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BLUE ECONOMY
TETRAS

Policy Recommendations and Future of RAS in the Baltic Sea Region with the Impact Circle

Keywords

Primary Keywords: Impact Cycle, strategic clarity, and actionable policy pathways for Recirculating Aquaculture Systems (RAS) in the Baltic Sea Region

Secondary Keywords: systems, energy cooperation, and community-linked food systems

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Abstract

Recirculating Aquaculture Systems (RAS) offer a high-potential technological pathway toward sustainable fish production in the Baltic Sea Region (BSR), where environmental pressures, resource constraints, and food system vulnerabilities demand innovative solutions. This scientific report applies the Impact Circle Method, a systemic innovation framework, to evaluate the multidimensional implications of RAS adoption. The analysis integrates environmental, social, economic, technological, institutional, and cross-sectoral dimensions to identify leverage points, policy gaps, and opportunities for accelerating sustainable aquaculture transitions. Findings demonstrate that RAS can become a cornerstone technology for nutrient circularity, regional food resilience, and climate-neutral aquaculture—provided that coherent policy support, cross-industry cooperation, and long-term investment structures are established. A multi-level policy roadmap (2025–2050) is proposed to guide EU, national, regional, and local authorities in integrating RAS into broader sustainability and circular economy strategies.

1. Introduction

1.1 Purpose and scope

Over the past two decades, RAS has transitioned from a niche experimental technology to a maturing production system capable of supporting commercial-scale operations. Early forms of RAS suffered from inconsistent water quality control, insufficient filtration capacity, and high operational instability (Badiola et al., 2018). Advances in mechanical filtration, biological denitrification, oxygenation technologies, and system automation have changed this landscape dramatically.

Modern RAS facilities can recirculate up to 99% of their water, reducing water consumption to a fraction of that required by traditional flow-through systems (Martins et al., 2010). Improved biofilters—particularly moving-bed bioreactors and optimized nitrification units—allow for stable ammonia and nitrite management, ensuring consistent fish health. The integration of digital monitoring systems, including real-time sensors, automated feeding algorithms, and AI-based diagnostics, has significantly increased predictive control and reduced human error.

These technological developments are particularly important for the Baltic Sea Region, where climatic conditions limit outdoor and coastal aquaculture during large parts of the year. RAS provides producers with year-round control over temperature, oxygen, and lighting, enabling stable and predictable production cycles even in northern climates (Davidson et al., 2016). As a result, production of species such as salmon, trout, char, and pike-perch has become increasingly feasible at an industrial scale.

This report provides policy recommendations and a forward-looking assessment of the future viability of recirculating aquaculture systems (RAS) in the Baltic Sea Region (BSR). It is addressed to decision-makers at EU, national, regional and local levels, including those responsible for fisheries and aquaculture, environment, regional development, energy, innovation and rural policy. The report focuses on how RAS can contribute to a sustainable, competitive and resilient aquaculture sector in the BSR while helping to protect the sensitive marine environment of the Baltic Sea and advancing broader European Green Deal objectives.

Recirculating aquaculture systems (RAS) have rapidly evolved into one of the most promising technological platforms for sustainable aquaculture, particularly in ecologically sensitive marine basins such as the Baltic Sea. Recent meta-analyses confirm that RAS can reduce water use by more than 95% and retain up to 99% of nitrogen and phosphorus when coupled with advanced sludge capture technologies (Ende et al., 2024; Preena et al., 2021). These characteristics provide a unique opportunity to decouple fish production from direct impacts on fragile coastal ecosystems already affected by eutrophication, hypoxia and legacy nutrient loads (HELCOM, 2024; Rizzo & Jolliet, 2024).

Recent advancements – such as improved nitrification through microaerophilic reactors (Yogev & Gross, 2019), biochar-enhanced filtration (Behjat et al., 2025), hybrid UV-ozone oxidation (Xue et al., 2023), and digital monitoring with neural networks (Yang et al., 2023) – have significantly improved system stability, fish welfare and environmental performance.

However, RAS are not inherently low impact. Studies demonstrate that energy demand remains the dominant contributor to greenhouse gas emissions, especially in regions with carbon-intensive electricity grids (Badiola et al., 2018; Bergman et al., 2020). Moreover, RAS require substantial capital investment, highly trained personnel and sophisticated risk management.

To address these systemic tensions, this report incorporates the Impact Circle Method, a design-based framework for generating sustainable business ideas and identifying cross-sectoral innovation opportunities (Karahan & Stoeckermann, 2023). This method enables multi-dimensional analysis of RAS across environmental, economic, social, technological, institutional, and cross-sectoral domains.

Recirculating aquaculture systems are land-based, highly controlled production systems that continuously treat and reuse water within a loop. Compared with traditional flow-through or cage-based aquaculture, RAS can drastically reduce water use, improve control over effluents and biosecurity, and allow production close to consumers and value chains. Their deployment in the Baltic Sea Region is still modest compared with the potential, but recent technical advances and policy initiatives have created momentum for expansion.

The report provides science-based, policy-relevant recommendations targeted at:

- EU institutions (DG MARE, DG ENV, DG ENER, CINEA)
- National ministries for aquaculture, environment, energy and economic affairs
- Regional and municipal authorities responsible for spatial planning and infrastructure
- RAS operators, investors, technology developers, feed producers
- Research institutions, NGOs and civil society

The geographic scope includes Denmark, Finland, Sweden, Germany, Poland, Estonia, Latvia, and Lithuania, with stronger empirical grounding for Denmark, Finland, Sweden and Germany, which have the highest RAS penetration.

1.2 Methodology and evidence base

The report is based on a narrative synthesis of peer-reviewed literature, technical reports and policy documents on RAS and sustainable aquaculture. Particular attention is paid to recent reviews of RAS technology and sustainability, regional analyses of the RAS sector in the Baltic Sea Region, and EU and HELCOM policy frameworks that set the boundary conditions for aquaculture development. These include, among others, the European Commission's Strategic Guidelines for a more sustainable and competitive EU aquaculture for 2021–2030, HELCOM recommendations and BAT/BEP descriptions for sustainable aquaculture in the Baltic Sea region, and national studies on the status and economics of RAS in countries such as Denmark, Finland, Sweden and Germany.

In addition, the report draws on international best practices from leading RAS countries (for example Norway, Denmark, the Netherlands, the United States, Israel and Singapore), focusing on lessons that can be transferred to the Baltic Sea context. While the evidence base is substantial and growing rapidly, it is also recognised that RAS is a relatively young, innovation-driven sector, and that policy must be adaptive and learning-oriented.

Finally, the The Impact Circle methodology assesses the systemic effects of RAS adoption across interconnected domains:

- Environment: nutrient recycling, biodiversity protection, water use, emissions

- Economy: competitiveness, operational efficiency, innovation potential
- Policy and Governance: regulatory clarity, permitting, funding instruments
- Technology: energy efficiency, digital monitoring, circular integration
- Society: employment, community engagement, consumer acceptance

The report repeatedly emphasizes multi-dimensional leverage points where interventions create ripple effects across the system.

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- Technology: energy efficiency, digital monitoring, circular integration
- Society: employment, community engagement, consumer acceptance
- Cross-sector: links to energy, agriculture, circular economy, wastewater management

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The Impact Circle is well suited for RAS because it highlights systemic contradictions such as:

- RAS reduces nutrient discharge, but increases energy demand.
- RAS improves biosecurity, but requires higher operational expertise.
- RAS creates rural jobs, but often relies on urban-proximate industrial symbioses.

The method enables identification of bisociative innovation opportunities—solutions that emerge by linking contradictory domains, such as pairing RAS heat demand with data centre heat supply.

2. Aquaculture and RAS in the Baltic Sea Region

2.1 State of aquaculture and RAS deployment

Aquaculture in the Baltic Sea Region remains underdeveloped compared with its potential contribution to food security, rural development and the blue bioeconomy. EU-level analyses note that aquaculture accounts for roughly one quarter of seafood consumption in Europe, and the EU remains highly dependent on imports. Expanding sustainable aquaculture, including in the Baltic Sea Region, is therefore a strategic priority for the EU.

Within this context, RAS represents a promising pathway because it can decouple production from the most sensitive coastal and marine habitats. Recent assessments by research institutes in the region show that RAS activities are concentrated in a few countries, particularly Denmark, Finland, Sweden and Germany, with varying scales and degrees of commercial maturity. Denmark has pioneered freshwater RAS for trout and smolt, with well-documented improvements in nutrient discharge per unit of production. Finland, Sweden and Germany have a mix of small and medium-sized RAS operations, often linked to innovation projects, niche species or integrated value chains.

Despite these advances, the overall volume of RAS production in the Baltic Sea Region remains modest. Barriers include high upfront capital costs, energy intensity, limited access to risk capital, complex permitting procedures and regulatory uncertainty, as well as limited experience in operating RAS at commercial scale. At the same time, successful demonstration facilities and positive learning curves indicate that well-designed RAS businesses can be technically and economically viable when supported by appropriate policies and market conditions.

2.2 Environmental status of the Baltic Sea

The Baltic Sea is one of the most heavily impacted semi-enclosed seas in the world, with well-documented problems of eutrophication, hypoxia, hazardous substances and biodiversity loss. The sea's limited water exchange and stratified water column make it particularly sensitive to nutrient inputs from land and sea-based activities. Regional action under the Helsinki Convention and the Baltic Sea Action Plan has focused on reducing nutrient loads and improving ecosystem status, with measurable progress but significant challenges remaining.

In this context, any expansion of aquaculture must be designed with a strong precautionary and ecosystem-based approach. Conventional marine cage aquaculture can contribute to local nutrient enrichment and seabed impacts if not properly sited and managed. RAS offers a way to reduce direct emissions to the Baltic Sea by concentrating effluents on land where they can be treated, recovered and reused, for example in agriculture or biogas production. However, RAS is not impact-free: its environmental footprint depends on energy sources, feed, sludge management and the overall circularity of the system. Policymakers therefore need nuanced guidance, not simple assumptions that RAS is automatically "green".

2.3 Regulatory and policy landscape

RAS in the Baltic Sea Region is governed by a multi-layered policy framework. At EU level, key instruments include the Common Fisheries Policy, the Strategic Guidelines for sustainable and competitive EU aquaculture 2021–2030, the European Green Deal and its Farm to Fork and Biodiversity strategies, the Marine Strategy Framework Directive, the Water Framework Directive, the Habitats and Birds Directives, and the Maritime Spatial Planning Directive. Together, these instruments call for an expansion of low-impact aquaculture, better integration with environmental objectives, and the use of EU and national funds to support innovation and investment. The European Green Deal provides the overarching policy direction toward a climate-neutral Europe by 2050. RAS contributes directly by:

- Reducing land and water footprints compared to conventional aquaculture.
- Enabling integration with renewable energy systems.
- Facilitating circular nutrient management and waste valorisation.

Yet RAS is not explicitly recognised within Green Deal implementation packages, limiting its visibility in climate-transition investment agendas.

As the central component of the Green Deal's food dimension, the Farm-to-Fork Strategy promotes sustainable, resilient food production.

RAS supports these goals through:

- Controlled production environments reducing disease risks and veterinary inputs.
- Opportunities for local, year-round production that shorten supply chains.
- Improved traceability and food safety.

Nevertheless, Farm-to-Fork provides no dedicated aquaculture sustainability metric, resulting in limited policy guidance on how RAS should be rewarded for its environmental performance.

The Climate Law legally binds the EU to reach net-zero greenhouse gas emissions by 2050.

RAS can help national sectors reach their climate budgets via:

- Integration with low-carbon electricity and heat.
- Potential synergies with industrial symbiosis (e.g., waste-heat recovery).
- Reduced emissions associated with feed transport and distribution when localized RAS clusters are developed.

However, RAS operators currently encounter limited access to climate finance mechanisms, partly due to the absence of harmonised emission baselines and performance standards for the sector.

The WFD governs the protection and sustainable use of Europe's water bodies. RAS aligns with its principles by dramatically reducing water abstraction and discharge.

Yet national permitting authorities often interpret the WFD using conventional aquaculture benchmarks, creating:

- Overly stringent discharge requirements even when RAS effluent volumes are minimal.
- Uncertainty about classification of RAS sludge as a by-product vs. waste.

Even though RAS is land-based, the MSFD affects national aquaculture planning by requiring member states to consider good environmental status in marine regions.

This can result in:

- Additional assessments even for operations with negligible marine interactions.
- Duplicated approval steps across water, environmental, and marine agencies.

For Baltic Sea countries, the HELCOM Recommendations on Best Available Techniques (BAT) and Best Environmental Practices (BEP) set guiding principles for aquaculture permits. RAS generally meets or exceeds BAT/BEP criteria.

However:

- Operationalisation varies widely among member states.
- Lack of clear BAT values for RAS-specific parameters (e.g., recirculation efficiency, nutrient recovery) introduces uncertainty into the permitting process.

MFAF national strategic plans increasingly recognise RAS as a high-innovation, low-impact production system. Funding supports:

- Pilot facilities
- Digital monitoring technologies
- Energy optimisation

But disparities remain:

- Not all countries prioritise RAS
- Lack of harmonised eligibility criteria limits cross-border investment and industry scaling.

At regional level, HELCOM has adopted recommendation 42-43/10 on sustainable aquaculture in the Baltic Sea Region, together with detailed descriptions of Best Available Technology (BAT) and Best Environmental Practice (BEP) for marine and freshwater aquaculture. These documents provide practical guidance on how to minimise nutrient discharges, manage fish health, prevent escapes and use resources efficiently. They recognise the potential of RAS as a means to reduce nutrient emissions to the Baltic Sea, while also emphasising the need for robust environmental performance standards and monitoring.

At national level, Baltic Sea countries are developing or updating aquaculture strategies and multiannual national strategic plans under the European Maritime, Fisheries and Aquaculture Fund. However, there are differences in how clearly RAS is integrated into these strategies, how predictable and coordinated permitting systems are, and how effectively economic incentives and support schemes are aligned with environmental and innovation objectives.

Recirculating Aquaculture Systems (RAS) are increasingly recognised as a strategic technology for achieving Europe's environmental, food-security, and climate commitments. By enabling high-density fish production with minimal water use, strong biosecurity, and reduced nutrient discharge, RAS aligns closely with the EU vision for a climate-neutral, resource-efficient, and resilient food system.

However, RAS development occurs within a fragmented policy environment, marked by overlapping EU directives, diverse national interpretations, and high administrative complexity. Understanding – and streamlining – this policy landscape is essential for accelerating innovation and investment in sustainable aquaculture.

2.4 Barries for RAS Deployment

Recirculating Aquaculture Systems (RAS) represent one of the most promising technological pathways for sustainable aquaculture in Europe. Their ability to drastically reduce water consumption, minimise environmental discharge, and enable year-round fish production positions them as a strategic tool in meeting the EU's food security and Blue Economy objectives. Yet the deployment of RAS across EU member states continues to lag behind technological potential. The following analysis explores the persistent regulatory and administrative barriers that slow down RAS development. It examines these obstacles through a narrative, analytical lens to provide a deeper understanding of how fragmented governance structures, outdated classifications, and administrative complexity act as systemic constraints.

One of the most significant impediments to RAS deployment is the extended timeframe required to navigate permitting processes. While traditional aquaculture ventures often rely on well-established regulatory pathways, RAS installations tend to fall into regulatory grey zones because of their technological novelty and hybrid nature. In many jurisdictions, the full suite of regulatory clearances—environmental approvals, water-use permits, construction permissions, waste-management licenses, and sometimes even marine or coastal approvals—is applied cumulatively. This layering of responsibilities across agencies frequently leads to overlapping requirements rather than a streamlined evaluation.

These prolonged permitting periods, which commonly range from two to five years, introduce substantial uncertainty for investors. For an industry characterised by high upfront capital costs, delays of this magnitude can jeopardise project feasibility. Moreover, the lack of harmonised interpretations of EU directives means that two RAS facilities of similar size and design may face drastically different approval requirements depending on the member state in which they are located. Such inconsistency is often compounded by a limited familiarity among regulatory staff with RAS-specific technologies, including biofilters, recirculation loops, and integrated waste-recovery systems. As a result, permitting bodies may adopt overly cautious, risk-averse approaches, demanding additional studies or monitoring obligations that further extend project timelines.

A second major barrier is the absence of EU-wide harmonised standards governing RAS operations. Because RAS differ substantially from open-net or pond-based aquaculture systems, many existing regulatory frameworks fail to reflect their unique characteristics. In practice, this means that nutrient discharge thresholds, water quality metrics, and biosecurity requirements are interpreted differently across member states. Some countries impose discharge limits designed for conventional aquaculture, which do not account for the high-efficiency filtration and water reuse inherent in RAS. Others apply industrial wastewater standards, which may not be appropriate for nutrient-rich aquaculture effluents.

This regulatory fragmentation creates uncertainty for developers and restricts the ability of firms to scale operations across borders. Without consistent expectations, companies must redesign compliance strategies for each jurisdiction, increasing both cost and administrative workload. Moreover, the lack of common standards hinders knowledge transfer among regulators, researchers, and industry practitioners. Best-practice models—whether in monitoring protocols, biosecurity measures, or system design—remain siloed within national contexts rather than contributing to an integrated EU knowledge base.

RAS facilities generate nutrient-rich sludge as a by-product of fish metabolism and feed residues. This material holds substantial potential as a resource for fertiliser production, anaerobic digestion, and soil enhancement. However, in many EU countries, sludge from aquaculture is still categorised as waste rather than as a recoverable input to circular-economy processes. This classification triggers a series of costly obligations: specialised disposal procedures, transport restrictions, and in some cases, mandatory treatment processes that do not align with the sludge's potential environmental benefits.

This outdated classification represents a missed opportunity. Across other sectors—such as agriculture, municipal wastewater treatment, and food processing—the EU has begun recognising nutrient-rich by-products as valuable secondary raw materials when they meet defined quality criteria. RAS-generated sludge fits squarely within this paradigm. Its high nutrient density makes it a promising feedstock for fertiliser production, while its organic composition supports biogas generation and soil regeneration initiatives.

RAS projects frequently require engagement with multiple authorities, each assessing a different aspect of system design and operation. Water authorities evaluate abstraction and discharge; environmental agencies assess ecological impacts; planning and construction offices evaluate site suitability; and waste-management and energy regulators weigh in on sludge handling and energy demand. While each of these assessments serves a legitimate public interest, the absence of coordinated processes results in unnecessary administrative complexity.

For small and medium enterprises (SMEs)—which constitute a large portion of Europe's aquaculture sector—this fragmented administrative landscape can act as a prohibitive barrier. Each agency may require its own set of studies, monitoring plans, or technical reports, leading to duplication of effort and escalating costs. In some cases, one agency's approval may be contingent upon another's, creating sequential bottlenecks that significantly delay project timelines.

This extended analysis highlights how slow permitting processes, fragmented standards, outdated sludge classifications, and multi-agency administrative burdens form a complex web of challenges that hinder the expansion of RAS technology in Europe. Addressing these structural barriers will be key to unlocking the full potential of RAS as a driver of sustainable aquaculture, technological innovation, and circular-economy growth across the EU.

3. Future viability of RAS in the Baltic Sea Region

3.1 Technical and economic performance

The Baltic Sea Region (BSR) stands at a critical crossroads in shaping the future of sustainable aquaculture. As environmental pressures intensify—driven by eutrophication, biodiversity decline, climate change, and demographic shifts—the region must identify production systems capable of supplying high-quality seafood while alleviating ecological stress. Recirculating Aquaculture Systems (RAS) have gained increasing prominence as a potential solution, offering the ability to produce fish in controlled, land-based environments with minimal water use and reduced nutrient emissions (FAO, 2022).

Yet the long-term viability of RAS cannot be taken for granted. While technological advancements have significantly improved system reliability, RAS remains economically demanding, energy-intensive, and socially complex. Its success depends on a multidimensional balance: technological performance, economic competitiveness, environmental sustainability, climate resilience, societal acceptance, and integration into regional development strategies.

This chapter provides a detailed, narrative analysis of these factors. It expands earlier overviews into a full conceptual and policy-oriented examination, drawing from international research, cross-sectoral comparisons, and region-specific considerations. The goal is to offer a comprehensive understanding of whether—and under what conditions—RAS can become a cornerstone of sustainable aquaculture in the Baltic Sea Region.

The future trajectory of Recirculating Aquaculture Systems (RAS) in the Baltic Sea Region is emerging as one of the defining questions for sustainable aquaculture in northern

Europe. Across the region, policymakers, researchers, and industry leaders are confronting a dual challenge: on one hand, the Baltic Sea is under unprecedented ecological stress from eutrophication, pollution, and climate change; on the other, growing demand for locally produced, sustainable seafood is reshaping expectations of how food should be produced. RAS has entered this landscape as a highly promising, yet still demanding, technology. It offers a route toward environmentally controlled, biosecure, and spatially flexible fish production, but its long-term viability depends on navigating a complex mixture of technological feasibility, economic stability, environmental responsibility, and societal acceptance. The following analysis explores these dimensions in depth.

During the last decade, RAS technology has experienced an impressive period of maturation. What began as a relatively experimental approach to land-based aquaculture has evolved into a sophisticated, digitally enabled production system capable of achieving levels of environmental control unimaginable in earlier aquaculture models. At the heart of this transformation lies the refinement of water treatment technologies. Modern biofilters, more efficient solids removal systems, and advanced hydrodynamic engineering have enabled operators to maintain extraordinarily stable water quality. The ability to reuse up to 90–99 percent of water, while keeping key parameters such as ammonia, nitrite, and oxygen within narrow biological thresholds, provides producers with a degree of predictability that is especially valuable in the climatically variable Baltic Sea Region.

This stability translates into biological and commercial advantages. Year-round production becomes feasible even in the northernmost parts of the region, where traditional aquaculture faces long periods of low temperatures or ice cover. High stocking densities, coupled with controlled feed regimes and optimised water quality, allow for efficient growth rates and multiple harvest cycles within a single year. For species such as salmon, trout, or even emerging RAS species like pike-perch, this reliability is an essential part of building competitive supply chains and meeting local consumer demand.

Over the past two decades, RAS has transitioned from a niche experimental technology to a maturing production system capable of supporting commercial-scale operations. Early forms of RAS suffered from inconsistent water quality control, insufficient filtration capacity, and high operational instability (Badiola et al., 2018). Advances in mechanical filtration, biological denitrification, oxygenation technologies, and system automation have changed this landscape dramatically.

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These technological developments are particularly important for the Baltic Sea Region, where climatic conditions limit outdoor and coastal aquaculture during large parts of the year. RAS provides producers with year-round control over temperature, oxygen, and lighting, enabling stable and predictable production cycles even in northern climates (Davidson et al., 2016). As a result, production of species such as salmon, trout, char, and pike-perch has become increasingly feasible at an industrial scale.

However, technological capability alone does not secure economic success. The economic performance of RAS in the Baltic Sea Region is shaped by a delicate interplay of scale, cost of capital, energy prices, management expertise, and market positioning. RAS facilities require significant upfront investment due to their technological complexity and infrastructure requirements. This high capital expenditure, combined with often substantial energy demand for pumps, oxygenation, temperature control, and filtration, can lead to tight profit margins, especially in the early years of operation.

Economic viability therefore becomes highly context-dependent. Facilities with access to low-cost renewable energy—or those able to integrate industrial waste heat or district heating—are demonstrably better positioned to succeed. Similarly, operators targeting niche, premium, or sustainability-conscious markets often gain a commercial advantage by differentiating their products on quality, freshness, or low environmental impact. The Baltic Sea Region has seen rising consumer interest in these attributes, which can help offset the higher cost base associated with RAS.

Still, the most crucial determinant of economic performance may be managerial competence. RAS are unforgiving systems. A single failure in water circulation, oxygen supply, or biofilter function can lead to rapid fish mortality. Skilled staff, sophisticated monitoring technologies, and robust contingency plans are essential. This operational sensitivity raises the threshold for new entrants and makes risk-sharing mechanisms, investment incentives, and technological training critical components of the policy environment.

In this light, the future economic viability of RAS in the Baltic Sea Region cannot be viewed in isolation from broader policy frameworks. Access to renewable energy, targeted investment support, and research funding for technological optimisation all play decisive roles. In many respects, RAS development has become closely aligned with the region's wider green transition: if the political ambition to promote low-carbon industry continues, RAS stands to benefit substantially.

Recent international reviews conclude that RAS technology has progressed substantially in terms of water treatment, biofiltration, system design, digital monitoring and automation. Modern RAS can achieve very low water exchange rates, high stocking densities, and stable water quality, enabling year-round production close to markets with high biosecurity. Multiple studies document the potential for up to 90–99 % water reuse and substantial reductions in nutrient emissions per unit of production compared with flow-through systems, provided that effluent treatment and sludge management are properly designed.

Economic performance is more variable and depends on scale, species, market positioning, access to low-cost energy and capital, and managerial competence. Analyses in the Baltic Sea Region indicate that RAS operations can be profitable but often face tight margins, especially in the early years of operation. High capital expenditure, energy costs and the need for specialised staff can be offset by higher product prices (for example for local, high-quality, certified or organic products), shorter supply chains, reduced mortality, and multiple production cycles per year. The viability of RAS is therefore highly sensitive to policy-driven factors such as energy prices, access to green power, investment support and risk-sharing mechanisms.

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The economic viability of RAS in the Baltic Sea Region is strongly shaped by national and EU policy frameworks. Investment grants, innovation funding, favourable permitting regimes, and support for renewable energy significantly influence financial feasibility. The EU's aquaculture strategies and national multi-annual plans in Finland, Denmark and other BSR states increasingly emphasise RAS as a tool for reducing environmental pressure while enabling growth.

In practice, this means that RAS viability is tightly linked to the broader green transition. Where governments actively support decarbonisation, circular economy integration and innovation in aquaculture technologies, RAS benefits directly. Where policy environments remain fragmented or energy systems fossil-dependent, RAS may struggle to compete with traditional imports or sea-based production.

From a biological perspective, the strength of RAS lies in its capacity to provide a stable, optimised environment for fish growth. Temperature can be held at levels that maximise growth rates, oxygen levels can be kept high and constant, and the risk of external disease exposure is minimised. Studies consistently find that well-managed RAS can achieve high survival rates and competitive feed conversion ratios compared with traditional systems (Colt, 2011; Davidson et al., 2016).

However, high levels of control come with high levels of vulnerability. System failures—power outages, pump breakdowns, loss of oxygenation—can have rapid and catastrophic consequences because fish in RAS rely entirely on engineered life support. This requires redundancy in critical components, backup power systems and highly skilled technical staff able to diagnose and resolve issues quickly (Timmons & Ebeling, 2021). Case studies from Denmark, where several RAS facilities have experienced serious disruptions or fires, underscore that technical sophistication does not eliminate risk; it shifts it into new domains that require rigorous risk management.

Economically, RAS remains a capital-intensive and energy-intensive production model. Large grow-out facilities for Atlantic salmon—of the size currently being built or planned in Sweden and Denmark—require investments in the tens to hundreds of millions of euros (Jones, Campbell, & Little, 2021; Vielma et al., 2022). Smaller warm-water facilities (e.g. pike-perch, perch, sturgeon) can operate at lower absolute cost but still face high capital intensity relative to traditional pond or cage farming.

Operating expenditures are dominated by energy, feed, labour and maintenance. Energy use is particularly critical in the BSR, where electricity prices can be volatile. As a result, RAS profitability is highly sensitive to local energy markets and to the ability of operators to integrate renewable energy, industrial waste heat or district heating systems. In Finland's strategic plans for aquaculture, for example, improving the energy economy and reducing the carbon footprint of RAS farms is explicitly identified as a key policy objective.

Despite these challenges, RAS can be economically competitive when positioned in premium market segments. Consumers in Denmark, Sweden and Germany show increasing preference for locally produced, traceable and environmentally responsible seafood (European Commission, 2022). In Denmark, the company Danish Salmon—operating in an industrial area near the port of Hirtshals—has demonstrated that a land-based salmon RAS can achieve commercial profitability, reporting harvests of about 1,100 tonnes in 2023 and 2,000 tonnes in 2024 with positive gross profits, and targeting 2,700 tonnes in 2025. This case illustrates that with the right combination of technology, management and market positioning, RAS can move beyond proof-of-concept into sustained economic performance.

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3.2 Environmental performance and climate resilience

The Baltic Sea is one of the most sensitive marine ecosystems in the world, and its vulnerability has shaped regional aquaculture policy for decades. Against this backdrop, RAS has emerged as an attractive alternative to sea-based systems because of its potential to drastically reduce nutrient emissions, disease risks, and interactions with wild species. The closed-loop nature of RAS allows operators to prevent most nutrients from entering the marine environment. Instead, solid and dissolved waste can be captured, concentrated, and transformed into valuable by-products such as fertiliser or biogas. This possibility aligns precisely with the region's growing interest in circular bioeconomy strategies, where resource recovery is viewed not merely as environmental mitigation, but as an economic opportunity.

The environmental case for RAS in the BSR is grounded in the region's acute nutrient challenges. The Baltic Sea is one of the most eutrophic marine areas in the world, with persistent "dead zones" driven by nitrogen and phosphorus inputs from agriculture, wastewater and, to a lesser extent, aquaculture (HELCOM, 2021). Against this background, further expansion of open-water aquaculture is politically and ecologically sensitive.

RAS fundamentally changes the nutrient pathway. Instead of releasing large portions of dissolved and particulate waste into coastal waters, RAS retains most nutrients within the system. Solids can be separated and concentrated into sludge, which can then be processed into fertiliser, compost or used as a substrate for biogas production (Mirzoyan, Tal, & Gross, 2010). In Denmark and parts of Germany, emerging pilots are exploring integration of RAS sludge into regional bioenergy and agriculture value chains, illustrating how RAS can contribute to circular bioeconomy strategies.

By reducing nutrient discharges into the Baltic Sea, RAS can enable aquaculture growth without increasing pressure on already stressed marine ecosystems. This aligns closely with HELCOM's work on best available techniques (BAT) for aquaculture and with EU policy priorities around nutrient recycling and water quality.

The environmental advantages of RAS extend beyond nutrient control. Diseases and parasites, which have caused significant challenges in sea-based aquaculture, are much easier to manage in controlled environments. The risk of fish escapes, a serious concern for native biodiversity in the Baltic Sea, is also virtually eliminated. As a result, RAS provides an environmentally secure production model that avoids many of the ecological conflicts inherent to coastal aquaculture.

Beyond nutrient control, RAS effectively mitigates several ecological risks associated with sea-based cages: disease transmission, parasite infestations and fish escapes. By isolating farmed fish from wild populations, RAS reduces opportunities for pathogen exchange and external parasite exposure, including sea lice—a major challenge in marine salmon farming, though less relevant in the low-salinity Baltic Sea. Physical containment virtually eliminates escape events, protecting the genetic integrity of wild fish stocks (Torrissen et al., 2013).

This containment function is particularly important in countries like Sweden and Finland, where public concern over genetic impacts of escaped farmed fish has historically limited enthusiasm for large-scale marine salmon farming. Land-based RAS offers a way to expand salmonid production while avoiding these ecological conflicts.

Yet the environmental case for RAS is not without complications. High energy demand stands out as the most persistent challenge. Maintaining life-support systems—pumps, filters, temperature controls, oxygenation devices—requires continuous electricity. If that electricity is derived from fossil fuels, the indirect greenhouse gas emissions can undermine the environmental benefits achieved through reduced nutrient discharge and improved containment. This dilemma creates a paradox at the heart of RAS sustainability: the better RAS becomes at protecting local ecosystems, the more its climate footprint matters.

The most controversial environmental aspect of RAS is energy use. Pumping, oxygenation, water treatment and temperature control require continuous power. Life-cycle assessments show that, depending on the electricity mix, RAS can have equal or higher greenhouse gas emissions per kilogram of fish compared with some traditional cage systems (Aubin et al., 2009; Henriksson et al., 2018). In other words, RAS can trade local environmental impacts for global climate impacts if not coupled with low-carbon energy.

This trade-off is particularly visible in the BSR, where electricity mixes vary significantly between countries. In Sweden and Lithuania, where the share of renewables and low-carbon energy is relatively high, the climate footprint of RAS is considerably lower than it would be in regions with fossil-heavy power systems. In Denmark, companies such as Premium Svensk Lax (whose large RAS is located in Säffle, Sweden, but built by Nordic suppliers) explicitly aim for minimal climate impact as part of their design and funding rationale.

RAS therefore pushes environmental policy into a systems perspective: sustainable aquaculture cannot be evaluated solely at the farm level but must be considered in relation to national energy policy, feed sourcing and waste valorisation.

This tension highlights the importance of energy policy in shaping the environmental performance of RAS. In countries such as Sweden, Finland, or Lithuania, where the electricity grid is increasingly dominated by low-carbon sources, RAS is far more capable of delivering genuinely sustainable production. In regions where fossil-based power still plays a significant role, operators must take additional measures—such as on-site solar generation, heat recovery systems, or biogas integration—to reduce their climate impact.

A further environmental consideration relates to feed. Across nearly all aquaculture systems, feed production accounts for the largest share of life-cycle environmental impacts. This remains true for RAS, despite its innovations in water treatment. Thus, improving feed conversion ratios and developing more sustainable feed ingredients remain essential goals for reducing the total environmental footprint of the sector.

Nevertheless, when assessed through the lens of climate resilience, RAS provides an exceptionally robust model for future aquaculture in the Baltic Sea Region. The controlled indoor environment shields production from a growing array of climate-related risks. Marine heatwaves, harmful algal blooms, storms, and extreme weather events—which are projected to intensify in frequency and severity—pose major threats to sea-based farms. RAS, by contrast, offers stability, predictability, and insulation from many of these environmental stressors. As climate change accelerates, this resilience may become one of the strongest arguments for investing in RAS as a foundational pillar of regional food security.

From an environmental perspective, RAS offers several advantages that are particularly relevant for the Baltic Sea Region. These include reduced nutrient discharge into coastal and marine waters, the possibility of capturing and valorising fish sludge, better control of escapes and disease, and lower dependency on sensitive coastal sites. When combined with renewable energy and circular use of by-products (for example using waste heat from industry, biogas from sludge, or integration with horticulture), RAS can make a strong contribution to a low-carbon circular bioeconomy.

However, the environmental footprint of RAS is not negligible. Reviews highlight that RAS is energy-intensive compared with extensive or semi-intensive systems, and life-cycle assessments indicate that greenhouse gas emissions can be higher than for some traditional systems if electricity is generated from fossil fuels. Feed remains the dominant contributor to overall environmental impacts across most aquaculture systems, including RAS, underscoring the need for sustainable feed ingredients and improved feed conversion. Policymakers in the Baltic Sea Region must therefore ensure that support for RAS is coupled with decarbonisation policies, renewable energy deployment and circular resource use.

In terms of climate resilience, RAS has clear advantages. Because production takes place in controlled indoor facilities, RAS is less exposed to marine heatwaves, harmful algal blooms, storms and other climate-related stressors that are expected to intensify in the Baltic Sea. RAS can therefore serve as a risk diversification strategy for the region's aquaculture sector, helping to maintain production under changing climate conditions.

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RAS therefore pushes environmental policy into a systems perspective: sustainable aquaculture cannot be evaluated solely at the farm level but must be considered in relation to national energy policy, feed sourcing and waste valorisation.

When viewed through the lens of climate resilience, RAS offers an important strategic advantage for the Baltic Sea Region. Climate projections for the region include increasing sea surface temperatures, more frequent marine heatwaves, changes in salinity and oxygen dynamics, and a heightened risk of harmful algal blooms (IPCC, 2022; HELCOM, 2021). These changes threaten sea-based aquaculture operations, which remain directly exposed to fluctuating environmental conditions.

RAS decouples production from many of these external stressors. By controlling temperature, oxygen and water quality indoors, RAS can maintain stable production even when coastal waters become temporarily unsuitable due to algal blooms, hypoxia or extreme storms. For countries like Finland and Sweden, where coastal aquaculture sites are limited and increasingly contested, RAS thus represents not only an environmental solution but also a climate adaptation strategy that can secure domestic fish supply under changing climatic conditions.

3.3 Social licence, spatial planning and rural development

No assessment of RAS viability would be complete without considering the social dimension. Social licence—the informal societal permission for a project or industry to operate—is increasingly recognised as a critical factor shaping the future of aquaculture in the Baltic Sea Region. While RAS alleviates many of the environmental concerns associated with sea-based systems, it introduces a new set of social considerations.

Social licence—the informal societal approval required for industrial activities to operate—is an increasingly central concept in aquaculture governance (Mather & Fanning, 2019). In the Baltic Sea Region, public scepticism about aquaculture has often centred on visible impacts in coastal waters: aesthetic changes, perceived pollution, and competition with recreation or conservation objectives.

RAS changes the nature of the social debate. By removing cages from the sea, RAS reduces visibility in the marine environment; yet on land, large industrial-looking facilities may be perceived as intrusive by nearby communities. Concerns may shift from "what happens in the fjord or bay" to "what happens in the industrial park or rural landscape." Residents may question odour, noise, traffic, water abstraction and discharge, or more generally the idea of intensive animal production in their vicinity.

The Danish example of Danish Salmon, located in an industrial area near the ferry port in Hirtshals, illustrates how careful site selection and integration into existing industrial zones can help minimise land-use conflicts and visual impact. In Sweden, planned large RAS projects in Säffle, Sotenäs and Åre have prompted public debate not only about environmental performance but also about the scale and character of these new facilities.

The relocation of fish production from coastal waters to land-based facilities alters the geography of aquaculture. Instead of being located in remote fjords or along sparsely populated coastlines, RAS facilities often occupy industrial zones, agricultural land, or peri-urban spaces. This proximity to communities can create both opportunities and tensions. On one hand, RAS can relieve ecological pressure on sensitive coastal habitats, reduce visual impacts on landscapes, and avoid competition with recreational or conservation uses of marine space. On the other hand, large and technologically complex facilities may generate local concerns related to odour, traffic, noise, or water extraction. In communities unfamiliar with aquaculture technologies, the presence of an industrial-looking facility housing thousands of fish can provoke uncertainty or scepticism.

The experiences of leading RAS nations demonstrate that social acceptance is not automatic; it must be earned. Early, transparent, and continuous engagement with local residents, environmental NGOs, and municipal authorities is essential. Communities tend to respond positively when project developers articulate clear environmental safeguards, highlight local economic benefits, and demonstrate openness to collaboration. RAS facilities that integrate with local value chains—such as providing fresh fish to local restaurants, using waste heat from nearby industries, or supplying nutrient resources to local farms—often generate stronger community support and build positive identities within the region.

Importantly, RAS offers significant opportunities for rural revitalisation. Many areas of the Baltic Sea Region face population decline, limited employment prospects, and a shortage of skilled jobs. RAS can help address these challenges by creating technical, scientific, and operational employment opportunities. Beyond direct jobs, the presence of RAS facilities can stimulate the development of supporting industries, attract research partnerships, and foster innovation clusters centred on aquaculture technology and circular resource use.

In this way, RAS can contribute to a broader rural development agenda by diversifying local economies, attracting young professionals, and supporting regional food self-sufficiency. However, these benefits depend on careful spatial planning, supportive local governance, and strong community relationships. Without these elements, even technically advanced and environmentally responsible RAS projects may struggle to secure long-term acceptance.

Because RAS can be located inland, spatial planning becomes an important governance tool. Municipal and regional authorities must decide where RAS facilities fit in relation to residential areas, industry, agriculture and infrastructure. At the same time, land-based location enables novel forms of cross-sectoral integration. RAS facilities can be co-located with industries that generate waste heat, such as paper mills or power plants, or they can be integrated into bioenergy systems and horticulture, where nutrient-rich water and CO_2 become inputs.

RAS has notable potential to support rural development in the BSR. Many rural regions in Finland, Sweden, Poland and the Baltic states face depopulation, ageing populations and limited access to high-skilled employment. RAS facilities can create jobs in aquaculture biology, engineering, operations, IT and logistics. When linked with local universities, vocational institutes and research organisations, they can anchor innovation ecosystems around aquaculture technology and circular resource use.

In Finland, for example, Natural Resources Institute Finland (Luke) has documented how RAS companies such as Finnforel, Savo Lax and others have developed in close connection with regional industrial sites (e.g. pulp and paper mills) and have stimulated local employment and technological learning. Similar patterns are emerging in Denmark, where RAS technology suppliers and engineering companies have grown around the longstanding eel and trout farming sectors and are now exporting expertise internationally.

These developments suggest that RAS can be more than isolated production units; they can become nodes in broader regional innovation and value-creation networks, especially when supported by targeted policy instruments and cluster initiatives.

Public acceptance and social licence to operate are crucial for aquaculture expansion in the Baltic Sea Region. RAS can help by reducing visible impacts in coastal waters and allowing production in industrial or rural areas away from sensitive habitats. At the same time, large industrial-looking facilities may raise concerns about odour, traffic or visual impact at the local level, and communities may be sceptical of novel technologies.

Experiences from leading RAS countries show that early and transparent engagement with local communities, municipalities, environmental NGOs and other stakeholders is essential. Clear communication about environmental performance, job creation, integration with local value chains and opportunities for co-benefits (such as using waste heat from local industry or supplying local restaurants and schools) can build trust. RAS can also support rural development by creating skilled jobs in regions facing depopulation, especially when combined with training programmes and innovation clusters.

4. Policy recommendations at EU level

4.1 Anchor RAS in EU aquaculture and Green Deal strategies

Securing social licence for RAS in the BSR will require deliberate strategies of engagement and co-creation. Experience from both RAS and traditional aquaculture sectors indicates that early, transparent dialogue with municipalities, environmental NGOs and local communities is crucial (Stévant, Rebours, & Chapman, 2017). Providing accessible information about environmental performance, monitoring results, and contingency plans can build trust. Involving local actors in planning processes, and demonstrating concrete local benefits—such as jobs, cooperation with local schools and restaurants, and integration with local energy or agriculture projects—can further strengthen acceptance.

Importantly, social licence is dynamic rather than static. It must be maintained over time through consistent performance, responsiveness to concerns and visible accountability. For RAS in the Baltic Sea Region, this implies that companies cannot rely solely on technological superiority; they must also demonstrate social responsibility and community embeddedness.

At EU level, RAS should be explicitly recognised as a strategic technology for sustainable aquaculture under the European Green Deal, Farm to Fork Strategy and the Strategic Guidelines for EU aquaculture. This does not mean privileging RAS over other low-impact systems in all contexts, but rather acknowledging its particular suitability for sensitive marine basins such as the Baltic Sea.

The European Commission, in cooperation with Member States and stakeholders, should:

- Highlight RAS and land-based, low-emission systems as priority areas in guidance on implementing the strategic aquaculture guidelines and in future updates of the guidelines.

- Encourage integration of RAS-specific objectives and measures into Multiannual National Strategic Plans for aquaculture under the European Maritime, Fisheries and Aquaculture Fund and successor instruments.

- Promote RAS as part of the EU's blue bioeconomy and circular economy agendas, including in the context of the Net-Zero Industry framework and industrial policy discussions where relevant.

The future viability of RAS in the Baltic Sea Region is best understood not as a simple yes-or-no proposition, but as a conditional scenario. RAS offers clear advantages in nutrient control, climate resilience, biosecurity and spatial flexibility. It aligns well with EU and national objectives for Blue Growth, the circular economy and reduced pressure on vulnerable marine ecosystems.

However, its success will depend on several key conditions:

- Decarbonised energy systems, to ensure that RAS does not reduce local impacts at the cost of increased greenhouse gas emissions;
- Supportive regulatory and financial frameworks, including streamlined but robust permitting, innovation funding and risk-sharing instruments;
- Integration into regional resource networks, where RAS is combined with industry, energy and agriculture to maximise circularity and economic viability;
- Strong social licence, built on transparency, engagement and demonstrable local benefits;
- Continuous technological and managerial learning, particularly in relation to operational reliability and animal welfare.

Denmark's role as a pioneer, Finland's strategic repositioning, Sweden's large-scale RAS ambitions, and the emerging interest in Germany, Poland and the Baltic states together suggest that the BSR has the ingredients to become a leading region for RAS innovation and deployment. Whether it does so will depend on how effectively these ingredients are combined in the coming decade.

4.2 Use EU funding instruments to de-risk investment and support innovation

High capital intensity and technological risk are key barriers for RAS investors. EU-level funding instruments can play an important role in de-risking investment, supporting innovation and crowding in private finance. Recommended actions include:

- Prioritising RAS pilot and demonstration projects, especially those linked to renewable energy, sector coupling (for example with district heating, data centres or biogas plants), and circular use of nutrients, under the European Maritime, Fisheries and Aquaculture Fund, Horizon Europe and Interreg Baltic Sea Region.

- Facilitating blended finance models that combine grants, guarantees, loans and equity from EU-level financial institutions and national development banks to support commercially oriented RAS projects.

- Supporting innovation in RAS components (biofilters, sensors, control systems, sludge treatment, energy efficiency) through targeted calls in research and innovation programmes, with a focus on open standards and interoperability.

4.3 Develop harmonised guidance on environmental performance standards

To avoid regulatory fragmentation and provide clarity for investors, the EU should work with Member States and regional bodies to develop harmonised guidance on environmental performance standards for RAS. This guidance should:

- Build on HELCOM BAT/BEP descriptions, national best practices and existing environmental permitting frameworks.

- Address key parameters such as nutrient discharge limits, sludge handling and valorisation, energy efficiency benchmarks, fish welfare indicators, and monitoring and reporting requirements.

- Encourage life-cycle assessment approaches that consider both water quality impacts and climate/energy dimensions, promoting integrated performance metrics rather than narrow single-issue indicators.

While respecting subsidiarity and national competence for permitting, such guidance can help ensure a level playing field, facilitate cross-border investment in the Baltic Sea Region, and raise overall environmental ambition.

5. Policy recommendations at national level

5.1 Establish clear national RAS strategies and roadmaps

Baltic Sea countries should develop or update national aquaculture strategies to include explicit RAS roadmaps. These should:

- Identify priority species and market segments for RAS (for example smolt and post-smolt production, high-value niche species, local freshwater species, or integrated multi-trophic systems).

- Provide indicative targets for sustainable RAS capacity and production, aligned with nutrient reduction commitments, climate goals and regional development strategies.

- Outline planned improvements to permitting, support schemes and infrastructure, giving investors a predictable framework.

National roadmaps should be developed through participatory processes involving industry, research, environmental authorities, local governments and civil society, to ensure broad ownership and social legitimacy.

5.2 Simplify and streamline permitting while maintaining high environmental standards

Complex, fragmented and slow permitting processes are widely cited as a major barrier for aquaculture investment in Europe. Countries in the Baltic Sea Region should:

- Establish one-stop-shop or coordinated permitting procedures for RAS, where applicants interact with a lead authority that coordinates inputs from environment, water, land-use, veterinary and other competent authorities.

- Introduce clear, predictable timelines and transparent criteria for decision-making, reducing uncertainty and transaction costs while maintaining high environmental standards.

- Develop standardised permit templates and guidance for typical RAS configurations, drawing on BAT/BEP documents, which can reduce administrative burden both for operators and authorities.

- Encourage digitalisation of permitting and monitoring processes, including online application portals, geographic information system tools and electronic reporting.

5.3 Align economic incentives with environmental and innovation objectives

National financial and fiscal policies can significantly influence the viability of RAS projects. Recommended measures include:

- Providing targeted investment grants or tax incentives for RAS facilities that meet high environmental performance criteria, for example through eco-schemes or green investment programmes.

- Supporting access to long-term, low-interest loans or guarantees for RAS operators, particularly for first-of-a-kind projects and small and medium-sized enterprises.

- Designing energy policies that reward energy-efficient RAS and the use of renewable energy, for example through reduced grid fees, support for on-site solar or wind, or preferential access to waste heat.

- Encouraging the valorisation of RAS by-products (sludge, CO2, waste heat) through innovation grants, regulatory clarity on by-product status, and inclusion of RAS in circular economy and biofertiliser strategies.

5.4 Invest in skills, training and knowledge transfer

Operating modern RAS requires skilled staff in system engineering, water quality management, fish health, data analysis and business management. To support a competitive RAS sector, national authorities should:

- Integrate RAS and sustainable aquaculture into vocational education and training programmes, including apprenticeships and continuous professional development.

- Support specialised university courses and research groups focusing on RAS engineering, life-cycle assessment, fish welfare and circular resource use.

- Facilitate knowledge transfer and extension services, for example through national RAS competence centres, demonstration farms, advisory services and farmer-to-farmer networks.

- Encourage cross-border knowledge exchange within the Baltic Sea Region and with leading RAS countries elsewhere.

6. Policy recommendations at regional and local level

6.1 Integrate RAS into spatial planning and regional development strategies

Regional and local authorities in the Baltic Sea Region play a key role in land-use planning, industrial policy and infrastructure development. To foster RAS, they should:

- Proactively identify suitable areas for RAS facilities in spatial and land-use plans, considering access to water resources, electricity and heat, proximity to markets and infrastructure, and minimal conflict with other land uses.

- Integrate RAS and related value chains (feed, processing, logistics, horticulture using waste heat and CO2) into regional development and smart specialisation strategies.

- Encourage clustering and industrial symbiosis by locating RAS facilities near renewable energy plants, water-intensive industries, data centres or greenhouses, where waste heat and resources can be exchanged.

6.2 Develop enabling infrastructure and utilities

RAS facilities depend on reliable infrastructure for water, energy, transport and digital connectivity. Regional and local authorities can:

- Ensure that industrial zones suitable for RAS are equipped with adequate grid capacity, potential connections to district heating or cooling networks, and robust water supply and wastewater treatment capabilities.

- Facilitate access to fibre-optic networks and digital infrastructure to enable advanced monitoring, automation and remote operation of RAS.

- Explore public–private partnerships for shared services such as sludge treatment plants, biogas facilities or logistics hubs that can serve multiple RAS operators and reduce costs.

6.3 Strengthen community engagement and social licence

Local authorities are often the first point of contact for communities when new RAS projects are proposed. To build social licence and avoid conflict, they should:

- Facilitate early stakeholder engagement processes where project developers present plans, environmental assessments and expected benefits, and where community concerns can be addressed.

- Encourage transparent communication about monitoring results and environmental performance, for example through publicly accessible dashboards or annual environmental reports.

- Support initiatives that increase local co-benefits, such as supplying local markets, schools and hospitals with fresh fish, creating local jobs, and collaborating with local educational institutions on internships and research projects.

7. Cross-cutting future actions and roadmap

7.1 Short-term actions (2025–2030)

In the short term, the priority is to create enabling conditions for sustainable RAS growth in the Baltic Sea Region while demonstrating environmental and economic performance. Key actions include:

- Finalising and implementing HELCOM BAT/BEP guidance and ensuring that national permitting frameworks incorporate these criteria in a pragmatic and predictable way.

- Developing national RAS roadmaps and integrating RAS into EU-funded national strategic plans for aquaculture.

- Launching a portfolio of pilot and demonstration RAS projects across the region, including those that showcase integration with renewable energy, district heating, biogas or greenhouse horticulture.

- Establishing or strengthening national and regional RAS competence centres, networks and knowledge platforms.

- Improving data collection on RAS performance (production, economics, environmental indicators, fish welfare) to build an evidence base for further policy development.

7.2 Medium-term actions (2030–2040)

Over the medium term, the aim should be to scale up successful RAS models, deepen integration into the circular economy and achieve substantial contributions to regional food supply and rural development. Recommended actions include:

- Gradually increasing environmental performance benchmarks for RAS, including energy efficiency and climate performance, in line with decarbonisation pathways and technological progress.

- Expanding RAS capacity in well-suited locations, with a focus on clusters and value chain integration to achieve economies of scale and shared services.

- Mainstreaming the use of alternative and more sustainable feed ingredients, supported by research, certification and market incentives.

- Strengthening cross-border cooperation within the Baltic Sea Region, for example through joint research programmes, harmonised data collection and shared standards, and exploring opportunities for regional branding of "Baltic sustainable RAS products".

- Integrating RAS more systematically into national food security and nutrition strategies, recognising their ability to provide stable supplies of high-quality protein.

7.3 Addressing knowledge gaps and monitoring

Although the knowledge base on RAS has expanded rapidly, there remain important gaps that policymakers and funders should address in a coordinated way. These include:

- Long-term empirical data on the economic performance of commercial-scale RAS in the Baltic Sea Region, including risk factors, business models and reasons for success or failure.

- Comparative life-cycle assessments of RAS and alternative aquaculture systems under Baltic-specific conditions, with harmonised methodologies and transparent assumptions.

- Improved understanding of fish welfare in high-density RAS environments, including behavioural indicators, welfare-oriented system design and welfare-based management practices.

- Innovations in sludge treatment, nutrient recovery and integration of RAS with crop production, biogas or other bio-based sectors, including socio-economic and regulatory aspects.

- Socio-economic research on community perceptions, employment effects, gender dimensions and the role of RAS in just transitions in coastal and rural areas.

Policymakers should support coordinated monitoring frameworks for RAS, including indicators for environmental performance, animal welfare, socio-economic outcomes and innovation. Results should be made publicly available where possible, to support transparency, learning and adaptive governance.

8. Conclusions

Recirculating aquaculture systems represent a promising pathway for expanding sustainable aquaculture in the Baltic Sea Region while protecting the sensitive marine environment and contributing to climate and circular economy goals. Technological advances and emerging best practices worldwide demonstrate that RAS can achieve high levels of water efficiency, biosecurity and environmental control, but also highlight the importance of careful system design, energy decarbonisation and sound business models.

The future viability of RAS in the Baltic Sea Region will depend on coherent and forward-looking policy at EU, national, regional and local levels. Key elements include clear strategic positioning of RAS within aquaculture and green transition policies, streamlined but robust permitting, targeted economic incentives and risk-sharing instruments, investment in skills and innovation, and proactive regional and local planning that integrates RAS into wider value chains and industrial ecosystems.

By implementing the policy recommendations and actions outlined in this report, decision-makers can enable RAS to make a meaningful contribution to food security, rural development and environmental protection in the Baltic Sea Region. At the same time, they can ensure that RAS development is grounded in scientific evidence, adaptive management and social dialogue, making the sector resilient, competitive and trusted by citizens.

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