Circutech

Activity A6 Roadmap for European aquaculture sector

Document for Technical Validation by Partners

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Circular Competence Training for Aquaculture Waste Management using VR and AR Tools

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Index

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1. Executive Summary

1.1. Key findings and recommendations

In Spain, Portugal, and Italy, aquaculture shows significant strengths such as the use of certified systems for managing plastic, metal waste, and by-products; positive contributions to biodiversity and water quality; and increasing adoption of technologies that optimize production and minimize environmental impacts. However, challenges include the dispersed geographic distribution of farms, predominance of small-scale operations, lack of specialized training, and complex bureaucratic and regulatory frameworks that hinder effective implementation of sustainable practices. Waste collection and treatment infrastructure is insufficient in key areas, especially offshore zones or less developed regions. Opportunities focus on technological innovation (reusable packaging, recirculating aquaculture systems, nutrient recovery), collaboration between sectors and research centers, and potential uses of by-products for biogas, fertilizers, and animal feed. While there is growing interest in sustainability certifications, market acceptance remains limited and depends on raising awareness among producers and consumers. Major threats include climate change impacts (diseases, mortality, extreme weather), negative public perception influenced by misinformation, and fragmented regulations that complicate integrated waste management and by-product valorization. Overall, advancing toward more sustainable aquaculture requires simplifying regulations, improving training and communication, strengthening waste management infrastructure, promoting circular economy practices, and fostering multisector collaboration to optimize resource use and reduce environmental impact.

1.2. Purpose and strategic importance of the roadmap

The purpose of this roadmap is to provide a clear, actionable framework for advancing sustainable practices in aquaculture waste and by-product management across Spain, Portugal, and Italy. It aims to identify key challenges, leverage opportunities, and align stakeholders towards common goals that enhance environmental, economic, and social sustainability within the sector.

Strategically, the roadmap serves as a vital tool to guide policymakers, industry players, researchers, and support organizations in implementing innovative solutions that reduce environmental impact, promote circular economy principles, and improve resource efficiency. By addressing regulatory barriers, fostering collaboration, and encouraging the adoption of cutting-edge technologies, the roadmap supports the transition towards more resilient and responsible aquaculture practices. Ultimately, it contributes to preserving marine ecosystems, supporting local economies, and meeting the growing consumer demand for sustainably produced seafood.

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2. Introduction

2.1. Background and context

The aquaculture sector in Southern Europe—especially in Spain, Portugal, and Italy—is facing increasing pressure to adopt more sustainable and circular practices due to environmental concerns, regulatory demands, and evolving market expectations. The transformation towards a circular economy model is essential to reduce waste, improve resource efficiency, and mitigate the sector's environmental footprint.

This roadmap is developed to guide the sustainable management of aquaculture waste and by-products, fostering practices that support environmental protection, biodiversity preservation, and climate change mitigation. It integrates insights from national contexts and stakeholder experiences to address existing challenges such as fragmented waste collection systems, lack of harmonized regulations, and limited awareness or training on sustainable practices.

By defining strategic actions, technologies, and collaborative opportunities, the roadmap aims to support the transition of the aquaculture industry towards a more resource-efficient, competitive, and environmentally responsible future. This aligns with broader European objectives, including the EU Green Deal and Circular Economy Action Plan, which emphasize innovation, sustainability, and the development of blue economy skills to ensure long-term sector resilience.

2.2. Objectives of the roadmap

This roadmap serves as a strategic transformation plan to guide the transition of European aquaculture towards a more sustainable and circular model. As the foundational element of the project, it aims to support and accelerate the shift to circularity and sustainability within the sector.

The specific objectives are:

- To conduct fieldwork and analyze current waste management practices in European aquaculture, including compliance with European and national regulations, to understand sector-specific needs and challenges.
- To develop a management model tailored to aquaculture farms that integrates circular economy and eco-design principles into waste and by-product management.
- To establish clear criteria and indicators for evaluating circularity and sustainability in aquaculture operations.
- To design a model for measuring circularity, including assessing the impact of circular solutions.

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- To produce a comprehensive transformation plan (roadmap) outlining strategic actions and systems required to facilitate the sector's shift towards circular and sustainable practices.

2.3. Methodology (based on A1–A5 activities)

The roadmap development follows a structured methodology comprising five key activities. Fieldwork (A1) is conducted in Italy, Spain, and Portugal, involving surveys of aquaculture companies to collect data on waste management practices, the types of waste and by-products generated, and the adoption of circularity and eco-design principles. This includes desktop research, farm surveys, and site visits. Focus groups (A2) with 5 to 10 experts per country provide qualitative insights, culminating in SWOT analyses that identify strengths, weaknesses, opportunities, and threats within the sector. These inform the creation of a summary report. Subsequently, a management model (A3) tailored to aquaculture farms is developed, integrating circular economy and eco-design pathways. A set of criteria and indicators (A4) is defined to monitor circularity and sustainability in both inland and marine aquaculture. Finally, a measurement model (A5) is established to assess circularity, sustainability, and the effectiveness of circular solutions, providing a comprehensive framework to guide the sector's transformation.

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3. Current State of European Aquaculture

3.1. Overview of the sector

The European aquaculture sector is progressively integrating circular economy principles, aligning with major EU policies such as the European Green Deal and the Farm to Fork Strategy. These frameworks recognize aquaculture as a sustainable, low-carbon protein source critical for resilient food systems, with a focus on pollution reduction, climate change mitigation, and ecosystem preservation.

Technological advancements emphasize waste-to-resource approaches, valorizing aquaculture by-products through reuse and recycling, and improving circular feed production by utilizing effluents and sludge. Innovative production systems such as Integrated Multi-Trophic Aquaculture (IMTA) and Recirculating Aquaculture Systems (RAS) are increasingly adopted to enhance nutrient recovery and reduce environmental impact. Additionally, digital monitoring supports improved feed efficiency and waste bioremediation.

Policy support includes strategic EU guidelines promoting sustainable and competitive aquaculture, funding from the European Maritime and Fisheries Fund (EMFAF), and legislative efforts to streamline regulations and develop circularity indicators. Cross-sector collaboration further fosters synergies between aquaculture and agriculture, supporting a holistic circular bioeconomy.

Despite progress, the sector faces economic barriers such as high investment and recycling costs, social challenges including limited consumer awareness, regulatory complexity, and technical hurdles like infrastructure needs and recycling technology gaps. Nevertheless, successful practices across Europe—such as digital product passports for traceability, nutrient recovery in RAS and semi-closed systems, circular feed management, and IMTA—demonstrate the viability of a circular aquaculture model. Supported by targeted policies and funding, these strategies contribute to the EU's sustainable food and bioeconomy goals.

3.2. Main sustainability and circularity challenges

The aquaculture sectors in Spain, Italy, and France face common sustainability and circularity challenges, though with country-specific nuances. Climate change impacts—such as rising sea temperatures, extreme weather events, and ocean acidification—pose a significant threat across all three countries, affecting both marine and land-based systems. These environmental pressures also influence disease prevalence and water availability, especially under drought conditions.

Resource efficiency and input dependency remain major circularity hurdles. All countries report high volatility in feed ingredient costs and energy prices, with Spain and Italy particularly affected by

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dependency on imported inputs. Feed sustainability, waste management, and carbon footprint reduction are ongoing priorities. Transitioning to renewable energy and adopting circular feed solutions are crucial but still underdeveloped.

Regulatory complexity and administrative burdens, especially in Spain and Italy, hinder innovation and the scaling of sustainable practices. Furthermore, limited consumer awareness and weak market differentiation for sustainable products restrict the sector's ability to leverage its environmental efforts commercially.

Public perception challenges and the need to maintain social license—particularly in coastal areas shared with tourism and fisheries—are critical in all three countries. Strengthening transparency, stakeholder dialogue, and accurate communication about aquaculture's benefits is essential for long-term sustainability.

Finally, gender imbalance and limited social inclusion in the workforce persist, especially in Spain and Italy, pointing to a need for more inclusive policies to ensure equitable and resilient sectoral growth.

3.3. Summary of fieldwork findings (Spain, Italy, Portugal)

The fieldwork conducted in aquaculture companies across Spain, Italy, and Portugal reveals that the implementation of circular economy strategies remains limited, although there are scattered good practices and a growing awareness of sustainability within the sector.

Few companies have formal policies or measurable targets related to circular economy. However, some have started adopting practices such as water recirculation systems, material reuse, and valorization of organic by-products (e.g., shells and processing waste). In occasional cases, in Portugal, oyster shells are reused for soil consolidation, with plans to explore uses as fertilizers or animal feed ingredients. In Italy, by-products are sometimes directed to cosmetics or animal nutrition, while in Spain, efforts are focused on waste treatment technologies and improving energy and water efficiency.

The most common types of waste include plastics, nets, sacks, dead fish, and shells. While most companies separate waste at the source, the percentage of recycled material remains low. Additionally, there is a general absence of collaboration between companies to jointly valorize waste or by-products.

Regarding resource use, water and energy reduction efforts are relatively common, especially through closed-loop production systems. However, the use of renewable energy is still very limited. Operational efficiency is often the main driver of these improvements rather than structured environmental strategies.

In terms of economic impact, most companies have not evaluated the costs associated with waste management or circular practices, nor have they received specific incentives. There is a common demand

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for increased financial support, tax incentives, and technical assistance to facilitate the transition toward circularity.

Transparency is also limited: very few companies publish sustainability reports or define performance indicators related to circular economy. Nevertheless, environmental training is positively valued. Most companies offer training on best practices, the use of filter-feeding organisms, and waste management, and believe that awareness and education are crucial for sector-wide progress. A blended approach combining hands-on and e-learning formats is preferred.

The main challenges identified include the lack of critical volume for waste valorization, the cost of sustainable technologies, the limited availability of effective biodegradable materials, and the absence of clear regulatory frameworks. Despite these barriers, some companies are developing innovative strategies, such as production systems that deliver ecosystem services, artificial reef creation, and pilot projects to convert waste into useful products.

In conclusion, the circular economy in southern European aquaculture is still in an early stage, but encouraging signs of progress are emerging. To support this transition, it will be essential to strengthen institutional support, promote inter-company cooperation, highlight successful practices, and reinforce training and capacity-building efforts in the sector.

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4. SWOT Analyses by Country

4.1. Spain

Spain's aquaculture sector stands out globally for its innovation, research excellence, and sustainability, boasting the largest harvest in the EU and a highly diverse species portfolio. The industry benefits from strong environmental certifications, low carbon and water footprints, advanced waste management, and a firm commitment to animal welfare. Its diverse production systems and vertical integration provide adaptability and efficiency, supported by transparent sector collaboration. However, the sector faces challenges such as reliance on imports to meet domestic demand, geographic concentration, energy transition difficulties, complex regulations causing administrative delays, and limited consumer awareness of sustainable aquaculture. Social inclusion and gender equality remain areas needing improvement. Opportunities lie in leading the blue transformation, driving rural development, embracing digitalization and precision aquaculture, leveraging alignment with the Sustainable Development Goals, and tapping into rising consumer demand for certified and healthy seafood. Threats include climate change impacts, competition from lower-cost imports, evolving regulatory burdens, public perception risks, and resource cost volatility, all of which require strategic adaptation to maintain Spain's leadership and sector resilience.

4.2. Italy

Italy's aquaculture sector is characterized by a great diversity of farmed finfish species (25 species), which enhances biodiversity, and by the presence of farms both on land and in coastal marine environments, enabling frequent and thorough environmental monitoring. Aquaculture supports the physical and cultural preservation of many areas through sustainable management, especially in lagoons and confined zones with low-impact species, providing key ecosystem services such as climate regulation, bioremediation, and maintenance of hydrobiological cycles. The sector employs various technologies to optimize production, reduce waste, and improve animal welfare, including filtration systems, wastewater treatment, and digital monitoring, promoting circular resource management. However, weaknesses include the dispersed location of farms, which complicates waste collection, and the predominance of micro and small enterprises, which limits economies of scale, complicates bureaucracy, and hampers training. Managing wastewater remains technically and financially challenging, further hindered by inconsistent regional regulations and tariffs. Opportunities lie in using aquaculture waste for biogas and fertilizers, supported by national and EU funding programs for sustainable aquaculture and just transition. Collaboration to transform waste into valuable inputs, promotion of sustainability certifications—though currently with low market recognition—and adoption of innovative technologies like recirculating aquaculture systems (RAS), integrated multi-trophic aquaculture (IMTA), and integration with agriculture and tourism offer potential for impact reduction and diversification. Threats include climate change effects

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such as heatwaves, extreme weather, algal blooms, and disease outbreaks; a complex and fragmented regulatory framework; and widespread public and commercial misconceptions about aquaculture sustainability. Large-scale retailers often resist certified products, favoring private brands, which challenges consumer trust. Overall, coordinated efforts are needed to enhance the sustainability and competitiveness of Italy's aquaculture sector.

4.3. Portugal

While Portugal's bivalve farming sector showcases notable strengths in sustainable waste and by-product management—such as the collection and recycling of plastics, metals, styrofoam, and damaged or dead fish by certified companies—these practices are not exclusive to bivalve farmers, but are also implemented across other segments of the aquaculture industry. It is not a common practice, but, occasionally by-products like bivalve shells are reused in cement production, and efforts are made to reduce plastic waste, such as using larger feed bags. Bivalve aquaculture positively impacts the marine environment by maintaining ecosystems, preserving water quality, and supporting biodiversity, with generally good waste sorting and collection practices in place. Technologies supporting sustainability are emerging, although challenges remain, such as the limited availability of alternatives to problematic materials like plastic ties. Weaknesses include a widespread lack of knowledge and training among workers and business owners about waste separation, resource reuse, and sustainable practices, compounded by language barriers and poor accessibility of training platforms. Bureaucratic hurdles and poorly designed mandatory registration systems complicate waste management implementation, while some regions lack adequate disposal facilities, especially for offshore operations. Opportunities arise from innovations like reusable transport packaging and projects exploring alternatives to styrofoam, with active collaboration between aquaculture stakeholders, research institutions, and associations. Growing, though still uncertain, consumer interest in sustainably certified products exists. Threats include climate change impacts such as new diseases, algal blooms, and oxygen depletion affecting production, alongside misconceptions in legislation that wrongly attribute marine litter to aquaculture, despite low waste generation from offshore farms. Public perception of aquaculture remains biased, associating it with environmental harm and contamination, and pressure from sectors like fisheries complicates sustainability efforts. Overall, major obstacles to sustainable waste and by-product management include lack of awareness, inadequate training tailored to Portuguese aquaculture realities, insufficient waste disposal infrastructure, and limited consumer demand for sustainable products.

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5. Strategic Vision and Goals

5.1. Long-term vision for circular aquaculture in Europe

5.1.1. Spain

Spain's long-term vision for circular aquaculture is closely aligned with national and European sustainability frameworks, including the European Green Deal and the Farm to Fork Strategy. According to Apromar's 2025 Sustainability Report, the Spanish aquaculture sector is committed to continuous improvement towards 2030, focusing on environmental, productive, and social objectives. Key aspects include:

- **Resource Optimization:** Adoption of advanced technologies such as Recirculating Aquaculture Systems (RAS) and Integrated Multi-Trophic Aquaculture (IMTA).
- **Waste and By-product Valorization:** Aiming for zero-waste operations through innovative reuse strategies.
- **Environmental Stewardship:** Continuous monitoring and climate adaptation practices.
- **Technological Innovation and Digitalization:** Improving efficiency and traceability.
- **Social and Economic Sustainability:** Ensuring community benefits and sector resilience.

5.1.2. Portugal

Portugal's vision, framed by the Ocean Strategy 2030, the National Strategy for the Sea 2021–2030, and the Strategic Aquaculture Plan 2021–2030, focuses on:

- **Resource Optimization and Productive Circularity:** Efficient use of water, energy, and raw materials.
- **Valorization of By-products:** Promoting sustainable reuse of aquaculture residues.
- **Sustainability and Circularity:** Aligning national practices with EU priorities, such as reducing waste, improving environmental outcomes, and supporting a circular economy.

5.1.3. Italy

Italy's long-term vision is anchored in the National Strategic Plan for Aquaculture (NSPA) and Blue Economy strategies, particularly in bivalve farming (mussels and oysters). Key elements include:

- **Sustainable Mussel and Oyster Farming:** Leveraging low-impact production relying on natural filter feeding.
- **Circularity and Waste Reduction:** Promoting reuse of materials, including polypropylene socks and shell by-products, supported by pilot projects and EU research (e.g., LIFE MUSCLES project).

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- **Innovation and Digitalization:** Increasing traceability and efficiency through technological solutions.
- **Integration of Circular Practices:** Expanding IMTA systems and shell valorization to strengthen environmental and economic sustainability.

5.2. Key strategic objectives

5.2.1. Spain

- Promote productive circularity through waste prevention, monitoring, collection, and by-product valorization.
- Reduce environmental impact via carbon and water footprint reduction and effluent management.
- Drive technological innovation and adoption in circular aquaculture and sustainable feeds.
- Improve spatial planning and access to marine resources.
- Strengthen capacity building and skills development for circular economy practices.
- Simplify administrative processes to facilitate sustainable investment.
- Encourage digitalization and data-driven environmental monitoring.
- Establish best practices for reuse and valorization of waste streams.

5.2.2. Portugal

- Promote sustainability and resource efficiency in aquaculture.
- Implement ecosystem-based spatial planning and environmental monitoring.
- Support innovation, digitalization, and decarbonization of the sector.
- Maximize efficiency in the use of natural resources.
- Valorize and reuse by-products and waste.
- Ensure sustainable and competitive spatial planning.
- Simplify administrative processes and promote capacity building.
- Strengthen alignment with EU circular economy and environmental targets.

5.2.3. Italy

- Improve resilience and sustainability of the aquaculture value chain.
- Minimize waste through the creation of infrastructure capable of recycling materials into new products.
- Promote coastal zone planning and spatial management.
- Support innovation and technological advancement, including digitalization.

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- Enhance traceability, knowledge transfer, and skills across the sector.
- Encourage reuse of by-products and materials, e.g., polypropylene recycling.
- Contribute to EU circular bioeconomy and plastic reduction targets.
- Facilitate economically viable adoption of circular practices across all actors.

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6. Roadmap: Actionable Steps for Transition

6.1. Policy and Regulatory Recommendations

6.1.1. Spain

- **Current Situation:** Spain's regulatory framework is evolving to support circular aquaculture, with primary regulations managed at the autonomous community level but increasingly coordinated at the national level and aligned with EU directives. Current focus includes integrating circular principles into licensing and operational frameworks.
- **Key Challenges:** Regulatory fragmentation, complex administrative processes, insufficient support for by-product valorization, lack of harmonized environmental monitoring, and incomplete climate adaptation policies.
- **Opportunities / Best Practices:** MAR2030 and the Recovery and Resilience Plan (PRR) provide funding opportunities; strong alignment with EU directives; active industry engagement via Apromar; established environmental monitoring capabilities.
- **Recommendations / Actionable Steps:**
    - Harmonize regulations to simplify licensing and permits.
    - Introduce financial incentives and subsidies for circular practices.
    - Develop specific guidelines for safe by-product valorization.
    - Strengthen environmental reporting and monitoring standards.
    - Implement policies supporting climate adaptation and resilient infrastructure.

6.1.2. Portugal

- **Current Situation:** Portugal promotes circular aquaculture policies via co-creation involving academia, industry, and civil society. Legislation supports reuse and valorization, aligned with EU decarbonization goals.
- **Key Challenges:** Bureaucracy, technical capacity gaps, insufficient waste management and valorization, and climate adaptation requirements.
- **Opportunities / Best Practices:** Strategic Plan for Portuguese Aquaculture 2021–2030 promotes IMTA, RAS, and clean technologies; EU Green Deal and Farm to Fork guidelines support low-carbon circular practices.
- **Recommendations / Actionable Steps:**
    - Streamline administrative and licensing processes.
    - Enhance technical capacity and knowledge transfer.
    - Improve waste management and by-product valorization infrastructure.
    - Integrate climate adaptation measures into policy frameworks.

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6.1.3. Italy

- **Current Situation:** Italy's governance is fragmented; infrastructure is often outdated; regulatory gaps hinder reuse of aquaculture waste (e.g., polypropylene socks).
- **Key Challenges:** Delays in licensing, lack of harmonized port regulations, insufficient frameworks for circular waste reuse.
- **Opportunities / Best Practices:** LIFE MUSCLES project demonstrates recycling technologies; long-line farming leadership; regional initiatives for shell reuse.
- **Recommendations / Actionable Steps:**
  - Simplify permissions and harmonize regional and national regulations.
  - Reclassify polypropylene socks as recyclable by-products.
  - Support localized recycling legislation and infrastructure.

6.2. Economic and Financial Incentives

6.2.1. Spain

- **Current Situation:** National and EU funds available through MAR2030 and PRR; emerging green finance market.
- **Key Challenges:** High investment costs for SMEs, limited access to specialized finance, insufficient market-based incentives.
- **Opportunities / Best Practices:** Established funding programs; public-private partnership potential; increasing consumer demand for sustainable products.
- **Recommendations / Actionable Steps:**
  - Establish dedicated funding for R&D and infrastructure (RAS, IMTA).
  - Promote green loans and sustainable investment instruments.
  - Foster public-private partnerships to share risk.
  - Provide targeted support for SMEs.
  - Explore eco-labeling and certification schemes.

6.2.2. Portugal

- **Current Situation:** Funding from PRR (up to 75% for SMEs), MAR2030, and EMFAF; focus on circularity, digitalization, decarbonization, and innovation.
- **Key Challenges:** Bureaucracy, overlapping policies, limited co-financing capacity, lack of circularity-based evaluation criteria.
- **Opportunities / Best Practices:** Efficient water reuse, digitalization, energy efficiency, regional and EU collaborative projects.

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- **Recommendations / Actionable Steps:**
  - Simplify funding processes and reduce bureaucracy.
  - Improve communication on available incentives.
  - Integrate circularity indicators into evaluation criteria.
  - Encourage multi-stakeholder partnerships.

6.2.3. Italy

- **Current Situation:** Funding exists but is underutilized by small shellfish operators; high disposal costs for waste like polypropylene socks.
- **Key Challenges:** Limited SME access to finance, high waste management costs.
- **Opportunities / Best Practices:** LIFE MUSCLES project; potential markets for recycled plastics and mussel shells.
- **Recommendations / Actionable Steps:**
  - Simplify access to finance for SMEs.
  - Incentivize recycling technologies.
  - Support value chains for reused aquaculture materials.

6.3. Technology and Innovation Pathways

6.3.1. Spain

- **Current Situation:** Strong R&D capacity; focus on digitalization, sustainable technologies, and circular system development.
- **Key Challenges:** Technology transfer gaps, high initial costs, skilled workforce shortage, limited pilot infrastructures.
- **Opportunities / Best Practices:** Successful pilot projects, academia-industry collaboration, government innovation support.
- **Recommendations / Actionable Steps:**
  - Increase R&D funding for sustainable feeds, disease prevention, and water treatment.
  - Promote digitalization via IoT, AI, and data analytics.
  - Scale up RAS and IMTA systems through demonstration farms.
  - Develop innovative processing technologies for by-products.
  - Facilitate knowledge transfer between academia and industry.

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6.3.2. Portugal

- **Current Situation:** Initiatives like AlgaCycle and VALORMAR; innovation hubs and living labs for waste valorization.
- **Key Challenges:** Regulatory complexity, technical training, industrial scaling, integration with existing operations.
- **Opportunities / Best Practices:** RAS and IMTA improvements, circular production systems, digitalization, by-product value chains.
- **Recommendations / Actionable Steps:**
  - Invest in circular production systems and digital monitoring.
  - Develop value chains for waste-to-product conversion.
  - Align projects with EU low-carbon and circular economy targets.

6.3.3. Italy

- **Current Situation:** Low adoption of R&D; scarce digital and sustainable tools; recycling of polypropylene socks is difficult.
- **Key Challenges:** Lack of scalable recycling systems, need for biodegradable alternatives.
- **Opportunities / Best Practices:** LIFE MUSCLES mobile recycling machines; pilot testing of biodegradable ropes.
- **Recommendations / Actionable Steps:**
  - Promote eco-design of aquaculture materials.
  - Distribute mobile recycling systems in ports.
  - Test and implement biodegradable plastics alternatives.

6.4. Waste Management and Resource Valorisation

6.4.1. Spain

- **Current Situation:** Focus on transforming waste into resources; growing research on valorization.
- **Key Challenges:** Poor waste characterization, limited nutrient recovery, underdeveloped by-product markets, challenges in circular feed production.
- **Opportunities / Best Practices**: Established waste frameworks, industry commitment to zero-waste, industrial symbiosis potential.
- **Recommendations / Actionable Steps:**
  - Implement comprehensive waste characterization and segregation programs.
  - Develop nutrient recovery technologies.

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- Promote by-product markets (animal feed, cosmetics, fertilizers).
- Invest in circular feed R&D.
- Disseminate best practices across the sector.

6.4.2. Portugal

- **Current Situation:** Selective waste collection, focus on plastic reduction, efficient feed use.
- **Key Challenges:** Regulatory complexity, lack of investment, limited by-product value chains, low technical awareness.
- **Opportunities / Best Practices**: Circular economy models, partnerships with research centers, incorporation of waste into the blue bioeconomy.
- **Recommendations / Actionable Steps:**
  - Train operators in sustainable practices.
  - Replace fossil-based materials with bio-based alternatives.
  - Develop innovative waste treatment and valorization partnerships.

6.4.3. Italy

- **Current Situation:** Mussel shells and polypropylene socks largely discarded; lack of infrastructure.
- **Key Challenges:** Complex cleaning for reuse, insufficient regulatory support.
- **Opportunities / Best Practices:** Reuse of shells in construction/agriculture/cosmetics, recycling technologies for socks.
- **Recommendations / Actionable Steps:**
  - Finance recycling infrastructure.
  - Promote shell valorization in processing centers.
  - Enable conversion of aquaculture waste into value-added products.

6.5. Training, Skills Development and Education

6.5.1. Spain

- **Current Situation:** Commitment to workforce skill development; strong educational institutions.
- **Key Challenges:** Limited integration of circular economy in curricula, digital skills gap, lack of specialized programs.
- **Opportunities / Best Practices:** Professional development frameworks, industry commitment, international collaboration.

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- **Recommendations / Actionable Steps:**
  - Integrate circular economy in curricula and professional courses.
  - Develop specialized training programs (RAS, IMTA, waste valorization).
  - Provide digital skills training and outreach campaigns.
  - Foster international collaboration for knowledge exchange.

6.5.2. Portugal

- **Current Situation:** E-learning platforms (BlueAquaEdu), postgraduate courses in Blue Economy, technical courses, workshops.
- **Key Challenges:** Unequal access to training, shortage of experienced trainers, alignment gaps.
- **Opportunities / Best Practices:** Technical capacity building, collaborative innovation, applied knowledge integration.
- **Recommendations / Actionable Steps:**
  - Raise awareness on continuous training importance.
  - Promote online/blended learning for remote professionals.
  - Offer scholarships and financial support.
  - Train instructors with practical experience.

6.5.3. Italy

- **Current Situation:** Aging workforce, limited new talent, lack of tailor-made education.
- **Key Challenges:** Low awareness and training in circular practices, insufficient education on waste management.
- **Opportunities / Best Practices:** EU training projects, LIFE MUSCLES technical workshops.
- **Recommendations / Actionable Steps:**
  - Integrate circularity modules into vocational training.
  - Expand training on new materials and waste reuse.
  - Encourage collaboration between breeders, universities, and research centers.

6.6. Industry-Academia Collaboration

6.6.1. Spain

- **Current Situation:** Strong collaboration networks, established research institutions, growing partnership opportunities.

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- **Key Challenges:** Limited joint projects, weak technology transfer, gap between academic priorities and industry needs.
- **Opportunities / Best Practices:** Academic research capabilities, industry willingness, government support.
- **Recommendations / Actionable Steps:**
    - Encourage and fund collaborative research addressing circular challenges.
    - Establish technology transfer platforms (incubators, hubs).
    - Develop internships and apprenticeship programs.
    - Involve industry in setting research agendas.
    - Organize networking events and workshops.

6.6.2. Portugal

- **Current Situation:** Portugal has a growing ecosystem of collaborative laboratories (CoLABs) and universities engaged in blue economy research. Integrated master's programs, technical courses, and consortia already include industry participation, but the link between scientific agendas and real market needs remains weak.
- **Key Challenges:**
    - Mismatch between academic research and the operational needs of aquaculture companies.
    - Difficulty in co-creating solutions due to overly theoretical approaches.
    - Barriers to accessing innovation funding for SMEs.
    - Lack of clear systems to measure the impact of collaborations.
- **Opportunities / Best Practices:**
    - Collaborative labs such as **S2Aqua, GreenColab, and +ATLANTIC** fostering applied research.
    - Initiatives like **World Café "Aquaculture for the Future We Want"** promoting multi-stakeholder dialogue.
    - Technical-scientific events (Aquaculture Days, Aquaculture Horizons) integrating academia and producers.
    - Strong culture of EU-funded cooperative projects (e.g., IMTA and RAS pilots).
- **Recommendations / Actionable Steps:**
    - **Co-Creation Platforms:** Establish multisectoral platforms for academia, industry, public administration, and civil society.
    - **Applied Training Programs:** Strengthen workshops, internships, and joint courses with practical application.

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- **Impact Measurement:** Develop systems to track collaboration outcomes on circularity and innovation.
- **Funding Mechanisms:** Promote co-promoted projects and simplify access to collaborative grants.
- **Sector Integration:** Align scientific agendas with the concrete needs of aquaculture producers.

6.6.3. Italy

- **Current Situation:** In Italy, collaboration between academia and the aquaculture sector remains limited. Most innovations in circular aquaculture, particularly in shellfish farming, stay at the pilot or research stage, with weak mechanisms for transferring results to small and medium enterprises (SMEs). While projects such as LIFE MUSCLES have demonstrated innovative solutions, large-scale implementation is still lacking.
- **Key Challenges:**
  - Disconnection between research outputs and the practical needs of aquaculture producers.
  - Limited access to collaborative innovation funding for SMEs.
  - Uneven adoption of applied innovations across regions.
  - Absence of structured platforms for dialogue and cooperation between universities and industry.
- **Opportunities / Best Practices:**
  - Pilot initiatives like **LIFE MUSCLES** show concrete applications of recycling technologies and biodegradable alternatives.
  - Strong academic research capacity in marine sciences and aquaculture.
  - Growing recognition of the need for circular economy integration in aquaculture.
  - Potential for regional **living laboratories** and coastal cooperation projects to connect farmers, recyclers, and researchers.
- **Recommendations / Actionable Steps:**
  - Applied Innovation: Ensure academic research is translated into practical, economically sustainable technologies.
  - Pilot Project Scaling: Support replication and scaling of successful pilots (e.g., mobile recycling machinery, biodegradable materials).
  - Living Labs: Create regional hubs linking universities, waste processors, and farmers to co-develop circular innovations.
  - Funding Collaboration: Establish dedicated funds for joint academia-industry projects in circular aquaculture.

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- Capacity Building: Promote internships, training programs, and collaborative workshops to strengthen industry skills and technology uptake.

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7. Timeline and Phased Implementation Plan

7.1. Short-term actions (0–2 years)

7.1.1. Spain

In the short term, Spain should focus on removing regulatory barriers and creating the foundations for circular aquaculture. A comprehensive review of aquaculture regulations is needed to harmonize procedures, particularly in waste management and by-product valorization. Awareness campaigns targeting producers, policymakers, and consumers will help create a shared understanding of circular principles. Initial training programs on circularity and resource efficiency should be developed. Pilot projects for the valorization of specific waste streams (e.g., sludge and uneaten feed) will serve as proof-of-concept, while robust data collection systems should be established to monitor progress. Stakeholder dialogue platforms will be key to fostering trust and joint commitment.

7.1.2. Portugal

Portugal's initial focus should be on strengthening the link between industry and academia while promoting professional capacity building. Priority actions include encouraging applications to co-promoted R&D projects, raising awareness of continuous training needs, and aligning curricula with emerging sustainability goals. Online and blended training programs will allow professionals in rural and peripheral areas to access knowledge, while scholarships will ensure participation from small operators, youth, and reskilling workers. Pilot initiatives in waste valorization and reuse should be launched to build experience and credibility.

7.1.3. Italy

Italy's short-term priorities are centered on bureaucratic simplification and early pilots for circular practices. Key measures include the approval of implementing decrees for existing legislation, reducing licensing delays (e.g., for mussel farms), and launching training programs on waste compliance and circular aquaculture. Pilot projects for the reuse of polypropylene socks and mobile recycling—such as those tested under the LIFE MUSCLES initiative—should be expanded. Support for Integrated Multi-Trophic Aquaculture (IMTA) prototypes will also lay the groundwork for integrated, resource-efficient farming systems.

7.2. Medium-term actions (2–5 years)

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Project N. 2024-1-ES01-KA220-VET-000249427

7.2.1. Spain

In the medium term, Spain should scale circular solutions through targeted financial support. National and regional schemes such as grants, subsidies, and green loans should be fully implemented to support the adoption of advanced technologies like RAS and IMTA. Integrated circular value chains should be developed through industrial symbiosis, connecting aquaculture with other sectors. Training programs must evolve towards specialization in circular system management, digital tools, and waste valorization. Spain should also prioritize the commercialization of R&D outputs by supporting lab-to-market transitions, strengthening intellectual property frameworks, and facilitating business development.

7.2.2. Portugal

Portugal should advance towards the systemic implementation of circular production systems. Digitalization and automation will enable smarter water use and resource monitoring. Dedicated programs for the collection, sorting, and recycling of plastics and nets will reduce environmental impacts. By-products should be transformed into fertilizers, bioplastics, or animal feed, creating new value chains. Fossil-based resources must be gradually replaced with bio-based raw materials. Partnerships between research centers and industry should drive the development of innovative treatment solutions. Investments in training for instructors with practical experience will ensure that the next generation of professionals is adequately prepared.

7.2.3. Italy

Medium-term actions in Italy must focus on scaling up and removing structural barriers. Mobile recycling should be extended to major mussel ports, accompanied by the modernization of aquaculture equipment with eco-friendly alternatives. Waste collection hubs should be created at the municipal or port level, ensuring efficiency in managing by-products. A crucial reform will be the reclassification of polypropylene socks, which should no longer be considered “special waste,” reducing logistical and financial burdens on farmers. These changes will make circular practices more attractive and feasible across regions.

7.3. Long-term actions (5+ years)

7.3.1. Spain

By the long term, Spain should aim for the full integration of circularity across the aquaculture value chain. This includes establishing closed-loop systems with minimal reliance on external inputs and positioning Spain as a global leader in sustainable aquaculture. Climate resilience and neutrality should be achieved through emission reductions and carbon sequestration measures. Aquaculture must go beyond reducing impacts to actively enhancing biodiversity and ecosystem health. Consumer trust and demand should be

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driven by transparent labeling and traceability systems, fostering market transformation towards sustainable consumption patterns.

7.3.2. Portugal

Portugal's long-term goal is to consolidate a fully circular and climate-neutral aquaculture sector. This entails the widespread adoption of IMTA and RAS systems, reducing environmental impacts and ensuring sustainability. By-products such as sludge and shells should be reused in diverse applications (e.g., fertilizers, biogas, cosmetics, and construction). Renewable energy investments will support decarbonization, while multisectoral platforms—linking academia, industry, policymakers, and civil society—will guide continuous innovation. Digitization and advanced environmental monitoring will ensure resilience and long-term competitiveness.

7.3.3. Italy

In Italy, the long-term vision is to achieve full national integration of circular aquaculture, particularly in shellfish farming. Mussel shells should be reused at scale in multiple industries, including construction, agriculture, and cosmetics. Eco-sustainability certifications must be implemented to enhance product traceability and competitiveness, while exporting eco-certified shellfish and recycled aquaculture products will open new markets. By this stage, Italy should consolidate its leadership in sustainable shellfish aquaculture, ensuring that circular practices are both mainstreamed and internationally recognized.

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Project N. 2024-1-ES01-KA220-VET-000249427

8. Expected Impact and Monitoring Indicators

8.1. Environmental, social and economic outcomes

8.1.1. Spain

- **Environmental outcomes:** Reduced ecological footprint through lower water and energy use, improved water quality with advanced recirculation and filtration, conservation of biodiversity via responsible farming, mitigation of climate change through renewable energy, and maximized resource efficiency with minimized waste.
- **Social outcomes:** Stronger public perception of aquaculture as sustainable, enhanced local engagement and rural development, creation of a highly skilled workforce, increased food security through stable supply, and knowledge-sharing platforms for collaboration across stakeholders.
- **Economic outcomes:** Greater competitiveness and resilience via reduced dependency on external resources, new business opportunities from by-product valorization, significant operational cost savings, job creation in circular aquaculture technologies, and improved market access for sustainable products.

8.1.2. Portugal

- **Environmental outcomes:** Reduction in freshwater and fossil energy consumption through RAS and IMTA, lower carbon footprint and waste discharge by valorizing by-products, improved environmental quality and ecosystem biodiversity, and higher ecological sustainability through practices that sequester carbon.
- **Social outcomes:** Capacity building and technical training fostering inclusion and employability, stronger collaboration between communities, academia, and authorities, improved social acceptance of aquaculture through transparency and certification, and creation of continuous training and innovation opportunities in the blue economy.
- **Economic outcomes:** Higher production efficiency and reduced costs, development of value chains from by-products, attraction of funding and private investment into blue innovation, and promotion of certified sustainable products with joint branding for differentiated markets.

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8.1.3. Italy

- **Environmental outcomes:** Reduced seabed and coastal impact, improved water quality through filtration, and decreased plastic and marine litter via dedicated collection and recovery systems.
- **Social outcomes:** Job creation in waste reuse and valorization, higher attractiveness of green aquaculture for young professionals, and stronger resilience of coastal communities.
- **Economic outcomes:** Development of new markets for by-product reuse (shells, plastics), reduced disposal costs for farmers, and increased potential for eco-certified aquaculture products.

8.2. Proposed KPIs for progress tracking

8.2.1. Spain

- **Environmental KPIs:**
  - Water use efficiency (litres/kg, % reduction by 2030)
  - Energy consumption (kWh/kg, % reduction, % renewable by 2030)
  - Carbon footprint (kg CO_2e/kg, % reduction by 2030)
  - Waste valorization rate (% valorized by 2030)
  - Nutrient discharge (g/kg, % reduction by 2030)
  - Antibiotic use (g/ton, % reduction by 2030)
- **Economic KPIs:**
  - Revenue from by-products (% of total by 2030)
  - Investment in circular technologies (€ by 2030)
  - Operational cost reduction (% by 2030)
  - Export value of sustainable products (€ by 2030)
- **Social KPIs:**
  - Employment in circular aquaculture (new jobs created by 2030)
  - Training participation rate (% of workforce trained by 2030)
  - Public awareness index (annual increase by 2030)
  - Stakeholder collaboration index (annual increase by 2030)

8.2.2. Portugal

- **Environmental KPIs:**

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Project N. 2024-1-ES01-KA220-VET-000249427

- Reduction of water consumption per kg of aquaculture biomass produced (litres/kg)
- CO_2 equivalent emissions per kg of product (kg CO_2e/kg, annual reduction rate)
- Percentage of waste and by-products valorized (% recycled/reused/converted)

- **Social KPIs:**
  - Number of workers trained annually in circular economy practices
  - Number of joint training programs and inclusive innovation initiatives
- **Economic KPIs:**
  - Number of SMEs and start-ups integrated into circular aquaculture projects
  - Value of certified sustainable aquaculture products (€ added market value)
  - Investment attracted into circularity and blue innovation (€ per year)

8.2.3. Italy

- **Environmental KPIs:**
  - % of shellfish farmers adopting circular practices
  - Volume of recycled aquaculture waste (e.g., polypropylene, shells, tonnes/year)
  - Number of ports equipped with mobile recycling machines
- **Social KPIs:**
  - Number of new mobile cleaning/shredding machines deployed
  - Number of certified eco-labelled mollusc products introduced into the market
- **Economic KPIs:**
  - % reduction in waste disposal costs for farmers
  - Increase in revenue from reused shells and plastics (€ per year)
  - Market share of eco-certified aquaculture products (% growth annually)

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9. Conclusions and Way Forward

9.1. Summary of key proposals

To ensure the successful transition towards a circular aquaculture model in Southern Europe, several cross-cutting recommendations should be prioritized:

1. Adopt harmonized regulatory frameworks across the three countries.

Licensing, environmental monitoring, and waste valorization policies must be aligned with EU directives to remove existing barriers and promote coherence. Shared standards for the reclassification and recycling of by-products should be established, ensuring consistency and facilitating cross-border collaboration.

2. Create enabling financial ecosystems.

Stable funding lines for circular aquaculture should be embedded in both EU and national programs, with clear long-term commitments. Risk-sharing mechanisms are needed to support SMEs adopting innovative technologies, while the promotion of green finance instruments and eco-certification schemes can help increase the market value of sustainable products.

3. Scale circular technologies and infrastructure.

Circular technologies such as Recirculating Aquaculture Systems (RAS), Integrated Multi-Trophic Aquaculture (IMTA), nutrient recovery systems, and digital monitoring tools must become mainstream practices. This transition requires investment in supporting infrastructure for plastic and shell recycling, nutrient valorization, and wastewater treatment facilities.

4. Strengthen skills and workforce development.

Circular economy modules should be integrated into vocational and higher education across Southern Europe. Training initiatives must be inclusive, ensuring access for SMEs, rural workers, and younger professionals. At the same time, international knowledge exchange should be promoted to enable continuous upskilling and the dissemination of best practices.

5. Foster innovation through academia–industry partnerships.

New platforms such as living labs and co-creation spaces should be institutionalized to bring together academia, industry, and policymakers in the joint development of solutions. EU-supported joint projects should be expanded, ensuring that outcomes are applied, scalable, and aligned with sectoral needs. Companies should be actively engaged in setting research priorities in collaboration with universities and research institutions.

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6. Mainstream circularity into market transformation.

Eco-labeling and certification of sustainable aquaculture products should be broadened to increase market differentiation. Public communication campaigns and transparent information systems are essential to strengthen consumer awareness and trust. Finally, Spain, Portugal, and Italy should position themselves as European leaders in circular aquaculture, exporting eco-certified products and sharing best practices globally.

9.2. Recommendations for mainstreaming and policy uptake

9.2.1. Spain

- **Policy and regulation:** Simplify and harmonize regulatory frameworks across autonomous communities, embedding circular economy principles into licensing, monitoring, and compliance processes.
- **Economic and financial**: Establish dedicated funding streams and tailored incentives to accelerate adoption of circular technologies (RAS, IMTA), promote by-product valorization, and facilitate SMEs' transition.
- **Technology and innovation:** Scale up digitalization, IoT-based monitoring, and closed-loop systems; prioritize pilot projects focused on nutrient recovery and high-value transformation of by-products.
- **Waste and valorization:** Implement systematic segregation and nutrient recovery programs; develop new markets for aquaculture by-products, including applications in feeds, cosmetics, and fertilizers.
- **Skills and training:** Incorporate circular aquaculture modules into vocational and technical curricula, reinforce digital and technical skills development, and strengthen public awareness through targeted campaigns.
- **Industry–academia collaboration:** Expand joint R&D programs, establish innovation hubs, and align research agendas with practical industry needs.

9.2.2. Portugal

- **Policy and regulation:** Promote co-created circular policies involving academia, industry, and civil society; streamline licensing frameworks to reduce bureaucratic barriers.
- **Economic and financial:** Facilitate access to MAR2030, PRR, and EMFAF funding, ensuring simplified procedures and stability of financial support for circular aquaculture initiatives.

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- **Technology and innovation:** Advance the adoption of RAS, IMTA, and algae-based innovations; strengthen digitalization and automation; promote valorization projects focused on bioplastics, biofertilizers, and animal feed.
- **Waste and valorization:** Encourage business models integrating aquaculture waste into the wider blue bioeconomy; expand recycling systems and modernize wastewater treatment infrastructure.
- **Skills and training:** Broaden blended training platforms such as BlueAquaEdu and postgraduate programs; align curricula with evolving industry needs; ensure equal access for workers in rural and coastal areas.
- **Industry–academia collaboration:** Foster consortia, living labs, and co-creation platforms; enhance knowledge transfer and ensure research results are applied and impactful.

9.2.3. Italy

- **Policy and regulation:** Simplify licensing and harmonize fragmented governance; reclassify polypropylene socks as recyclable by-products and create enabling frameworks for regional waste reuse.
- **Economic and financial:** Expand SMEs' access to EU funding mechanisms; incentivize adoption of recycling technologies; support new value chains for shell reuse in construction, cosmetics, and agriculture.
- **Technology and innovation:** Scale up circular solutions piloted by projects such as LIFE MUSCLES (mobile recycling units, biodegradable ropes); invest in eco-design for aquaculture equipment.
- **Waste and valorization**: Develop infrastructure for collection, sorting, and treatment of mussel by-products; finance regional recycling hubs; enable localized reuse and valorization initiatives.
- **Skills and training:** Design tailored training programs in aquaculture, emphasizing waste valorization, green technologies, and circular practices; implement strategies to attract new talent into the sector.
- **Industry–academia collaboration:** Establish regional living labs, support joint innovation projects, and ensure that academic outputs are applied, scalable, and economically viable.

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