decarbonisation are addressed through the integration of renewable energy solutions and optimisation of system design. The use of on-site renewable energy sources, combined with energy-efficient water treatment and recirculation technologies, reduces the overall carbon footprint of the operation and increases resilience to energy price volatility.

5. Pilot scale open-sea IMTA with only two trophic levels

Within the framework of project BLUEBOOST (https://www.blueboost.eu), an experimental open-sea based IMTA system in the Gulf of Oristano (Italy) has been established to assess the technical, environmental, and socio-economic feasibility of polyculture under offshore conditions. The pilot integrates finfish production (European seabass and gilthead seabream) with extractive shellfish species, specifically the European flat oyster (*Ostrea edulis*), aiming to demonstrate nutrient recovery and production diversification in a marine open-water context.

The system is designed to operate under conventional coastal fish farming infrastructures without fundamentally modifying existing production layouts. The inclusion of flat oysters introduces a biological filtration component capable of valorising particulate organic matter from finfish cages. From an **economic perspective**, the BLUEBOOST IMTA model illustrates the potential of **open-sea IMTA to reduce business risk by diversifying farm outputs** and increasing overall value per production site. While still at pilot scale, the model provides an evidence base for evaluating cost–benefit ratios and investment requirements associated with multi-species offshore farming.

Despite its promising performance, the system remains at a research and demonstration stage, and several barriers to large-scale implementation persist.

Regulatory and permitting frameworks for open-sea IMTA are not yet fully adapted to multi-species configurations, potentially limiting commercial deployment. In addition, capital investment requirements for pilot and commercial-scale IMTA systems, including infrastructure adaptation and monitoring, may represent a significant barrier for small and medium-sized enterprises. Nevertheless, the BLUEBOOST experimental site demonstrates strong scalability potential, particularly for existing coastal farms seeking to diversify production and improve environmental performance without relocating or fully redesigning operations.

6. Pilot scale shore IMTA based on a high number of low trophic species

An innovative in-shore IMTA configuration was implemented at pre-industrial scale in the Gulf of Taranto (northern Ionian Sea, southern Italy) within the EU REMEDIA Life project (https://remedialife.eu/). An in-shore IMTA configuration was implemented around European seabass and gilthead seabream cages by integrating a suite of extractive organisms. The system combines mussels (*Mytilus galloprovincialis*), macroalgae, sponges, and filter-feeding polychaetes located on long-line structures positioned in the water column to intercept particulate and dissolved wastes and convert them into additional biomass streams. Reported outcomes at pilot/pre-industrial scale indicate measurable environmental benefits, including a significant reduction in dissolved inorganic nitrogen (from approximately ~43 μM to ~6 μM), improvements in benthic biodiversity indicators beneath/around the farm area, and lower coliform bacterial loads, contributing to improved water quality within a historically impacted and semi-confined bay. Beyond environmental performance, the project strengthens the social acceptability of mariculture by demonstrating visible, nature-based remediation in a sensitive coastal context. However, these complex designs face some constraints associated with multi-species operations, management complexity and monitoring needs requiring bigger initial investments (Giangrande *et al.* 2020).

7. Guide for IMTA in protected areas of Southern Europe's coastal wetlands

Within these successful circular models, we should also highlight the **guide developed in the project Aqua&Ambi**[40] for setting IMTA in Southern Europe's coastal wetlands (Alentejo–Algarve–Andalusia), especially in tidal channels also known as "esteros". Its core value is translating the **IMTA concept into a simple, low-impact "improved extensive" model** for regenerative aquaculture in the Natura 2000 network: farmed fish receive limited external feed, while bivalves (e.g.,

[40] https://www.ipma.pt/resources.www/docs/publicacoes.site/eppo/AquaAmbi-Aquacultura_Sistema_Multi-trofico_Integrado_Esteiros.pdf

oysters) and macroalgae capture particulate and dissolved nutrients, improving water quality and system stability. The guide emphasizes key ecological fundamentals including carrying capacity, water-quality parameters (temperature, salinity, dissolved oxygen, pH, ammonia/nitrite/nitrate, turbidity/light), and nutrient cycling; so, producers can avoid environmental thresholds and protect animal welfare.

This guide provides a step-by-step design and taking-decision orientation: site selection and canal conditioning with retention and anti-predator nets, oyster long-line/flotation set-ups with stocking guidance, and macroalgae culture on ropes/cages with indicative biomass loads. It also defines routine workflows (monitoring 2–3 times /week, mortality checks, periodic water renewal linked to tides and gate management, equipment maintenance, biometric sampling, oyster grading/splitting) and harvest timing (fish typically in autumn; oysters on demand after depuration; algae harvested more frequently).

3.2 Eco-Design and Eco-Innovation Examples

A key point for an effective transition toward circular aquaculture is increasingly supported by **eco-design and eco-innovation solutions** that integrate effective **materials, digital technologies, and nature-based solutions**. This involves innovations in product, process, service or method that combine economic benefits with the care of natural resources (García-Castillo *et al.* 2024). Some of these innovations include the development of **low-energy farming equipment** that harnesses natural forces such as tides and waves, the use of **bio-based and recyclable materials** to replace conventional plastics, and the adoption of **more efficient organisation circular production models** to increase performance of close nutrient loops. At the same time, **digital eco-innovations**, such as **IoT sensors, artificial intelligence, and satellite-based monitoring** favours real-time environmental control, early-warning systems and more precise feeding and management strategies. Complementary **advances in water treatment technologies**, such as chemical-free disinfection using **nanobubbles** (Yaparatne *et al.* 2024), and **energy-efficient recirculation systems**, further reduce disease risks and emissions. Many innovations are also arising as circularity is implemented in optimizing Aquafeed3.0 formulations and energy generation from anaerobic digestion process (Wang *et al.* 2021) or pyrolysis processes (Naqvi *et al.* 2021). Some examples of eco-design and eco-innovation to be applied in circular applied models are shown below:

a) Innovations for more efficient production of circular models

Seaducer (https://seaducer.fr) is a French company that has developed Roll'Oyster, an innovative **rotating basket system for oyster** farming. This eco-designed device uses natural tidal and wave motion to automatically rotate oysters, improving shell shape, growth uniformity, and overall product quality. By relying on passive hydrodynamic forces, the system significantly reduces manual handling and labour requirements, while also limiting biofouling through regular movement. Roll'Oyster exemplifies low-energy eco-innovation, aligning productivity gains with reduced operational effort and environmental impact.

Eco-Ecrin (https://la-perle-de-thau.com/innovation-eco-ecrin-oyster-france/) is an initiative that focuses on the design and manufacture **of environmentally friendly oyster farming equipment** adapted to coastal ecosystems. **Its modular growing structures** are engineered to improve water circulation around shellfish, reduce sediment accumulation, and enhance biological performance. Manufactured using durable and recyclable materials, Eco Ecrin's systems are conceived to extend equipment lifespan while minimizing ecological disturbance. This approach demonstrates how eco-design can reconcile farming efficiency with ecosystem preservation.

Diag4Zoo (https://diag4zoo.fr/en/) provides molecular diagnostic and genetic traceability tools tailored to aquaculture value chains. Using DNA-based technologies, the company enables pathogen detection, biodiversity monitoring, origin verification, and breeding program management. These solutions strengthen biosecurity contributing to more robust and responsible aquaculture systems.

Algabrava (https://algabrava.com) supports more efficient IMTA by developing seeded rope technologies for offshore seaweed cultivation. In this way, the company provides solutions for macroalgae farming focusing on local species catalogue and providing technology and supplying anchored on seeded ropes.

b) Digital eco-innovations

Bioceanor (https://www.bioceanor.com/) is a French startup specializing in real-time environmental monitoring solutions for aquaculture. Its AI-driven IoT platform, AquaREAL, integrates underwater sensors, satellite data, and predictive algorithms to continuously monitor water quality parameters such as oxygen, temperature, salinity, and turbidity. By anticipating risks such as hypoxia, harmful algal blooms, or thermal stress, Bioceanor facilitates a smart farm management, optimized feeding strategies, and improved animal welfare.

ACRI-IN develops advanced monitoring and decision-support systems for aquaculture and environmental management. Its solutions combine *in situ* measurements, numerical modelling, and satellite observations to analyze water quality, plankton dynamics, and coastal hydrology. These tools support site selection, environmental impact reduction, and adaptive farm management. Acri's technologies are particularly relevant for spatial planning and for integrating aquaculture activities within complex coastal environments.

c) Water treatment technologies

Bio-UV (https://www.bio-uv.com/en/). This group offers chemical-free water treatment technologies based on ultraviolet disinfection, ozone, and advanced oxidation processes (AOP). Its systems are focused to assist hatcheries, RAS, and land-based aquaculture to eliminate pathogens, reduce disease risks, and improve water quality.

COLDEP (https://www.coldep.com) develops innovative water treatment technologies using patented vacuum airlift systems. These solutions efficiently remove dissolved gases, fine particles, and excess nutrients from water while enhancing oxygenation and reducing energy consumption. COLDEP's technologies are particularly suitable for recirculating aquaculture systems and IMTA configurations, where water quality control and energy efficiency are critical.

Alumichem (https://alumichem.com) is a water and wastewater treatment specialist providing customized solutions for aquaculture effluent and sludge management, with a strong focus on RAS. Combining advanced chemical formulations, proprietary process know-how, and engineered treatment systems, Alumichem enables fish farms to efficiently remove solids, nitrogen, phosphorus, heavy metals, and other contaminants while minimizing footprint and operational costs. Its integrated solutions cover the full treatment chain, from intake water filtration and sludge thickening to dewatering, drying, and final polishing of discharge wate, transforming aquaculture sludge into a valuable resource for biogas production, fertilizers, or circular reuse, while ensuring full compliance with increasingly stringent environmental regulations.

Metfilter (https://metfilter.com) is a Spanish water technology company specialized in decentralized wastewater treatment solutions based on microbial electrochemical technologies. Its proprietary METfilter® systems use electroconductive biofilters to stimulate electroactive microorganisms, enhancing natural metabolic processes to efficiently degrade organic pollutants and remove nutrients from domestic and industrial aquaculture wastewater, including complex contaminants such as hydrocarbons, pharmaceuticals, and solvents. Designed as low-energy, low-maintenance, and sludge-free solutions, METfilter® systems offer modular, plug-and-play configurations suitable for urban, industrial, and rural applications, enabling water regeneration and reuse in line with circular economy and nature-based solution principles.

Waboost (https://waboost.com/industries/aquaculture) is a Ljubljana-based hi-tech startup founded that uses smart ultrafine (nanobubble) technologies to enhance water quality, biological performance, and resource efficiency across aquatic systems. In the context of circular aquaculture, Waboost solutions are designed to maximize oxygen transfer, stimulate beneficial microbial processes, and reduce waste accumulation, enabling water and nutrients to be continuously reused rather than discharged. Their applications span RAS, IMTA, aquaponics, and pond-based farming, where nanobubbles support efficient nitrification and denitrification, limit biofilm formation, mitigate eutrophication risks, and reduce reliance on chemical treatments and water exchanges.

3.2 Unlocking new business associated with circular production models

When defining business models for circular aquaculture, it is essential to adopt a **holistic, system-oriented perspective** that goes beyond primary fish production. Business models should be designed to maximize the production of aquatic biomass while fully exploiting the capacity of **circular production systems to recover and reuse nutrients from wastewater**, thereby enhancing overall system productivity and resource efficiency. In parallel, circular business models must explicitly incorporate the recovery, **processing, and up-cycling of side streams**, such as ABPs, sludge, and any solid wastes generated along the aquaculture value chain (**Table 12**). The transformation of these side streams into **high–added-value products** following a **downstream biorefinery** for functional feed ingredients, biofertilizers, biostimulants, biopolymers, energy carriers, and nutraceutical compounds, represents a critical source of additional revenue and risk diversification. The viability of these business models needs to bring together enough biomass production of high-quality and at a competitive cost with the alignment of technological feasibility, market demand and regulatory pathways ensuring economically robust and scalable business models

Table 12. *Main market sectors associated with circular aquaculture*

MARKET SECTOR	RESOURCE INPUT	PROCESS	HIGH-VALUE OUTPUT
Food	Edible aquatic biomass	IMTA, RAS, Aquaponics, BFT	Enhanced edible biomass production
food additives, cosmetics, nutraceuticals	Algae, halophytes, bivalve extracts, shells	Antioxidant extraction, purification, lyophilisation	polyphenols, flavonoids, carotenoids, fucoidans, salt
pharmaceuticals, cosmeceuticals	Fish trimmings, processing by-products	fractionation, enzymatic digestion	gelatin, collagen, marine oils
Recreational fisheries	polychaeta	IMTA, depuration	sea baits
Aquafeeds, nutraceuticals	Algae, halophyte, biofloc, microbial consortia, shells, polychaeta, by-products	IMTA, fermentation, protein extraction, enzymatic hydrolysis	protein hydrolysates, marine peptides, bioactive amino acids
Bioplastics, biomedical	Chitin-containing biomass (crustaceans), supplements halophytes, algae	demineralisation, deacetylation, lyophilisation	chitin, chitosan, biopolymers, PHB, polyphenols
Agriculture	sludge, algae, halophyte shells, by-products	IMTA, composting, extraction	soil amendments, organic fertilisers, biostimulants
Energy & circular carbon markets	Sludge and solid residues, by-products	anaerobic digestion, pyrolysis	biogas/biomethane, bio-oil, biochar

Here some examples of business associated with circular production models by market sector

a) Food and new species from IMTA to the market

- **ALGAplus** (https://www.algaplus.pt) is a Portuguese company and one of the leading producers of organic-certified farmed seaweeds in Europe, operating a land-based IMTA system in the Ria de Aveiro coastal lagoon (Natura 2000 site). Founded in 2011 following the development of a pioneering cultivation concept initiated in 2006, ALGAplus integrates the cultivation of macroalgae (10-100 T), mainly Ulva spp., Codium tomentosum, Gracilaria spp., Palmaria palmata, and Porphyra spp, with seabass and seabream production. The company produces fresh, salted, dried, and frozen seaweed for food, cosmetic, and feed markets, exporting more than half of its production to Europe, North America, and Australia, while also developing its own branded products. With a workforce of approximately 18 employees, ALGAplus demonstrates how IMTA-based seaweed farming can be economically viable, environmentally sustainable, and socially embedded, providing a scalable circular aquaculture model that replaces wild harvesting with controlled, high-quality European production.

- **HOLOPROD** in Occitania (France; https://www.groupebarba.com) and **GUATIZAMAR** in Andalusia (Spain; https://guatizamar.com/en/home/) focused on the farming of sea cucumbers (Holothuroidea), a group of marine invertebrates with strong commercial, ecological, and bioeconomic potential. This initiative is built on the cultivation of Holothuria tubulosa, particularly suitable for circular aquaculture and IMTA systems. By integrating sea cucumber culture with existing oyster and mussel farming activities, the project creates a closed-loop nutrient pathway in which organic wastes generated by filter feeders are converted into additional biomass. This approach transforms environmental services into productive outputs and offers a practical solution to reduce organic enrichment beneath shellfish farms. From an **economic perspective**, sea cucumber farming offers new diversification opportunities for shellfish farmers, enabling them to generate additional income without significant changes to existing infrastructure.

b) Food additives, cosmetics, nutraceuticals

- **GREENTECH** formerly GREENSEA (https://www.greentech.fr/en/greensea-algae-and-micro-algae/) is a French marine biotechnology company recognized for its long-standing expertise in microalgae, macroalgae, and marine coastal plants. develops and produces high–added-value **bioactive ingredients for aquaculture, cosmetics, nutraceuticals, pharmaceuticals, and medical diagnostics**. In aquaculture, the company supplies nutritional ingredients for fish farms and hatcheries, contributing to improved health and performance of cultured species. Its production relies on controlled cultivation of algae and microalgae using annular and tubular photobioreactors, ensuring consistent quality, traceability, and low environmental impact. GREENSEA's portfolio includes patented marine actives derived from species such as Ulva lactuca, Porphyridium cruentum, and Halymenia durvillei, used as functional ingredients with applications ranging from skin health to immunodiagnostics. By valorising marine biomass through biotechnology and transforming it into recyclable, high-value functional compounds, GREENSEA represents a mature and scalable downstream industrial model that complements circular aquaculture and IMTA systems.

- **Marisma Biomed** (https://marismabiomed.com) is a Spanish biotechnology company specialized in the valorisation of halophytes from salt-marsh ecosystems, with a strong focus on **human health, nutrition, and preventive medicine**. The company develops and commercializes **high–added-value food and nutraceutical products** derived mainly from **Salicornia**, Marisma Biomed's production model is based on controlled sourcing and processing of halophyte biomass produced in IMTA in collaboration with fish producers, ensuring high quality, traceability, and low environmental impact, while fully aligned with circular economy principles. Main product portfolio includes **Salicornia-based low-sodium food** ingredients, and B-Salicornia®, a clinically validated **nutraceutical supplement** formulated to support cardiovascular health, healthy ageing, and metabolic balance.

- **Seabites Pet Care** (https://seabites.pet) is an innovative startup specialised in the formulation, production, and marketing of natural **food supplements and functional snacks for domestic animals, with a strong focus on dogs and cats.** The company's distinctive value proposition lies in the use of **marine-derived ingredients, particularly algae** and sustainably sourced fish products, selected for their high nutritional density and proven health

benefits. SeaBites' product portfolio includes dietary supplements, functional oils, dehydrated marine snacks, and nutraceutical blends, designed to support key aspects of animal health such as joint function, skin and coat condition, dental hygiene, digestion, and overall vitality. Marine ingredients such as **algae, salmon oil, anchovies, tuna, mackerel, and other small pelagic species** are leveraged for their richness in PUFAS, minerals, antioxidants, vitamins, and bioactive compounds, offering a natural alternative to synthetic additives. Commercially, SeaBites operates through direct-to-consumer (D2C) channels, supported by an online platform that combines product sales with educational content, veterinary guidance, and customer engagement. The brand emphasises trust, quality, and accessibility, targeting pet owners seeking premium yet natural solutions for the long-term well-being of their animals.

c) Pharmaceuticals, cosmeceuticals

- **Seagarden** (https://seagarden-norway.com) is a marine ingredient company specialized in the development and commercialisation of **fish-derived collagen peptides for the nutraceutical, pharmaceutical, and cosmeceutical sect**ors, responding to the growing global demand for high-performance, non-mammalian bioactive ingredients. Its production model is firmly aligned with circular economy and blue bioeconomy principles, offering an alternative to bovine and porcine collagen with fewer cultural, ethical, and health-related constraints. **Seagarden Marine Collagen** is produced exclusively from high-quality marine raw by-product materials, mainly fish skin from cod, whitefish, and salmon. These raw materials originate from established seafood processing chains and are valorised as high-value inputs rather than discarded as waste.

d) Recreational fisheries

- **Topsy Baits** (https://www.topsybaits.nl/) is a European leader in the production and commercialisation of farmed marine polychaetes (Nereis virens), supplying high-quality live bait for recreational fisheries and specialized maturation feeds for the global aquaculture sector. Operating from the south-western Netherlands, the company has developed a production model based on extensive, near-natural farming conditions using clean seawater from the protected Oosterscheldt Bay. Topsy Baits' strategy is firmly grounded in biological optimisation and long-term observation, aligning with sustainable production and blue

bioeconomy principles by prioritizing animal welfare, biosecurity, and resource efficiency.

Topsy Baits' polychaetes are produced in pond-based systems designed around the natural behaviour and physiological requirements of the species, allowing the farming protocols to evolve with the organism rather than forcing it into conventional aquaculture systems. Production has been scaled progressively in response to market demand, reaching 94 ponds (approximately 17 hectares) and an annual output exceeding 100 tonnes. The company's portfolio includes live **worms supplied to sea anglers across Europe and flash-frozen, specific-pathogen-free (SPF) polychaetes** marketed as a premium maturation diet for fish and shrimp broodstock.

e) Aquafeeds, nutraceuticals

- Seaweed Concept (https://seaweedconcept.com) is a marine biotechnology company headquartered in Brittany, France, dedicated to the sustainable valorisation of seaweed through innovative processing and industrial supply of high-quality seaweed-derived ingredients. At the core of Seaweed Concept's approach is a combination of mobile, modular biorefinery units and a patented lacto-fermentation technology. These portable processing units enable on-site preservation and stabilisation of seaweed immediately after harvest, addressing logistical and supply-chain challenges associated with conventional processing. Seaweed Concept's product portfolio includes **fermented seaweed, fermentation juice, and seaweed juice derived from multiple macroalgal species** (e.g. *As cophyllum, Fucus, Himanthalia, Saccharina latissima, Solieria chordalis*), adapted for use across diverse markets such as food and agri-food, animal feed, plant production and soil management, cosmetics, and biomaterials.

f) Bioplastics and biomaterials

- **Eranova** (https://eranovabioplastics.co). This start-up located in South of France produces 100-1000 T of Ulva. This biomass is upcycled into **biosourced resins** that can be processed using conventional **plastic manufacturing techniques**. The resulting materials are designed to be recyclable and compostable, ensuring compatibility with circular economy principles across their full life cycle. Its porfolio includes four Biodegradable resins suitable for preparing biodegradable Meal trays, garbage bags, short-life materials, fruit & vegetable bags and packaging for bio-waste collection.

- **Futuralga S.C.A** (https://futuralga.com) is a cooperative enterprise focused on the development and manufacture of sustainable **packaging solutions for the fruit and vegetable** sector, based on the valorisation of **macroalgal biomass** collected from coastal areas. By applying technological processes to convert algal biomass into biodegradable and compostable packaging materials, the company provides a functional and environmentally sound alternative to conventional plastic containers.

- **Algaeing** (https://www.algaeing.com). Algaeing™ is a clean-color technology company that develops algae-powered dyes and inks as sustainable alternatives to conventional, petroleum-based colorants for the textile, fashion, and design industries. As “The Clean Color Company,” it enables brands and manufacturers to eliminate toxic chemicals while maintaining high performance, color fastness, and consistency, with solutions that integrate seamlessly into existing production processes without additional capital investment. Its core products, ALGADYE™ for large-scale textile dyeing and ALGAINK™ for textile printing and multi-surface applications, are renewable, biodegradable, and certified toxic-free, delivering immediate environmental benefits including up to 70% reductions in greenhouse gas emissions and up to 98% water savings, while improv ng health and safety for workers and consumers across the value chain.

g) Energy & circular carbon markets

- **Solrød Biogas** (https://solrodbiogas.dk/) is a circular bioenergy initiative in Solrød, Denmark, developed to address multiple interlinked challenges faced by Danish local authorities, including waste management, environmental protection, climate mitigation, and renewable energy supply. At the core of Solrød Biogas’ operational model is the **systematic collection and valorisation of seaweed** washed ashore along the Solrød coastline, primarily originating from Køge Bay. Through continuous removal and controlled processing, this **marine biomass** is redirected into a valuable raw material for **biogas production** and **organic fertiliser**, closing local nutrient and energy loops. The anaerobic digestion of seaweed at Solrød Biogas converts this excess biomass into renewable, CO_2-neutral energy, supplying the local heat network and displacing fossil fuels. In parallel, the digestate produced is returned to agriculture as a climate-friendly fertiliser, replacing mineral ones and further reinforcing circular resource use.

3.4 Industrial Symbiosis

Industrial symbiosis is defined as “the economic exchange of material flows, resources, and residual waste within a multiple, collaborative network facilitated by trust, information availability, and existing incentives” (Agudo et al. 2022). Although industrial symbiosis can generate competitive advantages by reducing costs, and creating new value streams, its implementation remains limited. This is largely due to the perceived complexity, time investment, and costs associated with coordination and long-term development, which often discourage companies despite the potential benefits (Rentería Núñez & Perez-Castillo 2023) For this reason, industries must first understand and adapt their own business models to identify symbiotic opportunities with other companies and identify shared value creation.

The increasing integration of digital information and data-driven decision-making facilitate new services and information and the transition from early awareness to effective, coordinated action. Thi is the key role of a **facilitating organisation** since realisation of symbiotic exchanges rarely succeeds without a dedicated entity to lead, structure, and sustain collaboration. Building on the pre-emergence phase, the facilitating organisation must define its identity, mission, business model, and skillset in close alignment with the local, cultural, and institutional context, as well as the strategic scope and constraints of its mother organisation. These elements are deeply interlinked: the organisation’s purpose and stakeholders shape its strategy; its legal and financial set-up determines how it secures base and project funding; and its human competencies underpin trust-building, matchmaking, fundraising, and long-term coordination across companies, public authorities, academia, and civil society (Lasthein *et al.* 2021).

Circular Aquaculture provides an excellent ecosystem for industrial symbiosis. Under this integrated umbrella, aquaculture is transitioning from a single-output protein industry to a circular bio-resource platform capable of generating multiple products, new economic niches and cross-sector symbiosis. The result is a regenerative system in which every biological fraction is valorised. A clear opportunity is that focused on the use and valorisation of IMTA biomass. Algae, halophytes, fish by-products, sludge or bivalve shells appear as key elements of a successful symbiosis ecosystem. If we focus particularly on the valorisation and reuse of bivalve shells (Bellei *et al.* 2024; Magalhães *et al.* 2024), this sector is the niche for producers, purification platforms, distributors and commercialisation actors, particularly relevant in Portugal or France with large experience in largest bivalve production areas, contributing significantly to regional live hoods and coastal ecosystems. Currently, most producers usually report losses of 10-30% outside the harvesting period and around 15% during normal seasons. Regarding shell management, most of producers they do not reuse shells, disposing of them after consumption, while only 12% reported an internal reuse policy, primarily in restaurants (Magalhães *et al.* 2024).

A potential symbiosis under a Blue Circular Economy approach would frame shells as a recoverable biogenic mineral resource throughout a stakeholder-based "bivalve circuit" (Magalhães *et al.* 2024) involving different actors with key resources and partners:

- **Specialised operators** (producers associated in cooperative platforms or not and purification companies) are responsible for accumulate bivalve shells and converts them into standardized secondary raw materials (e.g., graded shell sand, shell powder, $CaCO_3$-rich filler. This sector directly associated with circular production models anchor points for steady volumes and controlled streams
- **Intermediaries or waste generators** (final consumers, restaurants, hotels, seafood shops, and supermarkets.): reduced disposal burden and improved compliance through segregated collection
- **Municipalities**: permits, collection integration, and potential co-financing as waste-reduction measure.
- **Off-takers** (Construction Companies and Building Materials Companies, agriculture/soil amendments, water treatment, composites): reliable local reusing marine waste supporting circular procurement claims.
- **R&D/technical partners**: performance testing, LCA/footprinting, and standardisation support.

4. Guidelines for Transitioning to Circular Aquaculture

The transition to circular aquaculture is an opportunity and necessity for the aquaculture industry. As global demand for seafood continues to rise, traditional aquaculture practices require a revision and update of operational frameworks. This section outlines **comprehensive guidelines for both existing businesses and new entrepreneurs to adopt circular aquaculture principles.** A first assessment of circular practices in the eight countries participating in AZA4ICE (**Table 13**) indicated they are still at the beginning. Across most countries (BU, FR, GR, PO, MO), aquaculture sludge, uneaten feed, and organic sediments are not formally valorised. Moreover, valorisation remains at pilot scale, or experimental, with no certified value chains, quality standards, or market outlets and in most of cases there is absence of dedicated bio-waste collection systems. Some ABPs such as shells are underutilised and often landfilled despite clear agronomic and industrial potential. With respect to aquafeeds, transition from Aquafeed 2.0 to Aquafeed 3.0 is slow. While research on alternative ingredients (insects, algae, agro-industrial by-products) is widespread (IT, FR, ES, MO, PO), commercial uptake remains limited. There is a heavy dependence on imported feeds in MO, GR, and BU and regulatory approval for novel ingredients remains slow, fragmented, and costly, particularly for SMEs. Transparency on plant-based feed components is uneven limiting full assessment of feed–food competition. With respect to resource efficiency, many farms apply resource-efficient practices (gravity-fed systems, feed optimisation, basic RAS). However, data on water, energy, and nutrient efficiency are not standardised or reported and impacts are rarely quantified at regional or national level.

Table 13. *Current practices assessment on circular aquaculture in the eight countries involved in AZA4ICE project*

Country	***Valorisation side streams***	***Reduce Feed-food competition***	***Increase resource efficiency***
IT	• Multiple initiatives focused on the recovery and valorisation of aquaculture by-products, including sludge, fish processing residues, and uneaten feed. • Valorisation pathways include composting, bioconversion using Black Soldier Fly larvae to produce insect protein, and	• Research and innovation programs are actively targeting the replacement of fishmeal and plant-based ingredients with more sustainable alternatives such as microalgae, insect meal, and agro-industrial by-products. • Pilot-scale trials have demonstrated	• Circular aquaculture increasingly relies on production models that optimise water, nutrient, and space use, including RAS, BFT and IMTA. • In regions such as Sardinia, the dominance of shellfish farming already represents a highly resource-efficient production model. • The implementation of Aquaculture

	the transformation of residual streams into bio-fertilizers. • While shellfish farming inherently generates relatively low waste, its integration into waste-to-value schemes is increasingly encouraged through national and EU funding instruments.	the nutritional and functional viability of these ingredients in aquafeeds. • Public support through national programs and EU funding mechanisms is facilitating validation, regulatory alignment, and gradual scale-up toward commercial adoption.	Allocation Zones (AZA) further strengthens environmentally compatible site selection and spatial planning.
CR	• There exist several initiatives aimed at the recovery and valorisation of aquaculture by-products, particularly through transnational cooperation. Projects have tested innovative waste management systems to extract biofuels and convert marine and freshwater aquaculture sludge into bio-based fertilizers or soil amendments using advanced dewatering technologies. • Circular-economy approaches have also been applied to transform bio-waste into innovative hydroponic substrates, demonstrating solutions readily transferable to nutrient-rich aquaculture residual streams.	• Primary strategy focuses on reducing dependence on marine-derived ingredients (fishmeal and fish oil from wild fisheries) and terrestrial crops competing with human food systems, such as soy. • Research and innovation efforts prioritise alternative ingredients including insect meals, microalgae, and by-products from other food industries. Initiatives under projects such as PerformFISH and GAIA aim to reposition Croatian aquaculture toward higher-quality, differentiated products with a reduced environmental footprint, moving away from low-margin commodity production.	• Improving resource efficiency is a strategic objective of SMEs. Supported by EU funding and collaborative programs, the focus is on adopting innovative technologies and practices rather than expanding physical production capacity. • Several projects target improved water and land-use efficiency, including the uptake of RAS for niche, high-value production such as land-based marine fish or shrimp.

BU	• Although the potential for valorising aquaculture by-products has been identified, no concrete or operational valorisation pathways are currently in place. • Circular use of sludge, uneaten feed, or processing by-products remains largely unrealised.	• Efforts are focused on increasing the proportion of recycled and secondary products in aquafeeds. • Beyond economic benefits, this approach is framed as a social opportunity, supporting local communities through job creation, lower production costs, and improved access to affordable, nutritious seafood.	• Some resource-efficiency practices exist at farm level, but there is no systematic data on their extent, performance, or impact, limiting assessment and scalability.
FR	• In seabream/seabass aquaculture, there is no structured valorisation of waste streams. • Undersized or defective fish are downgraded and often donated to charities, while mortalities are sent to rendering plants, presumably for fishmeal production. • Feed bags, a major waste stream by volume, are recycled. • Dissolved nitrogen wastes are not valorised through IMTA or extractive species and are instead assimilated by the surrounding environment.	• Fishmeal used in aquafeeds is largely derived from fisheries by-products (carcasses, heads, trimmings- Approx 11% of fishmeal originates from forage fish • Available figures indicate that only around, with the remainder coming from by-products. Information on the plant-based fraction of feeds is less transparent, limiting full assessment of feed–food competition.	• Efficiency gains rely mainly on feed optimisation and waste management at farm level, rather than on integrated circular production models such as IMTA or nutrient recovery systems.
GR	• There is currently no company or organisation in Greece that systematically collects or processes aquaculture sludge or uneaten feed.	• Feed sustainability efforts focus primarily on optimising conventional formulations and reducing reliance on marine resources, but structured national	• Resource-efficiency improvements are mainly incremental and farm-based, with limited deployment of circular or integrated systems. The absence of downstream valorisation options constrains incentives

	• Indirect valorisation opportunities exist: a biogas plant in Crete processes a wide range of organic wastes and produces electricity, heat, and a digestate marketed as a biofertiliser. • Although aquaculture sludge is not yet included, this model represents a potential pathway for future integration.	initiatives targeting alternative ingredients or by-product-based feeds remain limited.	for nutrient recovery and system-level efficiency gains.
MO	• Valorisation of aquaculture by-products in Montenegro remains at a pilot stage. • In freshwater farms, sludge is collected in sedimentation tanks, sun-dried, and occasionally used as a soil conditioner, but without commercial processing or certification. • Mussel farming generates 50–70 tonnes of shells annually, partly reused for soil liming or construction fill, though most are landfilled. Pilot initiatives are testing composting of crushed shells with aquaculture sludge to produce organic fertilisers, while integration of aquaculture bio-waste into municipal waste systems is under exploration.	• The sector remains dependent on imported feeds based on fishmeal and soy, but gradual improvements are emerging. • Precision feeding practices have improved feed conversion ratios (≈1.8 to 1.5), reducing feed inputs per unit of production. • Some farms use certified sustainable feeds compliant with ASC and GlobalG.A.P. standards. • Research led by IMBK and the University of Montenegro is testing locally sourced plant proteins and algae extracts, achieving up to 20–25% soy substitution in pilot trials. • Short-term progress relies on feed optimisation and certified imports, with medium-term potential for locally produced alternative feeds.	• Resource efficiency is improving through gravity-fed freshwater systems with low energy demand, pilot partial recirculating aquaculture systems achieving up to 90% water reuse, and nature-based filtration using vegetated channels. • National spatial planning designates aquaculture zones based on ecological carrying capacity, while pilot multi-use sites integrate aquaculture with eco-tourism and renewable energy. • Solar-powered feeding and aeration systems and automated feeders further reduce energy use and operational costs, supported by EU and national programs.

PO	• There is currently no documented evidence of systematic valorisation of aquaculture waste streams in Portugal. Uneaten feed, sludge, and organic sediments are generally managed on-site with limited recovery or reuse. • Integrated coastal initiatives such as Salinas do Grelha illustrate how traditional production systems can combine ecological restoration, renewable energy, and eco-tourism, offering transferable principles that could inspire future circular aquaculture waste-valorisation strategies.	• Efforts to reduce feed–food competition remain largely at pilot scale. • Research institutions are testing alternative protein sources, including insect meal, algae, and food-industry by-products, as partial substitutes for fishmeal and soy. However, these initiatives have not yet translated into commercial-scale adoption and dedicated national support mechanisms for alternative aquafeeds are still lacking.	• Future improvements in resource efficiency depend not only on reducing water and energy use but also on optimising land and space management. Priority areas include the reuse of existing aquaculture sites, restoration of degraded production areas, and integrated spatial planning that balances aquaculture development with ecosystem protection, supporting long-term, resource-efficient coastal aquaculture.
SP	• Andalusia has legally recognized Integrated IMTA as a production model, providing a favourable framework for circular practices. • There is a high level of social and industrial awareness regarding recycling and upcycling, partly driven by strong environmental concerns, in part due to the management of invasive algae. • Aquaculture activities in protected areas are subject to heightened scrutiny, reinforcing responsible resource use. • A growing number of companies are engaged in industrial symbiosis, developing	• Research and innovation efforts are strongly oriented toward Aquafeed 3.0, focusing on alternative ingredients and functional feeds that reduce reliance on conventional feedstocks. • Although regulatory barriers still limit the rapid uptake of novel raw materials, the regulatory framework is gradually adapting. • At present, Aquafeed 2.0 formulations remain dominant at commercial scale, reflecting a transition phase rather than full	• Resource efficiency is being enhanced through the adoption RAS for high-value species such as Penaeus kerathurus, Seriola spp., and flatfish. • The integration of renewable energy sources is increasingly common, alongside IMRAS configurations that maximize the reuse of water, nutrients, and thermal energy. • Digital tools for feed delivery, monitoring, and optimisation are being implemented to reduce feed losses and improve feed conversion efficiency

	circular value chains that valorise by-products such as aquaculture sludge, shells, and low-trophic biomass.	market penetration of next-generation feeds.	

The technological development (**Table 14**) acts as a key driver of circular transition. However, this is uneven throughout the eight countries. RAS, IMTA, and BFT technologies are technically mature but not equally accessible in all territories. Adoption is concentrated in countries with strong R&D ecosystems (IT, ES, FR) and among large or vertically integrated producers, while SMEs remain largely excluded. **The scale drives the production model.** _Large producers_ can absorb the high capital expenditure (CAPEX), energy costs, and technical complexity of RAS and advanced IMTA. _Small and medium producers_ are more compatible with modular, low-tech, or nature-based solutions (IMTA extensions, aquaponics, wetlands, eco-tourism integration). Although **IMTA shows the highest cross-country relevance, this model is still weakly implemented.** IMTA is consistently identified as environmentally and socially beneficial, particularly in protected or spatially constrained areas, yet remains mostly pilot-scale due to regulatory ambiguity and lack of co-licensing frameworks. **Other circular models such as BFT remains underutilised despite high potential**. BFT offers strong water and feed efficiency benefits but is constrained by skills requirements and lack of demonstration farms, especially in EU Mediterranean and Balkan regions. Moreover, **demonstration hubs and pilots were identified as critical enablers.** Regions with living labs, pilot zones, or demonstration farms (e.g. LiRRIEs, AZA pilots, Interreg projects) show higher stakeholder engagement and faster learning curves.

Table 14. *Technology Adoption about circular aquaculture in eight countries involved in AZA4ICE project*

	Available circular production models	***Feasibility for small vs. large-scale producers***
IT	• There exist high levels of technology diversification. IMTA systems are implemented in Sardinia, combining seabass/seabream with oysters and halophytes. • RAS is commercially established for high-value species, including Litopenaeus vannamei (shrimp) and marine finfish in Emilia-Romagna and Tuscany.	• Large and vertically integrated producers are best positioned to adopt RAS and advanced IMTA due to high CAPEX and technical requirements. • SMEs more easily engage with IMTA extensions (bivalves, plants) and aquaponics, particularly when supported by regional funding and research partnerships.

	• Biofloc Technology (BFT) is tested in shrimp and tilapia pilots in southern regions (Sicily, Apulia), • Aquaponics remains limited to small-scale educational and pilot initiatives (e.g. Bluegrass, BeBlue – Interreg IT–SLO).	• BFT remains technically feasible but constrained by expertise requirements.
CR	• RAS is present but limited, mainly due to high investment and energy costs, although attractive for niche, high-value products. • BFT is under academic research with high theoretical potential for scaling, reducing water exchange and providing microbial protein. • IMTA is at early research and demonstration stages, with projects such as BIOBASED aiming to transfer the model to SMEs.	• Large producers can better absorb RAS costs and employ skilled staff. • SMEs face financial and technical barriers but may adopt lower-cost circular solutions (e.g. IMTA add-ons or BFT in water-limited contexts) if supported by targeted funding and training. EMFAF incentives partially mitigate adoption risks.
BU	• RAS adoption remains limited and mostly experimental, with few commercial examples such as African catfish (Clarias gariepinus) production in Panagyurishte. • There are no documented operational examples of IMTA or BFT.	• High-tech circular systems (RAS, IMTA) require substantial capital investment and specialised expertise, making them more suitable for medium to large producers. • Small farms face significant barriers due to financing constraints and limited technical capacity.
FR	• Circular production models remain largely at pilot scale. • Business cases such as Les 4 Marais and Eauzon explore integrated and low-impact systems, but commercial-scale IMTA, BFT, or nutrient-recovery systems are not yet widespread.	• Pilot and experimental systems are accessible to innovative SMEs with public support, but scaling to commercial circular systems remains challenging. • Large producers retain an advantage due to capital access and regulatory capacity.
GR	• Circular technologies such as RAS, IMTA, and BFT are mainly confined to research or pilot initiatives. • Commercial marine aquaculture remains dominated by conventional cage systems, with limited integration of nutrient-recovery or multi-trophic approaches.	• Large companies have greater capacity to test advanced systems, while SMEs face high financial and regulatory barriers. • The absence of downstream valorisation pathways further limits incentives for circular adoption.

MO	• Montenegro operates a hybrid mix of traditional and emerging circular systems. • RAS pilots for trout are operational inland • IMTA demonstrations combine finfish and mussels in Boka Kotorska Bay, • Aquaponics and constructed wetlands are implemented in LiRRIEs pilot zones. • BFT is recognised as promising but not yet implemented commercially	• Small producers (<50 t/year) can feasibly adopt low-cost systems such as aquaponics, constructed wetlands, and eco-tourism integration. • Medium to large farms (>100 t/year) are better positioned for RAS and IMTA. Scaling depends on grant co-financing and technical training led by IMBK.
PO	• Circular aquaculture is emerging, with RAS as the most advanced model (e.g. SEAentia producing meagre). • IMTA is explored mainly in research contexts combining macroalgae, bivalves, and finfish, while BFT remains experimental.	• Large producers and R&D-oriented startups can invest in capital-intensive RAS. Small coastal farmers face financial and knowledge barriers, limiting access to circular technologies. • Expanded funding, advisory services, and demonstration systems are required for inclusive adoption.
SP	• RAS is well-established for high-value species such as flatfish, shrimps and Seriola spp., • Hybrid IMRAS coupling RAS and ponds for low-trophic biomass appear as a highly competitive model • Aquaponics is present mainly in freshwater systems and at pilot scale in marine water. • BFT is restricted to demonstrations, while open-sea IMTA is not operational and remains at land-based pilot scale.	• RAS is largely restricted to large investors due to high capital and skill requirements including digitalisation, life-cycle, biosecurity and market • . IMTA and aquaponics offer stronger potential for SMEs, particularly in protected marine or peri-urban areas when species combinations and scale are carefully designed. • BFT is low explored

With respect to the regulations (**Table 15**), most of the countries did not identify dedicated national or regional regulatory incentives or frameworks explicitly targeting circular aquaculture models. Although most of strategic plans identify **sustainability as a key driver in aquaculture** and some law recognise IMTA, the current regulation for circular aquaculture is scarce. Most of respondents highlight that regulatory and financial support for circular aquaculture s primarily anchored in EU frameworks. Some gaps re related with regulation fragmentation, high costs, limited skill labour and lack of specific certifications.

Table 15. *Regulatory Support about circular aquaculture in eight countries involved in AZA4ICE project*

	Regulations/incentives for circular transitions	**Regulatory gaps or barriers**
BU	• This country has adopted a National Strategy and Action Plan for the Circular Economy (2022–2027) and the BULGARIA 2030 National Development Programme, which provide an overarching policy basis for sustainability and circularity, including aquaculture.	• Licensing remains complex and slow, involving multiple authorities with limited digital integration. • There is no specific legislation or guidance for advanced systems such as RAS or IMTA, which must operate under traditional monoculture regulations, creating legal uncertainty. • The absence of targeted tax incentives, simplified procedures, and accessible funding instruments further constrains uptake, particularly for SMEs.
CR	• Regulatory support is strongly aligned with EU policy and financing instruments. • EMFAF provides substantial funding for low-carbon aquaculture, water efficiency, pollution reduction, organic production, and green technologies such as RAS and IMTA. • The national “Beyond the Pond” roadmap (2020–2030) promotes a shift toward higher-quality, sustainability-based market positioning. • Eco-certification schemes (ASC, organic) are encouraged to improve transparency and market access, while Interreg projects (e.g. AdriaAquaNet, BIOBASED) support knowledge transfer and SME capacity-building.	• Despite strong incentives, several barriers persist: complex and time-consuming licensing procedures • Lack of a fully coordinated national circular economy framework; regulatory ambiguity regarding the classification and reuse of aquaculture by-products • High upfront costs for SMEs • Limited availability of skilled labour • Still-developing consumer demand for certified circular products.
FR	• There are currently no dedicated regulatory incentives or	• Sanitary and zoo sanitary approval procedures are extremely complex and represent a major obstacle to

	frameworks explicitly targeting circular aquaculture models.	new projects, regardless of species or system. • Regulatory inconsistencies create additional barriers: for example, aquaponics systems cannot be certified organic because fish-derived nutrients are not recognized as organic inputs for plants
GR	• Greece benefits from a relatively strong mix of certification schemes and financial incentives. International eco-certifications (ASC, Friend of the Sea) and the national "Fish From Greece" protocol promote environmentally responsible practices and market differentiation. • State laws (Development Law 4887/2022 and amendments) and the EMFAF 2021–2027 programme allocate substantial funding to sustainable, circular, and low-carbon aquaculture investments, including waste reuse, energy efficiency, and innovation.	• Administrative complexity remains a major constraint, as subsidy applications require coordination across multiple ministries. • Circular economy principles are not yet fully embedded in aquaculture licensing procedures, leading to unclear eligibility and longer approval times for IMTA, RAS, and waste-valorisation investments, particularly for SMEs.
IT	• Regulatory and financial support for circular aquaculture in Italy is primarily anchored in EU frameworks. • The European Maritime, Fisheries and Aquaculture Fund (EMFAF 2021–2027) provides funding for eco-innovation, waste management, energy efficiency, and sustainability certification. • At regional level, Sardinia's Aquaculture Allocation Zones (AZA) plan, currently under Strategic Environmental Assessment (VAS), facilitates sustainable siting and simplifies permitting. • While no national eco-label specific to circular aquaculture	• The main barrier is the fragmentation of competences between national and regional authorities, resulting in lengthy and complex authorisation processes. • This particularly affects innovative systems such as RAS and IMTA, where permitting pathways remain unclear or inconsistent across regions.

	exists, producers can access international schemes such as ASC certification and local environmental quality labels in protected areas, which reward good practices and enhance market positioning.	
MO	• Regulatory framework is evolving toward circularity through strategic alignment rather than dedicated legislation. • National sectoral strategies, IPARD III funding, and environmental regulations support eco-innovation, waste minimisation, energy efficiency, and sustainable aquaculture. Preparatory work is underway to introduce eco-certification schemes aligned with EU standards, supported by national institutions and EU-funded projects.	• Key gaps include the absence of a legal definition of circular aquaculture, lack of rules enabling reuse of aquaculture by-products, fragmented institutional responsibilities, outdated EIA procedures, missing eco-labelling systems, and limited financial instruments tailored to small-scale circular upgrades.
PO	• Currently lacks dedicated regulatory instruments or incentive schemes specifically supporting circular aquaculture. • Although strategic plans promote sustainability and low-carbon systems, practical incentives and eco-certification frameworks remain limited. Support for organic aquaculture exists but could be strengthened to offset certification costs and administrative burdens.	• Existing legislation does not distinguish circular or integrated systems (IMTA, RAS) from conventional aquaculture, resulting in regulatory uncertainty. • The absence of targeted financial mechanisms, simplified licensing, and circular-specific guidance limits the effective transition toward circular production models.
SP	• Transition toward circular aquaculture primarily through new funding instruments under EMFFA 2021-2027. • At strategic level, Spain is also advancing the Circular Bioeconomy Action Plan for the Agri-Food Value Chain (2025-2030), which provides a broader policy framework to integrate	• Lack of sufficient financing to cover both the initial investment required for innovation and the long-term economic viability of projects. • National regulatory framework for circular solutions-particularly remains incipient and, in some cases, restrictive, limiting project development and scalability.

	circularity across primary production systems, including aquaculture, with a focus on innovation, sustainability, and territorial cohesion. • Andalusian regional low identifies IMTA as targeted production model • There are no specific incentives for circularity in aquaculture.	• Fragmented permitting processes and absence of harmonised indicators to measure circularity in aquaculture systems at national and EU level. • Financial uncertainty, regulatory complexity, and limited performance metrics contributes to low social acceptance and stakeholder mistrust toward circular projects.

Across countries, **markets demand** (**Table 16**) for circular aquaculture products grows faster in **low-trophic species, particularly molluscs**, and **territorially branded products** than in novel foods such as algae. Entrepreneurial success depends on matching sustainability narratives with local preferences (origin, freshness, trust) and targeting urban, premium, or export markets where circular value is recognised. The circular products and services identified with the highest potential for market uptake, scalability, and investment attractiveness were:

1. **Established demand segments with immediate market potential. Low-trophic species,** particularly **bivalves**, represent the most mature and reliable market segment for circular aquaculture. Also, in some territories, **salicornia and other halophytes** is rapidly gaining interest as gourmet products. These food products benefit from strong consumer acceptance, low feed dependency, and favourable environmental performance. Demand is especially robust in all the Mediterranean regions where shellfish consumption is culturally accepted, and supply chains are already established. **Considering this market demand**, **IMTA and IMRAS systems integrating shellfish and Salicornia** has a high potential with a short supply-chain production models, and the valorisation of shell by-products into construction materials, soil amendments, or industrial inputs.

2. **Policy-driven markets with medium-term growth potential.** Demand for **eco-labelled** and **sustainably certified seafood** is increasing, supported by EU policy frameworks, public funding instruments, and export market requirements. While consumer willingness to pay premiums varies across regions, certified products seem to benefit from improved market access, differentiation, and long-term competitiveness. **Entrepreneurial opportunities** in this segment include certified finfish and low-trophic production, territorial branding strategies, traceability and digital labelling services, and export-oriented processing and logistics.

3. **Emerging markets for biomass and non-food applications.** Marine and coastal biomass derived from circular aquaculture systems represents a strategic growth area, driven more by industrial and policy demand than by direct consumer markets. Applications in aquafeeds, bioactive compounds, soil amendments, and circular agricultural biofertilizers show higher scalability and fewer behavioural barriers than food markets such as algae for direct consumption. Opportunities include IMTA/IMRAS-based biomass production and biorefinery-oriented business models. These activities are well suited for regions prioritising circular bioeconomy development and industrial symbiosis.
4. **Niche and experimental markets.** Certain circular aquaculture products such as sea cucumbers and some algae remain niche, including under-utilised species and novel food products. Market acceptance is highly dependent on effective communication, food safety assurance, and territorial or gastronomic positioning. These markets are best addressed through pilot projects, living labs, eco-tourism integration, and demonstration farms rather than large-scale commercial deployment.

Table 16. *Market Insights for entrepreneurs about circular aquaculture in eight countries involved in AZA4ICE project*

	Demand for circular products	**Opportunities for new ventures**
BU	• Domestic demand for circular or eco-certified aquaculture products remains low. Purchasing decisions are largely driven by price and availability rather than sustainability attributes. • Awareness of eco-labels and low-trophic species (mussels, oysters, seaweed) is limited, and export opportunities are constrained by small production volumes and weak certification uptake.	Urban aquaculture and circular startups theoretically offer potential, but practical deployment is constrained by high costs, limited expertise, regulatory complexity, and lack of trained personnel. Market development would require parallel investment in skills, infrastructure, and targeted consumer communication
CR	• Demand for sustainable and circular aquaculture products is growing but remains price-sensitive. Eco-labels are recognised but are not yet the primary purchasing driver; consumers prioritise species, local origin, and freshness. • Low-trophic species such as mussels and oysters enjoy strong coastal	• Urban aquaculture (RAS, aquaponics) represents a strong opportunity, enabling production close to consumers, reduced transport emissions, and premium positioning based on freshness and traceability. • Additional opportunities exist in waste-stream valorisation

	demand, while interest in algae and seaweed is emerging but not yet mainstream.	(biofertilisers, nutraceuticals, alternative feeds) and in service-oriented businesses providing IMTA implementation or smart-farming solutions (sensors, data analytics) to existing farms.
FR	• Markets for circular or alternative aquaculture products remain niche, with uncertainty regarding volume demand. While sustainability is discussed, consumer acceptance of non-traditional species (e.g. mullet) is uncertain, limiting incentives for diversification beyond established species.	• Although many innovative concepts and pilot projects are proposed, relatively few reach implementation. Market uncertainty and regulatory barriers reduce investor confidence, slowing the emergence of new circular aquaculture ventures.
GR	• A majority of Greek consumers state that environmentally friendly production is important, but willingness to pay a price premium remains limited. Awareness and understanding of eco-labels (ASC, MSC) are relatively low, although preference for local, fresh, and domestically produced seafood is strong. • Studies indicate openness to underutilised or novel species when safety and certification are clearly communicated.	• Entrepreneurs can target a growing segment of environmentally conscious consumers by emphasising local origin, freshness, and credible certification. Low-trophic and underutilised species offer strategic potential, particularly when paired with strong branding and assurance of food safety. • Certified producers may access export markets and premium segments, although certification costs and communication efforts remain critical challenges
IT	• Consumer demand for sustainably produced seafood is steadily increasing, particularly in large retail chains and the restaurant sector. Eco-labels such as ASC and MSC are increasingly recognised as signals of traceability and environmental responsibility. • Low-trophic species (mussels, clams, oysters) already have strong market acceptance, especially in Sardinia, where shellfish farming is well established and aligned with sustainability expectations.	• Italy offers strong opportunities linked to product diversification and innovation, including new farmed species, algae-based functional foods, and nutraceutical ingredients. • Additional potential lies in upgrading existing farms through energy efficiency, digitalisation, and ecosystem-friendly technologies. • Access to finance is supported by EU instruments and venture capital (e.g. Blue Revolution Fund), while sectoral events

		(AquaFarm, Pordenone) and incubators (e.g. I3P – Politecnico di Torino) foster entrepreneurship and technology transfer.
MO	• Market demand for explicitly circular or eco-labelled aquaculture products is still limited, with consumption driven mainly by freshness, price, and local origin rather than sustainability attributes.	• Opportunities lie in niche markets combining local production, eco-tourism, and short supply chains, particularly around lakes and coastal areas. Pilot-scale aquaponics, IMTA-linked products, and territorially branded seafood could gradually build demand as awareness increases
PO	• Demand for eco-certified and circular aquaculture products remains modest but is slowly increasing. • Consumers prioritise price and freshness, yet international markets show growing interest in eco-labelled seafood and low-trophic species. • Territorial branding and certification (e.g. Ria Formosa products) demonstrate the potential to enhance recognition and value.	• Promising opportunities include freshwater aquaponics in inland regions and the valorisation of shell-derived materials for ponds, shellfish beds, and urban applications. • Pilot initiatives combining municipalities, research centres, and private actors can support local value creation and circular business models.
SP	• Demand for molluscs is very high, and interest in halophytes such as salicornia is increasing, while consumer demand for algae as food remains limited. • There is growing demand for marine biomass as key sector of blue economy for non-food applications and side-stream valorisation. • Products linked to protected areas and sustainability narratives benefit from strong market positioning.	• Spain offers significant opportunities in regenerative and circular aquaculture, particularly in high-protection areas. • Promising models include flatfish IMRAS systems, marine aquaponics, and the upscaling of marine biomass as a new resource for side-stream applications (feed, bioactive compounds, ecosystem services). • These ventures align well with policy priorities and premium market segments

Strategic investment points

- **Circular aquaculture offers a portfolio of opportunities** with differentiated risk profiles, ranging from low-risk shellfish systems to higher-value biomass and biorefinery applications.
- **Low-trophic species provide a stable entry point for entrepreneurs,** combining market acceptance, environmental performance, and policy alignment.
- **Aquaculture close to local markets and peri-urban** aquaculture models favours premium positioning through freshness, traceability, and reduced environmental footprint.
- **Biomass valorisation represents a key scaling pathway**, with strong alignment to feed, agriculture, and bioeconomy markets.
- Public funding instruments significantly de-risk early investment stages, enabling private capital to focus on scaling and replication.
- **Market success benefits** on the integration of production efficiency, certification, and credible sustainable models.

4.1 Transition for Existing Businesses

Circular transition in existing businesses is expected to meet the increasing global demand for seafood while minimizing its ecological footprint. Some key points for this transition are:

a) Assess current aquaculture practices.

A first step is to carry out a structured, LCA-based audit to identify material and energy inefficiencies across the production chain, with particular attention to waste streams such as uneaten feed, sludge, and dissolved nutrients. Applying PEF/OEF methodologies in line with recommendation (EU) 2021/2279 facilitate the operators to benchmark environmental performance, prioritise hotspots, and define realistic improvement targets based on comparable indicators.

b) Analyse and transition toward circular technologies

A critical step in the transition to circular aquaculture is the systematic analysis and progressive adoption of circular production technologies, such as RAS, IMTA, BFT, or the hybrid systems. For existing businesses, the transition should *not be framed as a single technological choice*, but as **the detailed analysis of a portfolio of circular production models**, such as those described in this guide, tailored to **local environmental conditions, cultured local species, site characteristics, and regulatory constraints**.

Once suitable options are identified, operators must evaluate the **technical, economic, and regulatory feasibility** of transforming the current business model toward a more circular design. Investment requirements, system design, and operational complexity should be carefully balanced against expected outputs, market opportunities, and risk exposure. Given the wide range of possible species–system-environment combinations, decision-support tools, such as those developed within the AZA4ICE framework, are essential to support evidence-based planning and reduce uncertainty during the transition phase.

Beyond farm-level redesign, transitioning businesses should **actively foster collaboration** across the value chain to enhance resource efficiency and minimize waste. Partnerships with agriculture, food processing, or energy sectors can enable the valorisation of by-products (e.g. reuse of organic residues, nutrient recovery, or energy integration), reducing operating costs while strengthening local circular economies.

c) Implement eco-design principles.

Production units should be redesigned using **eco-design concepts**, such as modular configurations, prioritizing low-trophic extractive species, and flexible scaling. Moreover, the integration of advanced monitoring systems and data analytics can significantly enhance the transition to circular aquaculture by providing **real-time insights into environmental conditions and operational efficiencies**. For instance, employing sensors to monitor water quality parameters facilitate timely interventions. Additionally, the adoption of biodegradable materials o renewable energies not only support the sustainability of aquaculture operations but also align with the broader objectives of the circular economy.

d) Engage in industrial symbiosis.

Circular performance can be significantly enhanced by establishing cross-sector partnerships. Aquaculture by-products such as sludge or heat can be repurposed for biogas production, soil fertilisation, or energy recovery, creating additional revenue streams while reducing disposal costs and environmental externalities. Moreover, new technologies need to be integrated such as the application of anaerobic digestion processes that can convert sludge into biogas or employing pyrolysis techniques that can yield biochar from waste products, providing not only a means of carbon sequestration but also a valuable soil amendment.

e) Pursue eco-certification.

The successful transition to circular aquaculture necessitates a robust framework for monitoring and evaluating the impact of implemented practices over time. involves the establishment of **key performance indicators** (KPIs) that assess not only environmental outcomes but also social and economic dimensions, thereby ensuring a holistic approach to sustainability.

Obtaining **recognized sustainability certifications**, such as those from ASC, strengthens market access, improves transparency, and signals environmental and social responsibility to buyers, retailers, and consumers. As the market for eco-labelled seafood continues to evolve, the potential for innovative financing models, such as impact investing or green bonds, could provide the necessary capital for aquaculture businesses to scale their sustainable initiatives.

Additionally, as businesses adopt these circular practices, it is imperative to recognize the **role of consumer education** in fostering a sustainable aquaculture market. By increasing awareness of the environmental benefits associated with circular aquaculture consumers can make more informed choices that align with their values. This shift in consumer behaviour can drive demand for sustainably produced seafood, thereby incentivizing producers to invest in eco-friendly practices. Furthermore, the integration of technology in consumer engagement, such as blockchain for traceability, can enhance transparency in the supply chain and build trust among consumers regarding the sustainability of their food sources.

f) Train and upskill staff

Human capital is critical for circular transition. Targeted training in LCA, PEF/OEF methodologies, IMTA or RAS operation, low trophic biomass technology, digitalization, and regenerative practices ensures that staff can operate complex systems effectively, interpret sustainability metrics, and continuously improve performance.

g) Apply a life-cycle approach.

Finally, integrate life cycle thinking into strategic and operational decision-making based on LCA application across feed sourcing, on-farm production, processing, and waste management.

4.2 Transition for New Entrepreneurs

For new entrepreneurs, they should analyse clearly the local markets and opportunities using this roadmap:

a) Identify market needs

New entrants should start by identifying **clear and differentiated market needs and opportunities** aligned with sustainability and circularity objectives. Priority markets include **eco-labeled products, low-trophic species** (e.g. carp, bivalves, seaweeds, halophytes), and **close-to-market or peri-urban aquaculture models** that respond to local demand, short supply chains, and environmental constraints.

Entrepreneurs should focus on **market pull rather than technology push**, assessing who the final buyers are (retail, horeca, processors, bioindustry), what attributes they value (freshness, origin, certification, environmental performance), and what price premiums are realistically achievable. Positioning products within **circular and zero-waste narratives from the beginning** allows new ventures to access higher-value niches, anticipate regulatory trends, and reduce long-term market and compliance risks.

b) Feasibility and system selection

Conduct a technical, economic, and regulatory feasibility study for circular technologies (e.g. IMTA, RAS, BFT, hybrid systems), supported by experts or LCA to compare environmental performance and system suitability for local conditions.

c) Develop a circular business plan

Circularity should be embedded at the **core market strategy** not added as a secondary feature. Business plans should integrate **eco-design**, biomass upcycling, and **next-generation aquafeeds** (Aquafeed 3.0). From a market perspective, these elements strengthen product differentiation, support certification claims, and enhance resilience to input price volatility.

Entrepreneurs should assess the **value-chain network** as an integrated system combining technical, legal, economic, and environmental dimensions (Cadena *et al.* 2024):

- *Technical dimension*: seasonality of production, geographic dispersion of suppliers and buyers, cold-chain and storage requirements, and logistics constraints.
- *Economic dimension*: CAPEX, operational expenditure (OPEX), revenue streams, and sensitivity to market price fluctuations.
- *Legal dimension*: compliance with feed and food legislation, validity of permits, and quality parameters relevant to market access (e.g. peroxide value, free fatty acids).
- *Environmental dimension*: carbon footprint, acidification potential, freshwater eutrophication, and water use.

The resulting performance scores provide a pragmatic basis for identifying strengths, weaknesses, and priority areas for improvement in the business model.

d) Pilot and proof of concept

Implement small-scale pilot systems designed around zero-waste objectives, nutrient recovery, and low-risk species combinations. Pilots allow validation of technical performance, management skills, and market response before full investment.

e) Progressive scaling and monitoring

Scale up operations with financial and technical support, maintaining continuous monitoring of water, nutrients, and resource efficiency. Use PEF/OEF indicators to track environmental performance and demonstrate compliance and improvement over time.

f) Join to partnerships and knowledge networks.

New entrepreneurs often face technical and regulatory complexity. Collaborating with research institutions, technology providers, clusters, or NGOs can significantly reduce entry barriers. These partnerships provide access to expertise in regenerative practices (e.g. IMTA, biofilters, extractive species), and monitoring tools, while also strengthening project credibility during licensing and funding applications.

g) Secure targeted funding.

Access to finance is critical during the early stages. Entrepreneurs should actively explore public grants, innovation vouchers, green loans, or blended finance instruments specifically targeting GES-aligned and circular aquaculture projects. Aligning proposals with EU Green Deal objectives, Blue Economy strategies, and nutrient reduction policies increases success rates and can reduce capital costs during system deployment and scaling.

h) Market integration and continuous improvement

Strengthen market positioning through eco-certification, transparent communication, and traceability, while continuously refining system design and partnerships. Feedback loops between production, market demand, and environmental performance ensure long-term adaptability and competitiveness.

5. Circular Aquaculture Business Opportunities

5.1 Market Gaps

Aquaculture is rapidly growing and currently overpassed fisheries contribution to seafood (see section 1.2 Overview of Aquaculture in Europe). This is **tremendous opportunity for Europe to engage new generation of producers** of high-quality products. In 2022, global aquaculture reached 130.9 MTn, **with Asia accounting for 91.4% of total output (119.7 Mt), and Europe only 2.7%**. This imbalance reveals a structural dependence on Asian supply, driven largely by China alone (57.6% of global production), exposing international markets to supply risks, price volatility, and geopolitical tensions (APROMAR 2024; FAO 2024).

From a growth perspective, Asia (+3.7%), North and South America (+10.3%), and Africa (+0.7%) expanded **whereas Europe contracted (-1.7%) in 2022**, highlighting a widening gap between regions with expansion capacity and those constrained by regulatory, environmental, and social limits. In Europe, this decline occurs despite **rising demand for aquatic products**, **deepening the trade deficit** and underscoring a clear opportunity to pivot toward **more efficient, circular, and higher value-added production models** rather than competing on volume.

When production is assessed in economic terms, **fish account for the largest share of value, generating €131.5 billion in 2022 (52.6% of total aquaculture value), but crustaceans move into second place**, contributing €72.8 billion (29.1%), despite their lower production volume. Molluscs generated €25.3 billion (10.1%), while seaweeds accounted for €13.6 billion (5.4%). This **divergence between volume and value** clearly illustrates a structural market gap between **bulk biomass production and high-value aquaculture products**, a gap that is particularly relevant for future development strategies in Europe.

From an environmental perspective, 54.8% of global aquaculture production takes place in freshwater systems (71.8 Mt), while 45.2% occurs in marine and brackish waters (59.2 Mt). This balance underscores the strategic importance of inland aquaculture for global food security, while simultaneously highlighting the **significant growth potential of marine aquaculture**, particularly in regions facing land and water constraints. A typical feature of **marine aquaculture** is the high number of aquatic species cultivated (730 globally in 2022) including fish, molluscs, crustaceans, seaweeds, and other organisms. The global marine aquaculture market was estimated at USD 120.7 billion in 2024 and projected to grow 10.2% annually from 2025 to 2034 (Global market insights, Inc.). Nevertheless, production remains highly concentrated, as only 17 species accounted for approximately 60% of total global aquaculture output. **This combination of diversity and concentration reveals both technological lock-ins and a substantial untapped**

potential for species diversification, especially in regions with strong regulatory and environmental constraints.

Europe faces a paradox: it has one of the lowest shares of global aquaculture production, yet it combines high market demand, advanced technological capacity, strong research infrastructures, and ambitious environmental policies. These conditions position Europe as an **ideal region to lead the transition toward circular aquaculture models**, rather than competing on volume. Circular aquaculture offers Europe a clear pathway to close the gap between production volume and economic value. By integrating **extractive species (seaweeds, bivalves, polychaetes), valorising by-products, and reducing environmental pressures**, circular systems directly address Europe's **spatial, regulatory, and social constraints**. At the same time, they transform the production toward **high-value, certified**, and **low-impact products** aligned with consumer expectations and sustainability policies.

While all marine aquaculture production has a high potential as a business, particularly fish, shrimps and bivalves, **special attention deserves** Europe's underutilized potential of **low-trophic species** including primary producers (e.g. macroalgae) and **some primary consumers** (e.g. bivalves, worms, sea cucumbers), and **multifunctional biomass** (food, feed, bio-materials, ecosystem services) representing a **major market opportunity**. Rather than replicating high-volume Asian models, **Europe can strategically position itself as a global reference** for circular aquaculture, transforming structural limitations into a competitive advantage and contributing to long-term food security, environmental protection, and blue bioeconomy growth.

If we focus in the better studied sector of **primary producers micro- and macroalgae**, the global commercial **seaweed market size** has been extensively analysed. In 2025, this market value was estimated at USD 72.3 billion in 2025, and it was expected to grow to USD 142.6 billion in 2035, at a CAGR of 6.9% according to latest report published by Global Market Insights Inc.[41]. The global commercial seaweed market evolved from €41 billion in 2020 reached USD 72.3 billion in 2025. Europe led USD 9.5 billion in revenues in the commercial seaweed market and is expected to sustain strong growth in the coming decade. The region is increasingly positioning itself as a global hub for innovation in the seaweed bioeconomy, based on circular economy objectives, advanced research capacity, and a progressively supportive regulatory environment. A key driver is the **EU Algae Strategy** (2022)[42], which establishes a coordinated framework to scale up production, strengthen sustainability certification, and mobilize investment in research, pilot infrastructures, and downstream value chains.

[41] *https://www.gminsights.com/industry-analysis/commercial-seaweed-market*
[42] *https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:52022DC0592*

While in Eastern Asia algae have been an integral part of human diets for centuries, in Europe they are mainly considered as *niche or novel food product*. However, **direct consumption of whole seaweeds** is increasing in both Western and Asian markets since they are increasingly recognized for their high iodine content, dietary fiber, bioactive compounds, and antioxidant properties. Products such as nori-based snacks, kelp noodles, seaweed flakes, and seasonings are gaining market acceptance, particularly among flexitarian, vegetarian, and vegan consumers.

However, **this seaweed-based industry has a limited demand,** and the sector is transitioning from a predominantly **commodity-based model** toward a high-value bioeconomy platform. **Hydrocolloids** remain the economic backbone of the sector, while biofertilizers, nutraceuticals, and advanced biomaterials represent rapidly expanding revenue streams. Hydrocolloids (alginate, agar, and carrageenan) constitute account for more than 40% of total commercial seaweed sales worldwide. From a market structure perspective, **red algae** such as *Eucheuma* and *Gracilaria* are the primary raw materials for carrageenan and agar, while **brown seaweeds,** particularly *Laminaria*, are the backbone of alginate extraction. This segmentation reflects clear value chains in which red and brown algae supply high-volume, high-value industrial markets with strong price stability compared to niche or emerging applications. Food and beverage sector represents the largest market (by hydrocolloids), accounting for 33.9% of total revenue in 2025, and is projected to expand at a 6.8% until 2035.

As biofactories, the biochemical compounds and properties make algae a valuable ocean material, paving the way for a growing number of potential commercial applications also outside the food industry: animal/fish feed and feed additives, medical devices, pharmaceuticals, nutraceuticals, fertilisers, plant biostimulants, bio-packaging, cosmetics or biofuels (Commission *et al.* 2025).

Despite the high potential of the algae sector, this faces **significant challenges to overcome**. Algae farming is urgent. Most of algae are harvested annually from wild stocks or beach-cast Currently, handling costs remain high, data are still lacking for several applications, cultivation volumes are limited, and further research and technological development are needed (European Parliament: Directorate-General for Internal Policies of the 2023; Commission *et al.* 2025).

As previously noted, **halophyte cultivation within marine aquaponics systems** is still at an early stage of development, much like the algae sector. Nevertheless, halophytes share many of the same application pathways as macroalgae, ranging from food and feed to nutraceuticals, bioactive compounds, and environmental services thereby supporting the emergence of a new, high-potential niche for entrepreneurs. Their integration into aquaponic and IMTA-type systems offers opportunities to valorise saline water streams, recover nutrients, and develop diversified, circular production models tailored to innovative markets and novel applications.

Numerous studies have estimated the incomes associated with the valorisation of **aquaculture by-products** based on their biochemical composition and their potential as sources of high-value biomolecules. The re-utilisation of these sub-products makes feasible the recovery of ingredients with substantial market value for multiple industrial sectors, including food, nutraceuticals, cosmetics, pharmaceuticals, and animal feeds (Fraga-Corral *et al.* 2022) as indicated below:

- **Protein ingredients** represent the largest market (Food and nutraceutical), reaching approximately USD 52.5 billion in 2020, driven by the growing demand for sustainable food and nutraceutical products.
- **Omega-3 polyunsaturated fatty acids** (PUFAs) also account for a significant market (Food, infant formula, nutraceutical, pharmaceutical and animal feed, valued at around USD 2.2 billion in 2020, reflecting their widespread use in food, infant formula, pharmaceuticals, and animal nutrition.
- **Collagen and gelatine,** extensively applied in food, nutraceutical, medical, and cosmetic industries, reached market values of approximately USD 3.5 billion and more than USD 1.5 billion, respectively.
- Other biomolecules with slightly smaller but rapidly expanding markets include **chitosan** (Food, food industry, cosmetics, and water treatment), with an estimated global market size of USD 1.5 billion, and high-value pigments such **as astaxanthin and β-carotene** (Nutraceutical, cosmetics, aquaculture and animal feed) whose markets exceeded USD 0.6 billion and USD 0.5 billion, respectively. Although these latter compounds represent lower volumes, their high added value and functional properties make them particularly attractive for specialised applications

5.2 Funding and Financing Opportunities

This section outlines the financial requirements and identifies potential funding sources needed to implement the proposed actions effectively. It should address both investment costs and operational sustainability.

Public funding will play a catalytic role, particularly in the early phases of system design, piloting, and validation. Main EU funding sources for aquaculture were previously identified by *EU Aquaculture Assistance Mechanism* [43]*:*

sources including:

- European Maritime, Fisheries and Aquaculture Fund (EMFAF)
- BlueInvest, Horizon Europe
- European Innovation Council (EIC)

[43] *https://aquaculture.ec.europa.eu/knowledge-base/guidelines/background-paper-eu-funding-opportunities-available-aquaculture*

- Programme for Environment and Climate Action (LIFE)
- European Regional Development Fund (ERDF)
- Erasmus+
- Innovation Fund (IF)
- European Agricultural Fund for Rural Development (EAFRD)
- European Social Fund (ESF+)
- Modernisation Fund (MF)
- Recovery and Resilience Facility (RRF)

5.2.1 European Maritime, Fisheries and Aquaculture Fund (EMFAF)

The EMFAF[44] is the fund for the EU's maritime and fisheries policies for 2021-2027. It provides support for developing innovative projects ensuring that aquatic and maritime resources are used sustainably. This leads to:

- food security through the supply of seafood products
- growth of a sustainable blue economy
- healthy, safe and sustainably managed seas and oceans

It also helps achieve the UN's Sustainable Development Goal 14 (Conserve and sustainably use the oceans, seas and marine resources), to which the EU is committed. Furthermore, the EMFAF helps fulfil the objectives of the European Green Deal, the roadmap for the EU climate and environmental policies.

Beneficiaries of the EMFAF may include, unless otherwise provided in the Regulation:

- **Operators**, that is, any natural or legal person who operates or holds any undertaking carrying out activities related to any stage of the production, processing, marketing, distribution, and retail sale chains of fisheries and aquaculture products.
- **Fishers or fishermen, or their organisations**. For example, association from the fisheries, shellfishing, and aquaculture sector.

The EMFAF 2021–2027 is organised into four priorities:

- **Priority 1**. Fostering sustainable fisheries and the restoration and conservation of aquatic biological resources.
- **Priority 2**. Fostering sustainable aquaculture activities, and processing and marketing of fisheries and aquaculture products, thus contributing to food security in the Union.

[44] *European Maritime, Fisheries and Aquaculture Fund (EMFAF) https://oceans-and-fisheries.ec.europa.eu/funding/emfaf_en*

- **Priority 3**. Enabling a sustainable blue economy in coastal, island and inland areas, and fostering the development of fishing and aquaculture communities.
- **Priority 4**. Strengthening international ocean governance and enabling seas and oceans to be safe, secure, clean and sustainably managed.

Each of these priorities is associated with specific objectives (SO) that must be met by the beneficiary countries. Four **objectives are directly related to circular aquaculture**:

- 1.5. Promoting a level-playing field for fishery and aquaculture products from the outermost regions,
- 2.1. Promoting sustainable aquaculture activities, especially strengthening the competitiveness of aquaculture production, while ensuring that the activities are environmentally sustainable in the long term.
- 2.2. Promoting marketing, quality and added value of fisheries and aquaculture products, as well as processing of those products.
- 3.1. Enabling a sustainable blue economy in coastal, island and inland areas, and fostering the sustainable development of fishing and aquaculture communities.

To advance towards a **more circular, resilient and competitive aquaculture**, the AZA4ICE partner countries establish the following objectives and lines of action:

- **Modernisation and expansion of aquaculture farms**, supporting investments in existing marine and freshwater facilities, as well as the establishment of new production capacities using technologies that reduce pressure on water resources and minimise environmental impacts.

- **Diversification of species and production**, promoting the transition from low-value to higher-value species, the development of new aquaculture products with higher market potential, and reducing dependence on a limited number of species.

- **Improving energy efficiency and decarbonisation**, through investments in renewable energy systems, resource-efficient technologies and climate-resilient production models, contributing to the reduction of the carbon footprint of aquaculture activities.

- **Innovation, digitalisation and knowledge transfer**, supporting the introduction of innovative production processes, digital monitoring systems, traceability tools and cooperation between research institutions and aquaculture operators, including synergies with Horizon Europe.

- **Reduction of waste and promotion of circular economy**, encouraging better utilisation of processing by-products, improved waste management and valorisation of side streams from aquaculture and processing activities.

- **Animal health, welfare and food safety**, strengthening biosecurity measures, sanitary control systems and quality standards to ensure safe and high-quality aquaculture products.

- **Development of processing and value-added activities**, supporting the processing of aquaculture products, reducing reliance on imported raw materials, increasing added value and improving the balance along the supply chain.

- **Market development and producer organisations**, fostering the creation of producer organisations, short supply chains, direct sales and improved market positioning of aquaculture products at national and international level.

- **Skills development and workforce renewal**, improving qualifications and technical skills of workers in the aquaculture sector, addressing labour shortages and supporting generational renewal.

The total budget for 2021-2027 is EUR 6.108 billion. The programme management is divided between shared management and direct management. EUR 5.311 billion is provided through national programs co-funded by the EU budget and EU countries and € 797 million is provided directly by the European Commission services or delegated to CINEA[45], with the relative calls being published in this Portal. **Table 17Table 17.** Fisheries and Aquaculture EMFAF Funding by Specific Objective and Country (values in EUR). PRIOR, Priorities; SO, Specific objectives shows the **contribution (in EUR)** allocated by each partner country in AZA4ICE to meet the aquaculture-related specific objectives under the **EMFAF 2021–2027**[46].

Table 17. *Fisheries and Aquaculture EMFAF Funding by Specific Objective and Country (values in EUR). PRIOR, Priorities; SO, Specific objectives*

	SO 1.5.	**SO 2.1.**	**SO 2.2.**	**SO 3.1.**	**EU PRIOR**	**EU SO**
BU	0	24.357.372	10.270.000	16.988.940	84.944.698	51.616.312
CR	0	47.104.770	49.361.701	33.242.915	243.687.047	129.709.386
FR	76.817.263	112.266.533	84.103.293	2.805.714	567.136.526	275.992.803
GR	0	62.160.000	29.120.000	49.910.000	363.746.026	141.190.000
IT	0	73.000.000	97.216.474	51.907.347	518.216.830	222.123.821
PO	48.807.867	66.000.000	74.500.000	33.750.000	392.572.022	223.057.867
SP	61.600.000	153.489.504	267.595.648	111.555.777	1.120.441.924	594.240.929

[45] *CINEA - The European Maritime, Fisheries and Aquaculture Fund; https://cinea.ec.europa.eu/programs/european-maritime-fisheries-and-aquaculture-fund_en*
[46] *Montenegro is not included in the analysis due to the lack of available data.*

Bulgaria, Portugal, Croatia and Spain allocate **more than 50% of their EMFAF 2021–2027 EU contribution** to prioritise specific objectives related to aquaculture, whereas **Greece allocates the lowest share (39%)**, followed by **Italy** (43%) and **France** (49%).

Regarding the distribution of funding across the aquaculture-related specific objectives, **Priority 2 objectives receive the highest allocation in all AZA4ICE partner countries** (**Figure 7**).

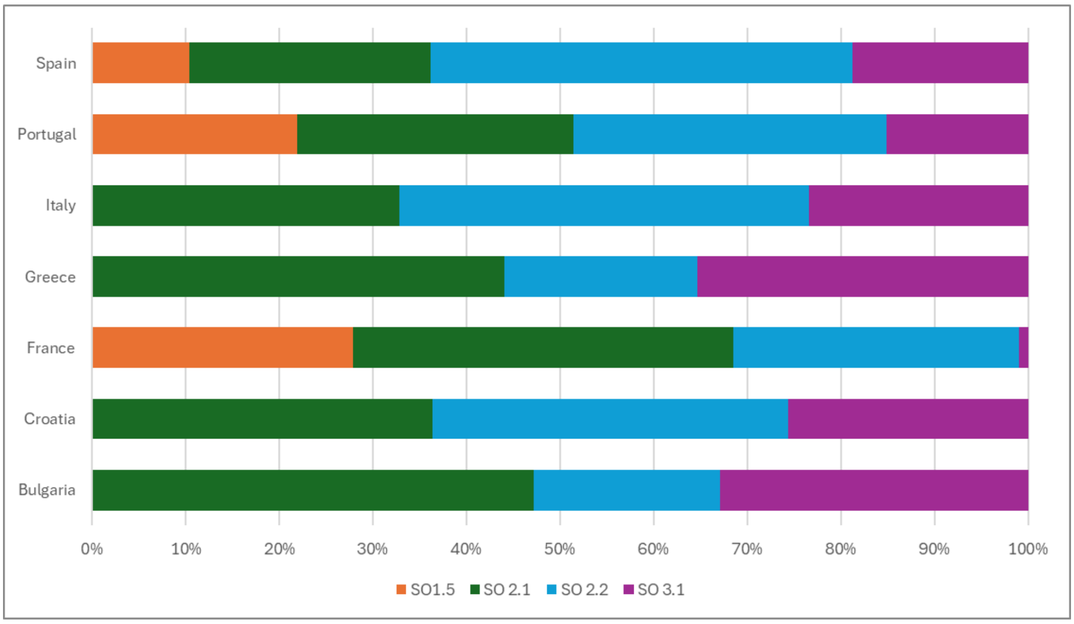

Figure 7. *Distribution of EMFAF 2021–2027 contributions to aquaculture by specific objective (%) across AZA4ICE partner countries.*

5.2.2 Other Funding and Financing Opportunities

Beyond the EMFAF, a range of complementary funding and financing instruments also support the transition toward circular and sustainable aquaculture across Europe. These opportunities combine EU-level financial mechanisms with national implementation pathways, facilitating operators and new entrepreneurs to access capital for innovation, diversification, skills development, and circular business models.

At the European level, circular aquaculture projects may benefit from **Horizon Europe**[47] and **Interreg programs**[48], which support applied research, pilot systems,

[47] *Horizon Europe; https://research-and-innovation.ec.europa.eu/funding/funding-opportunities/funding-programs-and-open-calls/horizon-europe_en*
[48] *Interreg Europe; https://www.interregeurope.eu/*

and cross-border cooperation on technologies such as IMTA, RAS, nutrient recycling, digital monitoring, and by-product valorisation. These programs are particularly relevant for early-stage innovation, demonstration projects, and partnerships between enterprises, research institutions, and public authorities.

In parallel, financial instruments supported by the **European Investment Bank (EIB)**[49] and the **European Investment Fund (EIF)**[50] increasingly target blue economy and sustainability-oriented SMEs, including aquaculture startups with scalable circular business models. These instruments facilitate access to loans, guarantees, and venture capital for aquaculture SMEs and startups, typically supporting the scale-up and market deployment of circular solutions that have already been validated through pilot or demonstration projects.

The EIB supported fisheries and aquaculture sectors with €229 million between 2019 and 2023 and they prioritised European bivalve and seaweed European sectors[51]. They proposed debt financing opportunities for the **seaweed industry** supporting farming infrastructure, processing and logistics and biorefinery facility, demo plant or commercial-scale plant. Moreover, debt financing opportunities identified for **the bivalve industry** in Europe **included** farming infrastructure and green transition for adaptation to viruses/heat waves, new farming infrastructure, hatchery to optimize spat resilience; and solutions to renew equipment and farm sites with climate-friendly alternatives, new equipment to mechanize seeding/bivalve management and handling/harvesting and IMTA for diversification of activities to include for instance seaweed farming as additional income stream

At national level, EMFAF programs are complemented by additional public and semi-public financing tools that reflect country-specific priorities while remaining aligned with EU strategic guidelines. In Bulgaria and Croatia funding opportunities for circular aquaculture are largely channelled through the national implementation of EMFAF and other EU-level instruments. At present, no additional dedicated national funding schemes specifically targeting circular aquaculture have been identified beyond these frameworks.

France

France combines European and national funding instruments to support innovation and circularity in aquaculture. **France 2030 Investment Plan**[52] supports innovation in circular aquaculture, including projects focused on energy efficiency, valorisation of by-products, and digital monitoring.

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[49] *SUSTAINABLE OCEAN FUND; https://www.eib.org/en/projects/pipelines/all/20160609*
[50] *EIF supports Blue Revolution Fund in boosting sustainable aquaculture investments backed by the InvestEU programme; https://www.eif.org/InvestEU/news/2024/eif-supports-blue-revolution-fund-in-boosting-sustainable-aquaculture-investments-backed-by-the-investeu-programme.htm*
[51] https://aac-europe.org/wp-content/uploads/2025/06/Financing-opportunities-EU-seaweed-bivalves-FULL-REPORT.pdf
[52] France 2030: un plan d'investissement pour la France; https://www.economie.gouv.fr/france-2030

In parallel, the **French Agency for Ecological Transition (ADEME)**[53] regularly launches calls for projects supporting the circular economy in food systems. These calls focus on waste minimisation, bioresource recovery, energy efficiency, and life cycle assessment approaches, offering targeted financial support to aquaculture initiatives that integrate circular economy principles into production and processing activities.

Greece

Greece supports circular aquaculture through a combination of EU funding and national legislative and financial instruments. **The PALYTH EMFAF Programme Greece 2021–2027**[54] includes a specific focus on a carbon-neutral and circular blue economy, supporting ecosystem restoration, pollution prevention, and sustainable aquaculture across coastal, island, and inland regions.

National legislation further complements these measures. **Law 4887/2022 (Development Law)** provides state aid and incentives for green transition, technological transformation, environmental protection, and resource efficiency, including waste reuse and recycling in aquaculture. Subsequent amendments under **Law 5203/2025** simplify procedures and strengthen incentives for environmentally sustainable investments.

In addition, the **Hellenic Development Bank of Investments (HDBI/EATE)**[55] plays a key role by mobilising venture capital and private equity funds focused on SMEs. Its investment strategy prioritises green and sustainable projects evaluated through ESG and "Do No Significant Harm" criteria, supporting aquaculture enterprises adopting circular and low-impact production models.

Italy

Italy implements circular aquaculture funding primarily through the **European Maritime, Fisheries and Aquaculture Fund (EMFAF) 2021–2027**[56], which supports sustainable aquaculture development, innovation, environmental restoration, and the green and digital transition. Eligible actions include nutrient management, waste reduction, circular production systems, and ecosystem-based approaches.

This framework is reinforced by national strategic planning instruments that guide the allocation of funds towards sustainability, IMTA, training, and innovation. At the

[53] Agence de la transition écologique – Financer; https://www.ademe.fr/nos-missions/financement/
[54] EMFAF Programme PALYTH (Greece) 2021-2027; https://projects.research-and-innovation.ec.europa.eu/en/funding/funding-opportunities/funding-programs-and-open-calls/horizon-europe/eu-missions-horizon-europe/restore-our-ocean-and-waters/emfaf-programme-palyth-greece-2021-2027
[55] HDBI Calls for Expression of Interest; https://hdbi.gr/en/cfp
[56] European Maritime, Fisheries and Aquaculture Fund – Italy Programme; https://oceans-and-fisheries.ec.europa.eu/document/download/ef4add4f-d9d2-4d70-ada4-545500ade649_it?filename=emfaf-programme-italy_it_0.pdf&prefLang=en

regional level, initiatives such as **Aquaculture Allocation Zones (AZA)**[57]—for example in Sardinia—simplify permitting procedures and integrate environmental assessments, thereby encouraging sustainable siting and planned aquaculture development.

In addition, **ISMEA / Fondo Innovazione**[58] provide financial instruments to support agri-food and aquaculture innovation. These instruments are applicable to **circular economy projects**, including waste valorisation and nutrient recycling.

Furthermore, **regional and national calls for proposals** support aquaculture projects focused on competitiveness, safety, innovation, environmental improvement and IMTA pilot initiatives. Eligible beneficiaries include **SMEs, Fisheries Local Action Groups (FLAGs), cooperatives and research partnerships**.

Montenegro

In Montenegro, circular aquaculture investments are supported through a combination of EU pre-accession funding, national programs, and institutional support. The **IPARD III Programme (2021–2027)**[59] provides grants covering a significant share of investment costs for aquaculture modernisation, environmental protection, renewable energy integration, and waste management.

Cross-border cooperation is facilitated through the **Interreg VI-A IPA South Adriatic Programme**[60], which supports innovation and circular aquaculture projects involving partners from Montenegro, Italy, and Albania. Additional support is provided by the **Innovation Fund of Montenegro**[61], which finances eco-innovation and pilot development in the bioeconomy.

Institutional actors such as the Institute of Marine Biology and national environmental authorities provide technical assistance, monitoring, and alignment with EU Green Deal objectives, reinforcing the enabling environment for circular aquaculture investments.

Portugal

Portugal supports the transition towards sustainable and circular aquaculture through several national funding instruments aligned with green transition objectives. The **Recovery and Resilience Programme (PRR)**[62] promotes

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[57] MARITIME SPATIAL PLANNING: MARINE AREAS AND SITES FOR AQUACULTURE; https://indicatoriambientali.isprambiente.it/en/aquaculture/maritime-spatial-planning-marine-areas-and-sites-aquaculture
[58] ISMEA; https://www.ismea.it/istituto-di-servizi-per-il-mercato-agricolo-alimentare
[59] IPARD III programme; https://www.gov.me/en/article/programme-for-the-development-of-agriculture-and-rural-areas-in-montenegro-under-ipard-iii-2021-2027
[60] IPA Italy Albania Montenegro (South Adriatic) https://interreg.eu/programs/ipa-italy-albania-montenegro-south-adriatic/
[61] The Innovation Fund of Montenegro; https://fondzainovacije.me/en/home/
[62] PRR – RECOVERY AND RESILIENCE PLAN; https://ani.pt/en/prr-recovery-and-resilience-plan/

investments in sustainability and digitalisation, including aquaculture-related innovation.

Besides, **Environmental Fund**, which finances climate action, resource efficiency and biodiversity initiatives, the Innovation Fund, which supports the demonstration of low-carbon and circular technologies and the Technology and Circular Economy Fund (FTECE), which provides investments for resource efficiency, eco-innovation and waste valorisation.

Spain

The **SME Sustainable Programme – MOB 2025**[63], promoted by the Spanish Chamber of Commerce, provides financial support covering **between 40% and 85% of the investment**, depending on the autonomous region, up to a **maximum eligible amount of EUR 7,000**. The aid is intended to cover costs related to environmental footprint studies (environmental, carbon and water footprints), life cycle assessment (LCA), eco-design, monitoring of energy efficiency in facilities, renewable energy solutions, consultancy for the development of new circular business models, or optimisation of production processes based on the minimisation of environmental impacts.

This support is targeted at **Spanish SMEs from all sectors**, and the call is usually launched on an annual basis. Other support schemes aligned with these objectives include the **Green Transition Program**[64], offered by the Department of Economic Promotion of the Provincial Council of Bizkaia, which subsidises **up to 70% of the investment** made by SMEs in Bizkaia, and the **Business Sustainability Voucher Programme**[65], offered by the Institute for the Development of the Region of Murcia (INFO), which provides SMEs with a **75% subsidy (up to EUR 7,000)** to cover the costs of calculating and registering their **carbon or water footprint**.

At the end of 2025, the **Call for Aid for the Fisheries and Aquaculture Sector of the Basque Country (2025)**[66] was published, with a total budget of **EUR 13,358,952**, largely financed through **EMFAF funds**. The call covers up to **50% of eligible investment costs**, including measures related to: innovation in aquaculture; added value, circular economy and food safety; productive investments and business creation in aquaculture; climate neutrality in aquaculture; increasing the potential of aquaculture production areas; the contribution of aquaculture to good environmental status and the provision of environmental services; specific advisory services for aquaculture farms; and the promotion of marketing within the

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[63] PYME SOSTENIBLE https://camaradesevilla.com/wp-content/uploads/2025/03/2025_Anexo-V.-Tipologia-y-Justificacion-de-Gastos-elegibles-Fase-de-Ayudas.pdf
[64] Programa de Transición Verde. https://www.camarabilbao.com/ayudas-subvenciones/programa-transicion-verde/
[65] Programa Cheques de Sostenibilidad Empresaria https://aselecconsultores.com/la-huella-de-carbono-y-ayudas-a-empresas/
[66] ORDEN de 8 de octubre de 2025, de la Consejeria de Alimentación, Desarrollo Rural, Agricultura y Pesca, por la que se aprueban, para el año 2025, las bases de la convocatoria de ayudas al sector pesquero y acuícola de la Comunidad Autónoma del País Vasco. https://www.euskadi.eus/servicios/1230270/web01-tramite/es/

framework of quality and added value of fisheries and aquaculture products, packaging and product presentation.

The CDTI[67] provides support for investment projects in aquaculture and in ways to process fishery and aquaculture products through **EMFAF funds.** Investment projects are eligible for aquaculture enterprises. New entrants to the sector must submit a business plan and a feasibility study, including an environmental impact assessment. Although not directly identified as circular aquaculture, eligible investments include:

(a) productive aquaculture investments improving resource efficiency

(b) diversification of species and production systems, (e.g. low-trophic and multi-species models)

(c) modernisation of facilities, including worker safety and eco-efficient technologies (e.g. RAS, IMTA)

(d) improvements in animal health, welfare, and biosecurity, including predator protection

(e) enhancement of product quality and added value, including by-product valorisation

(f) recovery and maintenance of ponds or lagoons through sludge management and prevention measures.

Innovative Financial Instruments

In addition, with public funding, a growing portfolio of innovative financial instruments is emerging to support circular economy projects and mobilize capital beyond traditional funding channels. Instruments such as **green bonds, sustainability-linked bonds, social impact bonds, and crowdfunding platforms** are enabling circular businesses to access a broader and more diverse investor base, including institutional investors, impact funds, and citizens seeking combined financial, environmental, and social returns.

These mechanisms help address key barriers faced by circular projects such as high upfront capital requirements, long payback periods, and perceived technological or market risks by improving risk sharing, enhancing transparency, and linking financial returns to verified sustainability performance. In addition, blended finance structures that combine public grants, concessional loans, and private investment are increasingly used to de-risk early-stage circular innovations.

[67] https://www.cdti.es/en/ayudas/emff-investment-projects

5.3 Mentoring and Training Programs

At EU level, training and mentoring for circular aquaculture are mainly supported through **EMFAF**, **Horizon Europe** and **Interreg** programs, where capacity building is integrated into research, innovation and cooperation projects. These initiatives typically include workshops, pilot demonstrations, study visits and mentoring activities focused on circular production models, IMTA, resource efficiency, digitalisation and by-product valorisation.

Complementary support is provided by EU mechanisms such as the **Aquaculture Assistance Mechanism** and **BlueInvest**, which offer technical guidance, business mentoring and matchmaking services, particularly for SMEs and startups developing sustainable aquaculture solutions.

At country level, training and mentoring opportunities related to circular aquaculture are **largely project-based** and delivered through universities, research institutes, producer organisations and regional authorities. Dedicated national programs are limited, and capacity building is often embedded in EU-funded projects, pilot initiatives and regional development actions.

Croatia

In Croatia, dedicated national training programs on circular aquaculture are limited. Training and mentoring activities are mainly delivered through EU-funded projects, applied research initiatives and occasional workshops, particularly targeting SMEs. These initiatives focus on practical aspects such as innovative technologies, waste management, efficient water use, eco-certification and diversification strategies.

Universities, research institutes and producer organisations play an important role in knowledge generation and dissemination, often through pilot projects and peer-to-peer exchanges. However, **access to structured training varies**, with high accessibility for producers directly involved in project consortia, while non-participating SMEs face more limited opportunities, highlighting the need for more coordinated knowledge-sharing systems.

The **AZA4ICE project** represents the most prominent local initiative supporting training and mentoring, promoting circular business models, nutrient valorisation and IMTA concepts through pilot zones and stakeholder engagement. Complementary regional initiatives, including mariculture infrastructure development and participation in Interreg cooperation programs, further support capacity building and technology transfer related to circular and sustainable aquaculture.

France

Training is supported through regional and national innovation ecosystems, with universities, research centres and regional platforms providing applied courses and workshops on sustainable aquaculture and circular economy practices, often linked to broader food-system transition strategies.

Greece

There are no permanent or on-demand training programs specifically dedicated to circular aquaculture. Training activities related to circularity—such as waste and by-product valorisation, feed efficiency or sludge reuse—are mainly **periodic and project-based**, often linked to EU-funded initiatives or academic calendars. SME-focused training opportunities exist but are generally limited in scope and rarely address the full circular aquaculture value chain.

Most training and mentoring activities are organised by **universities and research institutions**, including the Agricultural University of Athens (through the Blue Career Centre for Aquaculture Education – BlueAquaEdu[68]), the University of Crete, the Institute of Marine Biology, Biotechnology and Aquaculture (IMBBC), and the Hellenic Centre for Marine Research (HCMR). These initiatives typically combine academic training with applied knowledge and cover topics such as production systems, environmental impacts and by-product valorisation.

Italy

Training opportunities related to circular aquaculture are limited and mostly embedded in academic programs and occasional technical workshops, highlighting the need for more practice-oriented and locally delivered capacity-building actions.

In Italy, training and mentoring on circular aquaculture are mainly delivered through **EU-funded programs, universities and research institutes**, with a growing focus on **nutrient recycling and integrated production systems**. National and regional initiatives support training modules on IMTA, nutrient management and eco-innovation, often embedded within broader sustainability and innovation frameworks.

Universities and research centres, including the National Research Council (CNR-IRBIM) and several universities, play a central role by offering applied courses, workshops and pilot demonstrations integrating finfish, bivalves and seaweed production. While many programs are open access, **small-scale producers often**

[68] BlueAquaEdu 2nd Summer School In Greece; https://portal.blueaquaedu.eu/node/149?school_id=149

face barriers related to time, costs and digital skills. Regional cooperatives and demonstration farms help improve accessibility through locally adapted, practice-oriented training, though wider uptake would benefit from more modular and on-site support.

Montenegro

In Montenegro, **no dedicated national training programme on circular aquaculture exists yet**, but a rapidly evolving training ecosystem is emerging through **EU-funded projects and academic initiatives**. Capacity building activities increasingly address sustainability, circular resource use, digital monitoring and waste valorisation, particularly within the blue economy context.

Key initiatives such as **AZA4ICE (LiRRIEs), SKILLS and BLUECONNECT** combine academic training with hands-on mentoring and site-based demonstrations, coordinated mainly by the Institute of Marine Biology (IMBK). These programs have significantly improved access to practical training, especially through local pilot zones. However, **accessibility for small-scale and family-owned producers remains uneven**, due to geographic, financial and logistical constraints. Expanding local delivery, simplified materials in Montenegrin and formal certification pathways would further strengthen inclusiveness and long-term impact.

Portugal

Training opportunities related to circular aquaculture are **limited and mainly embedded within academic programs**, with a gradual expansion in recent years. Postgraduate and master's programs in blue and circular economy provide a solid theoretical foundation on sustainability, resource efficiency and innovation relevant to aquaculture, while some technical courses address RAS and sustainable production technologies.

However, **access for small-scale producers is limited**, as most training is delivered within higher education institutions and not specifically tailored to practitioners. Local initiatives and technical workshops, including demonstrations of IMTA and marine bioresource valorisation, provide valuable applied knowledge but remain occasional. Strengthening regionally delivered, practice-oriented training in cooperation with producer associations would be key to broadening adoption of circular aquaculture practices.

Spain

Within the measures and lines for updating the **primary sector and bioindustry** (circularity in biological cycles) under the production pillar of the **Second Spanish Circular Economy Action Plan**[69] (submitted for public consultation in October

[69] *Borrador II Plan de Acción de Economía Circular 2024-2026 /https://www.miteco.gob.es/content/dam/miteco/es/calidad-y-evaluacion-ambiental/participacion-publica/sgecocir/ecocir/IIPAEC%202024-2026_240924v2.pdf*

2024, with the final document not yet published), the development of the circular economy in aquaculture at regional level is proposed. To this end, the Ministry of Agriculture, Fisheries and Food, through the strategic instrument *"Spain's Contribution to the Strategic Guidelines for a More Sustainable and Competitive EU Aquaculture 2021–2030"*, sets out general actions to optimise efforts aimed at strengthening a more sustainable and efficient aquaculture sector, in line with the objectives of the **Spanish Circular Economy Strategy**[70].

In the field of training, the **Spanish Circular Economy Strategy 2030** identifies the preparation of the labour market for the transition towards a circular and low-carbon economy as a key challenge. However, its action plans do not include specific training on circular aquaculture, although they do address circular economy training in the fisheries sector. Regarding the generation of new knowledge in circular aquaculture, the **research, innovation and competitiveness** line of the **Second Spanish Circular Economy Action Plan**[25] promotes research into alternative sources of ingredients for aquaculture feed, in accordance with circular economy and sustainability principles. Specifically, this includes the study of alternative sources such as macro- and microalgae, plant extracts, underutilized species, microbial proteins and lipids, and processed animal- and plant-based by-products, among others.

The **National Catalogue of Professional Competence Standards (CNECP)**[71], within the professional family of **Safety and Environment**, includes the professional qualifications *"Develop actions related to the use, recovery and valorisation of organisational resources according to circular economy models"* and *"Carry out surveillance and protection of aquaculture establishments and maritime areas for fisheries purposes"*. Based on these qualifications, vocational education and training (VET) programs have been developed, including the **Intermediate VET qualification of Aquaculture Farming Technician** and the **Advanced VET qualification of Senior Aquaculture Technician**.

A key milestone in Spain's educational transition towards circularity is the mandatory inclusion of the module **"Sustainability Applied to the Productive System"** in all intermediate and advanced VET programs from the **2024–2025 academic year**, in accordance with **RD 659/2023**[72]. Regarding teaching staff, under the **Environmental Education Action Plan for Sustainability 2021–2025**[73], by 2025

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[70] *Estrategia Española de Economía Circular 2030 https://www.miteco.gob.es/content/dam/miteco/es/calidad-y-evaluacion-ambiental/temas/economia-circular/espanacircular2030_def1_tcm30-509532_mod_tcm30-509532.pdf*

[71] *El Catálogo Nacional de Estándares de Competencias Profesionales (CNECP) https://incual.educacion.gob.es/documents/d/extranet/cnecp_listado-ecps-con-nipo*

[72] *RD 659/2023, por el que se desarrolla la ordenación del Sistema de Formación Profesional en España. https://www.boe.es/buscar/doc.php?id=BOE-A-2023-16889*

[73] *Plan de Acción de Educación Ambiental para la Sostenibilidad 2021-2025 https://www.miteco.gob.es/content/dam/miteco/es/ceneam/plan-accion-educacion-ambiental/plandeacciondeeducacionambientalparalasostenibilidad2021-202508-21_tcm30-530040.pdf*

all teaching staff in primary, secondary, upper secondary, VET and higher education are required to have received training in sustainability.

In addition, Spain has launched **targeted mentoring initiatives** to support skills development and entrepreneurship in aquaculture. The **CultiVA mentoring programme**[74], promoted by the Spanish Observatory of Aquaculture with public and private partners, connects students and early-career professionals with experienced aquaculture practitioners to support career development and knowledge transfer. Complementarily, **BLUE CORE**[75], promoted by the Cádiz Free Trade Zone, provides a business incubator for innovative and sustainable blue economy projects, including circular aquaculture.

[74] *Programa de mentorización CultiVA; https://www.observatorio-acuicultura.es/%20programa-cultiva/*
[75] *BLUE CORE; https://www.zfbluecore.es/blue-core/*

6. Challenges and Solutions

Despite these advances in technology and strategic frameworks, the aquaculture sector faces persistent challenges related to the **adoption and scalability of circular practices**. Still persist knowledge gaps regarding the environmental impacts and restrictions, economic viability technological, and social implications of circular aquaculture models, especially in diverse geographic and socio-economic contexts (Masi *et al.* 2024; Olagoke-Komolafe & Oyeboade 2025; Silva *et al.* 2025). While some studies emphasize the environmental advantages of circular systems, others highlight barriers such as limited *technical expertise, regulatory inconsistencies, and market preferences* (Vu & Chi 2024). The successful transition toward circular aquaculture requires **integrated, multi-level solutions** that simultaneously address environmental constraints, economic feasibility, technological readiness, regulatory alignment, and stakeholder coordination. Advancing circularity in aquaculture requires more than redesigned production cycles; it calls for shared visions supported by social and political engagement, inclusive governance, and clear policy directionality to align collective efforts (Masi *et al.* 2026). Addressing these challenges in an integrated manner is essential to ensure that circular aquaculture becomes technically viable, economically sustainable, and socially accepted.

6.1 Challenges

The main challenges in transitioning to circular aquaculture include environmental issues, market and economic factors, technological limitations and gaps in knowledge, policy and regulation, as well as social and stakeholder engagement.

6.6.1 Environmental Challenges

Environmental constraints represent one of the most critical bottlenecks for circular aquaculture, particularly in sensitive coastal and transitional ecosystems. Main identified challenges are the following:

a) ***Nutrient management and eutrophication risks***. Circular aquaculture aims to retain and reuse nutrients; however, eutrophication can occur if extraction and assimilation processes are not adequately designed or scaled. This challenge is particularly relevant in semi-enclosed coastal systems and estuarine environments where assimilative capacity is limited.

b) ***Pollutant accumulation and contamination risks.*** Aquaculture operations are increasingly exposed to background contamination originating from other anthropogenic activities, including industry, ports, urban runoff, and maritime traffic. The accumulation of heavy metals and persistent pollutants in sediments or sludge poses risks for food safety, ecosystem health, and market acceptance, even when farms themselves are not the primary pollution source.

c) ***Climate change impacts***. Rising sea temperatures, heatwaves, and extreme weather events and floodings with rapid salinity variations are increasing physiological stress, disease susceptibility, and mortality in cultured species particularly in low trophic organisms such as in oyster farming. This climate variability might undermine the predictability of production cycles, complicating the design and management of circular systems that depend on stable biological performance.

d) ***Water quality instability.*** In areas with strong tidal influence or surrounded or urban areas, water fluctuations create additional stress on farmed species and complicate water management. Maintaining optimal conditions becomes more challenging in circular and semi-closed systems where water exchange is intentionally reduced.

e) ***Conservation of sensitive coastal ecosystems*****.** The expansion and eco-intensification of aquaculture must be carefully balanced with the protection of wetlands, salt marshes, lagoons, and Natura 2000 sites. Although circular systems reduce emissions, they still require space, infrastructure, and water access, often in ecologically valuable areas. Designs should carefully consider conservation regulation restrictions.

6.6.2 Market & Economic Viability Challenges

Economic barriers remain a major obstacle to the adoption of circular aquaculture models, particularly for SMEs due to:

a) ***Inefficient production models***. Many current aquaculture systems operate with suboptimal feed efficiency, water use, and nutrient recovery, limiting margins and increasing vulnerability to input price volatility. Transitioning to circular models often requires system-level redesign rather than incremental improvements, increasing capital intensity and financial risk.

b) ***Predation-related losses and uncontrolled access***. Bird and mammal predation are especially relevant in sites located in natura 2000 network. Control measures are often restricted by conservation regulations, further complicating management. In addition, open or semi-open production systems suffer from unauthorised access, vandalism, and theft, particularly during long production cycles. These losses directly reduce profitability and discourage investment in higher-value circular practices.

c) ***High transition costs and limited access to finance***. Shifting toward eco-efficient and circular systems requires substantial upfront investment in infrastructure, technology, and training. These capital requirements represent a major barrier for many producers, particularly small and medium-scale operators, in the absence of adequate public support, blended finance, or risk-sharing mechanisms. For SMEs, this upfront investment remains a critical constraint, even when public subsidies are available since farms are typically required to provide co-financing of 30–50%, a level that exceeds the financial capacity of many SMEs. This constraint is mostly identified by different countries as a limitation for adoption across countries.

SMEs and traditional aquaculture producers also face persistent barriers in **accessing credit, private investment, and green finance instruments**. Circular aquaculture initiatives are frequently perceived by financial institutions and investors as high-risk due to technological novelty, regulatory uncertainty, and the absence of widely proven, bankable business models. Uncertain revenue streams, fragmented markets for circular outputs, and long return-on-investment periods further reduce investor confidence.

Structural and scale-related constraints exacerbate these challenges. Many financial incentives and investment schemes are designed for large, capital-intensive projects, creating a scale mismatch that disadvantages smaller operators, particularly evident in those countries such as Greece, Spain, where aquaculture is dominated by small, family-run farms. In parallel, delayed disbursement of public subsidies often generates cash-flow bottlenecks, exposing SMEs to liquidity risks during critical investment phases.

d) *Undeveloped markets*. Many outputs generated through circular aquaculture practices such as valorised by-products, sludge, low-trophic biomass (algae, halophytes, worms) or nature-based treatment services lack stable demand, clear price signals, and established value chains. In many regions, these products compete with conventional alternatives that benefit from economies of scale, well-known standards, and established distribution channels, making market entry difficult for circular solutions. In some cases, initiatives fail without scale and logistics. Large biomass is required to mitigate the impact of high handling and transport costs

Market uncertainty is further affected by the absence of harmonised quality standards, certification schemes, and labelling frameworks that clearly communicate the added environmental and social value of circular aquaculture products to buyers and consumers. Moreover, fragmented value chains and strong seasonal variability affect biomass availability, pricing stability, and scalability. In addition, limited standardisation of quality and safety criteria restricts access to international markets and undermines confidence in these products, particularly in high-value food and nutraceutical applications.

e) Logistical challenges. Biomass and by-product valorisation faces significant logistical constraints. The collection, transport, and consolidation of effluents, sludge, and other by-products (e.g. mortalities, biofilters residues, low-trophic biomass, processing wastes) from numerous, geographically dispersed small and medium-sized farms is operationally complex and costly. These fragmented supply chains limit economies of scale, increase handling and transport costs.

f) High Energy Costs. High operational energy costs represent a major constraint. Although not exclusive to the sector, elevated energy prices significantly affect the economic viability of energy-intensive circular processes such as RAS, hatcheries, advanced aeration and feeding systems, water heating, lighting, pumping, and the treatment or drying of sludge and other by-products for valorisation. National and regional contexts further exacerbate this challenge. In all countries high electricity prices undermine the feasibility of energy-demanding circular operations, including continuous pumping in RAS or energy-intensive waste processing. Moreover, the combined effect of high energy and logistics costs significantly increases production expenses for circular systems.

g) Spatial planning conflicts. Aquaculture competes for space with other blue economy activities, including tourism, recreation, shipping, renewable energy, as well as archaeological protection zones, urban- and military-use areas. These conflicts restrict site availability and increase permitting complexity.

6.6.3 Technological and Knowledge Gaps

Technical readiness and knowledge transfer are key elements for a successfully transition toward circularity. Some challenges associated to this point are:

a) Insufficient validated circular production models at local scale.

The adoption of IMTA, IMRAS, RAS, BFT, aquaponics and other mixed circular specific configurations remain limited due to:

- Lack of locally adapted designs,
- Uncertainty regarding economic performance,
- Insufficient demonstration at commercial scale.
- Restricted access to advanced tools and data
- Many producers lack access to:
- Real-time water quality sensors,
- Automated feeding and monitoring systems,
- Decision-support tools,
- Selective breeding and genetics programs adapted to local conditions.

Particularly, systems such as IMRAS and aquaponics are inherently complex. They require advanced technical expertise, continuous monitoring, and significant upfront investment, which limits accessibility for small and medium operators. The integration of multiple species and high-tech components increases biological, regulatory, and market risks, particularly where performance depends on precise system balancing. Moreover, these models sit at the intersection of several regulatory domains (aquaculture, agriculture, water management, and food safety) each governed by different authorities and compliance requirements. This complicates authorisations and compliance.

b) Knowledge transfer and skills gaps

Across most countries, a persistent **gap exists between research outputs and farm-level** implementation of circular aquaculture practices. While scientific knowledge and pilot initiatives are available, effective knowledge transfer mechanisms remain weak, and training, extension services, and guidelines are often limited to conceptual descriptions rather than practical, site-specific solutions adapted to local environmental and production conditions.

6.6.4 Policy and Regulatory Gaps

Regulatory frameworks often lag technological and business innovation in circular aquaculture due to:

a) Absence or unclear regulatory pathways. While some regions, such as Andalusia (Spain), have begun to formally recognise circular production models (e.g. IMTA), in most countries circular and eco-intensive aquaculture systems still lack explicit legal recognition. This regulatory ambiguity generates uncertainty during licensing, inspection, and market placement, effectively limiting the development of IMTA-based revenue models and reducing economic **incentives** for innovation. The absence of clear **fiscal advantages** and predictable approval pathways continues to constrain short-term profitability and sector expansion (Murthy et al. 2023).

A particularly critical gap concerns the **regulatory treatment of circular by-products**. High-potential materials such **as fish sludge** face unclear or restrictive regulatory classifications when considered for reuse as fertilisers. Fish sludge has strong potential as a fertiliser or as a substrate for invertebrates and insects. However, EFSA has not assessed the use of animal manure or fish sludge as substrates for insects due to insufficient data (Committee 2015). Moreover, Regulation (EC) No 1069/2009 defines “manure” as excreta from farmed animals excluding farmed fish, leaving fish excreta outside established agricultural recycling pathways and further complicating its valorisation.

b) Feed law restrictions. Despite its high content of valuable nutrients, including marine lipids and proteins, fish sludge faces significant regulatory barriers to its use as a feed resource. Circular approaches based on rearing polychaetes or insects on fish sludge, followed by their use as aquafeed ingredients, represent promising pathways for sustainable resource use. However, current EU feed legislation makes approval unlikely without stringent hygienisation treatments to ensure feed safety, and key regulatory uncertainties remain unresolved (Pettersen et al. 2025).

Additional constraints relate to ABP regulations and intra-species feeding restrictions. Earlier frameworks (e.g. Regulation EC 1774/2002) prohibited recycling within the same species, limiting aquaculture feeds to fishmeal derived from wild fish. Subsequent EC 1069/2009 and EU No 142/2011 relaxed these restrictions by introducing traceability requirements, allowing fishmeal derived from farmed fish under strict labelling and species-separation conditions. While these revisions represent progress, compliance remains complex and costly, limiting uptake by SMEs.

c) Novel food restrictions. Some new biomass, including algae and halophytes might be considered as a novel food in Europe. This is defined as *any product with no significant degree of consumption before 15 May of 1997* and which was completely new to the European population. Under this definition, novel Foods comprise new or innovative food sources, foods produced using new technologies or processes, and foods traditionally consumed outside the EU but not within it, such as products derived from plants, microorganisms, fungi, algae, or animals. In this context, most algae (macro- and microalgae) are considered Novel Foods unless their consumption before 1997 can be demonstrated. To date, only a limited number of algal species are classified as “not novel” and listed in the EU Novel Food Catalogue[76], although some Member States, such as France, adopted specific national authorisations earlier. This regulatory framework has since been consolidated under Regulation (EU) 2015/2283, which provides a unified and transparent procedure for authorising Novel Foods across the EU (Cruz & Vasconcelos 2024).

For quality assurance and regulatory professionals, novel Foods represent a current and practical compliance challenge rather than a purely innovative or theoretical issue. **Ingredients that are traditional elsewhere may still be novel in Europe**, and reliance on supplier declarations or assumptions of historical use outside the EU can lead to non-compliance. Verifying Novel Food status must therefore be an integral part of product approval processes, alongside safety, labelling, and additive controls. Product reformulation, changes in sourcing, or modifications in processing can also alter Novel Food status, making continuous vigilance essential. As innovative ingredients such as algae, plant extracts, and fermentation-derived products increasingly enter the market, proactive integration of Novel Food checks into commercial strategies is essential to ensure legal compliance, support responsible innovation, and protect consumer trust.

d) Fragmented governance and competences. Aquaculture governance is typically shared across multiple authorities responsible for environment, fisheries, agriculture, water management, public health, and spatial planning. Overlapping or poorly coordinated mandates increase administrative burden and discourage innovation. Circular economy principles are not yet fully embedded in aquaculture

[76] https://www.eaba-association.org/en/news/breaking-news-news-algaespecies-entries-in-the-novel-food-status

licensing procedures, meaning that eco-innovative investments often face unclear eligibility criteria or extended approval timelines.

e) Complex bureaucracy. Administrative complexity further constrains circular aquaculture deployment. In Greece, applications for public support schemes (e.g. Development Law 4887/2022 or EMFAF 2021–2027) require coordination across several ministries and agencies, exceeding the administrative capacity of many SMEs. Similar challenges are reported in Portugal, where complex procedures and limited administrative support hinder investment, and in Italy, where lengthy and fragmented permitting processes delay IMTA and other innovative systems. In Croatia, the absence of a single, coherent strategic framework for the circular economy results in regulations dispersed across institutions with weak coordination, leading to slow, opaque, and investment-discouraging licensing processes. In Spain, as a decentralized state, there is no harmonized regional regulations with a complex framework of competences between national and regional competences including environmental and fisheries organisms.

6.6.5 Social and stakeholder engagement

Despite increasing policy attention to sustainability, social acceptance and stakeholder engagement remain key bottlenecks for the uptake of circular aquaculture.

a) Low awareness of eco-certifications. Many producers show limited awareness of existing eco-certification schemes (e.g. ASC, Friend of the Sea, Fish from Greece), their technical requirements, and their potential market advantages.

b) Perception barriers. Citizens in several regions continue to associate aquaculture with pollution, waste generation and environmental degradation, which undermines local support for EU-funded circular and eco-intensive initiatives. There exists limited public understanding of how circular systems function and what their environmental and social benefits are. The concepts of nutrient recycling, by-product valorisation, and circular resource use remain *abstract or poorly communicated to citizens and consumers.*

c) Consumer awareness. Awareness of safety, circular or eco-certified seafood remains low, and the limited willingness of local markets to pay a price premium discourages producers from investing in certification and circular products. Low awareness of seaweed and derived products: Seaweed as food is almost unknown in the local diets of several countries.

d) Consumer habits. Many mainstream consumers avoid low trophic ingredients due to unfamiliarity and declining interest in home cooking, as these foods often require more time or knowledge. Products seen as unusual or complex, such as whole seaweed or fish by-products, are typically excluded from everyday meals.

6.2. Potential solutions

The following section focuses on identifying potential solutions and enabling measures that can accelerate the transition toward circular aquaculture. These solutions aim to reduce administrative and financial barriers, strengthen technical capacity and infrastructure, stimulate market demand for circular products, and improve stakeholder engagement and consumer awareness. By linking challenges to concrete policy, financial, technological, and social interventions, this approach seeks to unlock the long-term environmental, economic, and social benefits of circular aquaculture and support its effective implementation across diverse regional contexts.

6.2.1. Environmental Challenges

Challenge	***Solution***	***Actions***
Nutrient management and eutrophication risks	Selection of adaptive harvesting and monitoring strategies	• Seasonal biomass removal should be adequately programmed based on full biological life-cycle. • Flexible species combinations, and real-time water quality monitoring established. • Contingency plans should be able to respond rapidly to fluctuations in assimilative capacity
Pollutant accumulation and contamination risks	Manage background contamination risks	• Production systems should implement robust segregation, monitoring, and valorisation strategies. Sediments and sludge should be systematically segregated, characterised, and directed toward appropriate valorisation pathways based on their contaminant profiles. • Regular and standardised monitoring of sediments, water, and bioaccumulation in extractive species for early detection of contaminants originating from external anthropogenic sources. • Clear traceability and compliance protocols to strengthen food safety assurance and market confidence
Climate change impacts	Species and strain diversification	• Use of locally adapted genotypes including the use of robust species, and multi-species production portfolios that distribute biological and economic risk.

	Operational flexibility	• Implement hybrid circular system designs by combining open or semi-open systems with buffering units such as modular RAS components, deeper ponds, or shaded and aerated infrastructures. These elements help stabilize water quality and temperature, safeguard animal welfare and performance, and ensure continuity of production under increasingly unpredictable climate conditions.
Water quality instability	Assess partial decoupling from ambient waters	• When possible semi-closed and circular systems should incorporate alternative water buffers (dwell water, reservoirs, settling tanks, equalisation ponds) that mitigate short-term fluctuations in salinity, temperature, turbidity, oxygen, and pollutants before water enters production units.
	Integration of nature-based treatment components	• Halophyte beds, constructed wetlands, or microbial biofilters provides additional stabilisation by progressively regulating nutrients and organic matter.
	Water quality monitoring and automated control	• Sensors with continuous monitoring and automated control systems.
Conservation of sensitive coastal ecosystems	Reconciling circular aquaculture with ecosystem conservation	• It requires co-design and cooperation with environmental authorities integrating protected areas for nest or organize activities according to reproduction periods facilitate conservation measures. • Collaborate in create low-impact areas for native species and not competing with natural spaces or resources
	Prioritisation of nature-based solutions	• Low-impact infrastructures, reversible or floating designs, and the help minimise habitat disturbance while delivering measurable ecosystem services

6.2.2. Market & Economic Viability Challenges

Challenge	***Solution***	***Actions***
Inefficient production models	Analyse adequacy of business model for each site and aquaculture system.	• There is no single, universally optimal circular production model; instead, solutions must be site-specific. Each location should be carefully assessed to determine the most suitable species combinations, valorisation pathways, and expected outputs, and the business should be properly dimensioned to ensure technical feasibility, economic viability, and optimal return on investment. • Modular system designs allow phased implementation, reducing investment risk while enabling scalability and adaptation to different farm sizes and species combinations.
	Shifting toward Precision aquaculture	• Precision Improve feed conversion ratios through local adapted strains, improved feeding strategies, supported by digital monitoring and AI-based feeding contro
Predation-related losses and uncontrolled access	Design-based prevention, regulatory alignment, and smart monitoring	• Prioritise predator-resilient infrastructure, including reinforced netting, tensioned anti-bird lines, and system layouts compatible with conservation objectives. • Early and continuous coordination with environmental authorities to co-design acceptable mitigation measures, exploring the use of non-lethal deterrents (visual, acoustic, or behavioural) and adaptive management plans that are compliant with biodiversity protection regulations. • Integrate low-cost digital surveillance and access-control solutions, such as remote cameras, sensor-based alerts, geofencing, and shared monitoring platforms at site or cluster level.

High transition costs and limited access to finance	Support system redesign	• Use an approach based on CAPEX-focused incentives, pilot-scale demonstrators, and risk-sharing instruments, recognising that circular upgrades often require structural changes rather than marginal improvements. Align funding schemes and regulations to reward efficiency gains and nutrient recovery rather than production volume alone.
	Establish targeted financial instruments and market de-risking tools	• Explore blended finance schemes, scale-up grants, risk-sharing facilities, and technical assistance for market access, certification, and contract negotiation. Combined with demonstration at relevant industrial scales, these instruments can bridge the gap between pilot success and commercial viability.
	Loans and Micro-Loans to circular aquaculture	• Support state-guaranteed green loans and micro-loans tailored SMEs. Instruments such as low-interest loans backed by 100% public guarantees and reduced co-financing requirements (e.g. 10–20%) can support shifting toward circularity
	Incentives to circularity and production	• Use EMFAF and complementary fiscal tools to offset initial investment costs, improve bankability, cover circular technologies (solar, composting, digital monitoring). • Increased investment and modernisation and de-risk early adoption.
	Incentives for restoration ecosystem services	• Returns on invested financial capital; payments for services including nutrient or carbon sequestration

Undeveloped markets	Promote symbiosis and clustering strategies	• Organising producers into cooperatives, regional hubs, or industrial symbiosis clusters. Collective structures allow products and by-products to be aggregated and supplied in consistent volumes, reducing unit handling and transport costs while increasing supply reliability for downstream users. • At policy and operational levels, support for cooperatives and shared facilities dedicated to circular aquaculture and by-product valorisation should be prioritised. • Cluster-based collaboration should be strengthened by consolidating the Blue Growth community connecting aquaculture with tourism and agriculture. Such clusters create integrated regional value chains that enhance market access.
	Create harmonised quality standards, certification schemes, and labelling frameworks	• Schemes should go beyond safety and technical compliance to explicitly capture and communicate environmental and social benefits.
	Create a truly systemic approach	• Developed a full value chain approach, from producers and industry associations to importers, retailers, consumers, scientists, NGOs and decision-makers. Cross-sector collaboration is crucial to achieve an integrated and lasting impact
	Promote demand-side stimulation mechanisms during early market phases.	• Public procurement policies, green purchasing criteria, and innovation-friendly tenders can act as lead markets for circular aquaculture products and services.

	Prioritise business model diversification and value-chain integration	• Rather than focus only in raw or semi-processed biomass, producers should be supported to move up the value chain through biorefinery approaches, co-product strategies, and cross-sectoral integration.
	Create fast-track schemes	• Establish an incentive-based green fast-tack permitting process for aquaculture projects that demonstrably integrate certified circular technologies such as RAS, IMTA, and waste or by-product valorisation. This will increase the regulatory certainty and reduce investment risks.
Logistical challenges	Integral logistics	• Invest in local centers for waste collection and processing to achieve economies of scale and ensure waste valorisation is economically viable.
High Energy Costs	Integration of renewable energy solutions	• Promote and subsidise the integration of renewable energy, particularly solar power, into aquaculture operations to reduce operating costs and carbon footprints. • Support applied research and pilot projects on aquavoltaics (solar installations over water bodies). • Create a targeted grant/voucher program to cover a high percentage of the cost (e.g., 70-80%) for installing photovoltaics (solar panels) on-site and implementing energy-efficient equipment (e.g., smart feeders, variable frequency drive pumps
Spatial planning conflicts	Integrated maritime and coastal spatial planning frameworks	• Circular aquaculture systems should be explicitly valued for their ecosystem services. Proactive co-location and multi-stakeholder strategies are required to reduce spatial pressure and integrate synergies across blue sectors. The designation of C-AZA or pre-assessed aquaculture areas can streamline permitting, reduce uncertainty, and provide long-term spatial security for investors.

6.2.3. Technological and Knowledge Gaps

Challenge	***Solution***	***Actions***
Insufficient validated circular production models at local scale	Pilot scale demonstration	• Direct engagement with producers, demonstrating practical benefits and showcasing successful initiatives.
Knowledge transfer and skills gaps	Establishment of regional Blue–Green innovation hubs	• Strengthen structured research–industry partnerships to ensure effective technology transfer and rapid scaling of proven solutions. • Create a network of regional Blue-Green Innovation Hubs, preferably located outside major metropolitan areas and developed in partnership with universities and applied research centres. These hubs would provide free or subsidised technical consultancy, hands-on training, and pilot-scale demonstrations of circular aquaculture technologies.
	Demonstration Sites and Living Laboratories	• Develop demonstration sites for circular production models across diverse environments (lagoons, salt marshes, urban and peri-urban settings). These living laboratories would allow producers, regulators, and students to observe and test circular practices under real operating conditions, improving confidence in system performance and regulatory acceptance. • Support applied experimentation and cross-environment learning to adapt circular models to local ecological and socio-economic contexts.
	International technology transfer and pilot testing	• Facilitate structured knowledge exchange with international partners that have advanced expertise in circular aquaculture. Pilot-testing programs, inspired by initiatives should act as enablers of local SMEs to test green technologies from experienced partners.

	Skills Programs	• Support mentoring and LiRRIEs programs nationwide, with targeted inclusion of targeted audience. This would build a skilled workforce capable of operating, maintaining, and innovating within circular and sustainable blue economy systems

6.2.4. Policy and Regulatory Gaps

Challenge	***Solution***	***Actions***
Absence of clear regulatory pathways	Formal legal recognition of circular aquaculture systems	• Establish explicit legal definitions and recognition of circular and eco-intensive aquaculture systems within national and EU aquaculture frameworks. • Create a clear classification of these systems as distinct production models.
	Dedicated regulatory and fast-track pathways	• Introduce dedicated licensing pathways or “green fast-track” procedures for certified circular aquaculture projects. These pathways should apply predefined technical and environmental criteria, shorten approval timelines, and provide regulatory certainty for pilot and commercial installations.
	Clear classification and valorisation pathways for circular by-Products	• Develop specific regulatory guidance for aquaculture by-products, particularly fish sludge • Create harmonised protocols for characterisation, hygienisation, and end-use categorisation (fertiliser, soil improver, substrate for invertebrates, or non-food applications).
Feed law restrictions	Advance risk-based regulatory approaches	• Developing standardised hygienisation and traceability protocols for rearing low trophic biomass and use of by-products for side-stream valorisation including. • Simplifying compliance procedures and providing technical guidance for SMEs would reduce costs and facilitate uptake, while maintaining feed safety and consume

Novel food restrictions	Strategic support for novel food compliance	• Provide targeted regulatory support for algae, halophytes, and other emerging biomass potentially classified as Novel Foods. This could include public guidance documents, pre-submission advisory services, and coordinated dossiers for commonly used species to reduce duplication of effort.
Fragmented governance and competences	Integrated and coordinated governance mechanisms	• Establish inter-ministerial coordination platforms or single-window authorities for aquaculture permitting that integrate environment, fisheries, agriculture, water, and public health competences.
Complex bureaucracy	Administrative simplification and SME support	• Streamline administrative procedures by standardising application requirements, digitalising permitting processes, and providing one-stop advisory services for SMEs. Single window. • Dedicated support units could assist applicants in navigating funding schemes, regulatory compliance, and reporting obligations. • Advocate for a more coordinated national approach to the circular economy, reducing administrative burdens for innovative projects.

6.2.5. Social and stakeholder engagement

Improving acceptance of circular aquaculture products requires a coordinated mix of targeted marketing, gastronomy partnerships, clear eco-labelling, and education.

Challenge	***Solution***	***Actions***
Low awareness of eco-certifications	Develop Integrated Eco-Labels with circularity criteria	• Design and promote harmonized national or European eco-labels that go beyond existing organic standards by explicitly integrating circularity criteria (e.g. nutrient recycling, low trophic integration, reduced water and energy footprints). These labels should clearly communicate food safety, environmental performance, and local value creation, making the benefits of circular aquaculture easily recognizable to consumers and retailers.

	Targeted branding and marketing campaigns	• Implement coordinated branding and marketing campaigns that emphasise food safety, traceability, and environmental responsibility as key selling points of certified circular products.
	Local awareness and experiential engagement	• Organise local-level awareness actions such as cooking workshops, tasting events, and open-farm days to directly connect consumers with certified products • Engage well-known chefs, culinary schools, and food influencers in promotional campaigns to showcase certified circular aquaculture products.
	Traceability, and Market Visibility	• Integrate advanced traceability tools and e-commerce modules into digital platforms such as the Blue Growth Digital Platform. QR-code-based product information, storytelling on production methods, and direct online sales channels would enhance transparency, reinforce certification credibility, and improve market access for producers.
	Digitalisation	• Digitalisation focus: Transparent supply chains, stronger consumer trust, and increased visibility of eco-certified circular products in regional and national markets
Perception barriers	Local transparency	• Initiatives to host open days, community visits, and school programs helps demystify production practices and builds trust at the local level. • Actions with simplified annual environmental reports focused on clear indicators such as waste reduction, nutrient reuse, and circular actions makes performance visible and accessible to residents and municipalities, reinforcing social licence to operate.
	Education and behavioural change initiatives	• Implement long-term education programs for schools, vocational training, and the public to improve understanding of circular aquaculture such as cooking workshops, school curricula on sustainable diets, and digital content explaining nutritional value, food safety, and environmental benefits.

		• Educational content: Highlight nutritional benefits, environmental gains, and traceability through social media and school programs.
	Consumer education targeted awareness campaigns	• Educational campaigns aimed to educate consumers on the value of eco-labelled and sustainably produced local seafood, linking certifications with freshness and local origin. • Launch "Eat Blue, Buy Local" campaign promoting mussels, oysters, and eco-labelled fish as healthy, sustainable Montenegrin products. Builds recognition and trust in low-trophic and circular seafood.
Consumer awareness	Promotion by professionals and gastronomy partnerships. culinary innovation	• Menu visibility, tasting events, and seasonal promotions to reduce the "unusual product" barrier and reposition low-trophic species as desirable, high-quality foods. • Establish strategic collaborations with chefs, restaurants, and culinary schools to introduce under-consumed local species (e.g. Ulva, Codium, Cystoseira, Gracilaria, sea cucumbers, microalgae) through attractive, ready-to-eat formats and modern recipes.
	Strong, recognizable eco-labels and storytelling	• Create clear and credible national or regional eco-labels (e.g. Fish From Greece, IMTA/circular aquaculture labels) that clearly communicate food safety, traceability, local origin, and environmental benefits. • Complement labels with effective storytelling tools such as QR codes, short videos, and farm profiles that showcase circular practices, nutrient recycling, algae-fed fish, and local job creation.
	Eco-Gastronomy Events	• Organize seafood festivals, chef collaborations, and tasting sessions (e.g., Blue Table Montenegro) highlighting circular aquaculture farms. Increases consumer familiarity through direct experience.
	Early engagement of buyers and distributors	• Collaborate with coastal tourism by organizing farm visits, tastings, open days, and storytelling events at aquaculture and local processing sites. Experiential marketing reconnects consumers with production systems, increases trust, and creates memorable associations with circular products. Particularly

		effective in Mediterranean regions with strong tourism flows.
	Tourism and experience-based marketing	• By-products should be away from "waste" narratives by integrating them into high-value applications such as cosmetics, nutraceuticals, supplements, and wellness products. • Co-branding with cosmetic, spa, or wellness brands, especially relevant where seaweed food consumption is low, • Links sustainability with local culture and hospitality
	Co-branding of by-products	• Address reluctance to cook unfamiliar ingredients such as seaweed, microalgae or sea cucumbers) by promoting convenient formats: pre-cut, dried, powdered, or incorporated ingredients (e.g. algae-enriched pasta, snacks, sauces, fish products with integrated low-trophic ingredients). • Product innovation should be supported by clear usage instructions and recipes.
	Targeted, co-funded marketing and awareness campaigns	• Launch co-funded campaigns supported by industry and public authorities, adapted to national and cultural contexts. Campaigns should emphasize local products, freshness, food safety, and simple messages explaining the benefits of circular aquaculture, origin, quality cues, and strong narrative approaches such as "from lagoon to plate". • Campaigns should combine social media, gastronomy and lifestyle media, influencers, and tourism channels to maximize reach. • Promote undervalued species - launch promotional tools for underutilized and "neglected" fish species with low commercial value.

Consumer habits	Retail Promotion	• Tailor product forms and labels - for new products like seaweed, introduce them in familiar formats (e.g., as a seasoning or ingredient in existing dishes) to ease consumer acceptance. • Tailor product labels to country-specific needs, ensuring the most important information (freshness, origin) is prominent, alongside sustainability claims. • Support the strong consumer preference for local products by emphasizing the loca origin and production features. Using campaigns like successful regional schemes like "Galician Mussels" can build trust.

6.3 Gaps and Future Directions

Circular aquaculture depends on effective cooperation between across multiple actors, but achieving this in practice remains challenging. Insufficient coordination between producers, research institutions, and public administrations leads to fragmented efforts and overlapping initiatives. Many stakeholders still lack a shared, systemic understanding of circular aquaculture. While producers and citizens usually focus on their immediate concerns, research, policy, and governance organizations take a broader, integrative approach. This difference was evident in different stakeholder surveys, where respondents consistently gave higher priority to interventions related to processes, products, and economics, rather than social or governance aspects (Masi *et al.* 2026). These trends can reinforce imbalances in how decisions are discussed and made, especially within governance systems lacking diverse perspectives, and risk underestimating the complexity of the networks involved in managing aquatic resources sustainably. Despite significant progress, the transition towards circular aquaculture remains constrained by a series of well-defined research and implementation gaps that require coordinated scientific, policy, and market-oriented responses.

A first critical gap concerns the **economic viability of small-scale circular aquaculture systems**. Empirical evidence on long-term profitability, investment recovery, and resilience to market fluctuations is still limited, particularly in developing regions. While circular systems may offer efficiency gains, their economic performance varies strongly with scale and local context. Small operators face higher capital intensity, limited access to finance, and weaker market integration, which together hinder the adoption of circular practices. Longitudinal economic studies that capture full cost structures and dynamic market conditions are therefore essential, alongside the development of tailored financial instruments and business models for smallholders (Oyeboade & Olagoke-Komolafe 2024a; Voicea *et al.* 2024; Silva *et al.* 2025).

Another major limitation is the **absence of standardised circularity metrics and assessment frameworks**. Current evaluations of environmental and circular performance are highly site-specific, making comparisons across species, technologies, and regions difficult. This lack of harmonisation hampers benchmarking, policy uptake, and regulatory recognition. Developing and validating universally applicable indicators for circularity and sustainability is therefore a prerequisite for scaling and mainstreaming circular aquaculture (Checa et al. 2024; Masi et al. 2024).

The **scalability of circular aquaculture technologies** represents a further bottleneck. Many innovations remain confined to pilot or demonstration scale due to infrastructural constraints, regulatory uncertainty, and market barriers. Research is needed to identify scalable business models and adaptive management strategies that respond to local infrastructure and market conditions, as well as policy instruments capable of supporting the transition from pilot projects to commercial operations (Gregg *et al.* 2019; Voicea *et al.* 2024; Silva *et al.* 2025).

Persistent challenges also arise from **policy incoherence and limited institutional support.** Circular systems such as IMRAS and aquaponics operate at the intersection of aquaculture, agriculture, water management, and food safety regulations, often governed by separate authorities. This fragmentation generates administrative complexity, regulatory uncertainty, and high compliance costs. Future work should focus on mapping regulatory gaps and designing integrated governance frameworks that harmonise sectoral policies while strengthening institutional coordination and capacity building (Gregg *et al.* 2019; Oyeboade & Olagoke-Komolafe 2024a)

The potential of **digital technologies to support circularity** is another underexplored area. Digital platforms, precision aquaculture tools, and traceability systems could significantly enhance resource efficiency, market access, financing opportunities, and stakeholder engagement, particularly for small-scale producers. However, research is still needed to assess their scalability, accessibility, and broader socio-economic impacts (Lal *et al.* 2024)

Similarly, **waste valorisation and market development remain weak points** in circular aquaculture systems. Despite technological feasibility, products derived from aquaculture by-products, such as circular feeds, biofertilisers, or biomaterials, face limited market acceptance and underdeveloped value chains. Future research should integrate market analysis, consumer acceptance studies, and the design of certification schemes and policy incentives to support commercial uptake (Vu & Chi 2024).

In parallel, evidence on the **long-term socio-economic impacts of circular aquaculture remains limited**. Most available studies focus on short-term or pilot assays, providing limited insights into sustained effects on livelihoods, employment, and community resilience. Longitudinal socio-economic impact assessments across diverse geographical and socio-economic contexts are needed to capture these dynamic effects and inform evidence-based policy design (Hossain *et al.* 2022; Oyeboade & Olagoke-Komolafe 2024a). Closely linked to this is the insufficient understanding of **social equity and inclusion within circular aquaculture transitions**. Quantitative assessments of social outcomes, such as gender equity, labour conditions, and participation of marginalised groups, remain scarce. Existing evidence suggests that without explicit social design, circular innovations may reproduce or even exacerbate existing inequalities. Future research should adopt mixed-methods approaches to evaluate social impacts and develop operational frameworks that embed inclusion criteria directly into circular business models (Bunting *et al.* 2023; Oyeboade & Olagoke-Komolafe 2024a; Aitken *et al.* 2025)

Another key gap relates to the **context-specific adaptation of circular practices**. Many circular technologies and management approaches are transferred across regions with insufficient consideration of local ecological, cultural, and economic conditions. Participatory and adaptive research frameworks are needed to tailor solutions to specific contexts, as one-size-fits-all models rarely deliver consistent or sustainable outcomes (Voicea *et al.* 2024).

Finally, there is a growing need for **comprehensive assessment of environmental trade-offs associated with circular aquaculture technologies**. While circular systems aim to improve resource efficiency, some may entail higher energy consumption or operational complexity. Applying life cycle assessment and emergy analysis is essential to quantify net environmental performance and ensure that circular gains are not offset by hidden environmental costs (Emerenciano *et al.* 2025).

7. Conclusion and Call to Action

Circular aquaculture represents a **strategic pathway to strengthen the Bioeconomy and Blue Economy** in the EU. By shifting from linear production models toward integrated, resource-efficient systems, circular approaches address key environmental, economic, and social challenges while unlocking new value chains, business opportunities, and sources of innovation. As demonstrated throughout this guide, circular production models can significantly **enhance overall productivity** by applying five basic principles. Substantial novel market potential exists for **low-trophic species** in most cases unexploited and technologically demanding.

While integrated systems combining **regenerative practices** based on high-value species such as finfish or shrimp with extractive organisms offer strong economic returns, they are often associated with higher capital and operational costs. In parallel, **restorative aquaculture** models based exclusively on low-trophic species present a major opportunity to occupy emerging market niches for direct human consumption, as well as largely untapped, high-demand commodity markets (e.g. feed ingredients, biofertilisers, biopolymers, and bioactive compounds). Together, these complementary pathways position circular aquaculture as a cornerstone for a more resilient, diversified, and future-proof European aquatic food system.

However, the transition to circular aquaculture requires coordinated action. **Technical solutions** are essential but alone are insufficient without enabling **regulatory frameworks, access to finance, skills development, and strong collaboration** across the **value chain**. **Policymakers** are called upon to provide clear and predictable regulatory pathways, integrate circularity criteria into licensing and funding schemes, and recognise circular aquaculture as a contributor to environmental objectives, food security, and regional development. **Financial institutions** and funding bodies should expand tailored instruments to reduce risk and support system redesign, pilot projects, and scale-up of proven circular solutions.

Aquaculture **producers and entrepreneurs** are encouraged to transition their business models, investing in eco-design, low-trophic and biomass production, and partnerships with agriculture, energy, and biotechnology sectors. **Research and innovation actors** should continue to co-develop practical, market-ready solutions with industry, while strengthening knowledge transfer, training, and demonstration activities. Pilot scales and living-lab demos appear as essential instruments to upscale circular production models

Ultimately, scaling up circular aquaculture in Europe demands a shared **commitment across the quadruple helix**, industry, public authorities, research, and society. This guide calls on all stakeholders to move from ambition to implementation, leveraging existing knowledge, funding, and cooperation mechanisms to accelerate the adoption of circular aquaculture systems that deliver environmental benefits, economic value, and long-term sustainability for coastal and inland communities.

Annexes

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Supplementary information

Supplementary Table 1*. Main characteristics of aquaculture production in Europe and in the eight countries participating in the AZA4ICE project.*

Country	Main Species	Total Production	Key Economic Notes
European Union (27)	Mussel, rainbow trout, seabream, oysters, seabass	~1.12 million Tn (2022)	Spain accounts for 24.6% of total EU aquaculture; fish value €2.885 B; marine production dominates (75.9%)
Bulgaria	Carp, trout, black mussel	9,400–16,500 Tn Finfish (73.6%) Shellfish (27.4%)	866 jobs, mussel production rising; low GDP contribution < 0.1%
Croatia	Tuna, seabass, carp, mussels, trout	29,369 Tn	0.2–0.7% GDP contribution; 1,450 direct jobs
France	Oysters, mussels, trout, seabream, seabass, micro/macroalgae	184,000 t Finfish (26.8%) Shellfish (76.0%)	€822M market value; 17,000+ shellfish jobs, + Marine fish farming: 3,00 jobs (37 companies); Algae production: 515 jobs
Greece	Seabream, seabass, meagre, great amberjack, sharp-snout sea bream, red sea bream, mussels	141,909 Tn Finfish (87.2%) Shellfish (12.7%)	€571M exports from seabass/seabream alone 3,489 employees in 2023
Italy	Seabass, seabream, mussels, clams,	145,877 Tn Finfish (35.6%)	€547.2M market value

	oysters, rainbow trout	Shellfish (64.4%)	
Montenegro	Sea bass, seabream, rainbow trout, mussels	1,682 t Finfish (57.1%) Shellfish (23.5%)	Strategic for coastal jobs & diversification GDP contribution 0.05–0.1%. 150–170 employees
Portugal	Turbot, seabream, seabass, carpet shell, mussels and oysters	20,872 Tn (2023) Finfish (38.3%) Shellfish (56.7%)	€205.9M income, 731 companies, mostly micro-enterprises. 2,014 employees.
Spain	Mussel, seabass, seabream, bluefin tuna, rainbow trout, turbot, meagre, sole	266,066 Tn (2023) Finfish (27.6%) Shellfish (68.7%)	€750.5 M total first-sale value; 10254 employees

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