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TETRAS

EVALUATION OF SUSTAINABILITY & RESILIENCE OF RAS TECHNOLOGIES, SYSTEMS & SUPPLY CHAINS

Table of Contents

Executive Summary

Ensuring stable, sustainable and resilient access to aquatic protein has become strategically significant for Estonia as global food-supply systems face increasing uncertainty. Domestic aquaculture production remains modest, concentrated in a small number of freshwater species, and heavily constrained by climatic conditions, limited water bodies suitable for traditional flow-through or cage systems, and the ecological sensitivity of the Baltic Sea. At the same time, national consumption of high-value fresh fish, particularly salmonids, continues to rise, creating a persistent dependence on imports transported through vulnerable cold-chain logistics. Recent disruptions in global supply chains, fluctuations in commodity and energy prices, and geopolitical tensions in the Baltic region have intensified the need for technologies capable of delivering stable and environmentally compatible domestic production.

Recirculating Aquaculture Systems (RAS) present one of the few technically viable pathways for establishing a reliable, high-performance aquaculture sector in Estonia. RAS enables inland, land-based production independent of climatic variability and external water bodies. Through continuous water recirculation, advanced filtration, controlled temperature regimes, automated monitoring and closed biological cycles, RAS can achieve high environmental efficiency, low nutrient emissions and significant reductions in freshwater withdrawal compared to conventional aquaculture technologies. These attributes align with Estonia's environmental obligations, circular-economy ambitions and constraints arising from the nutrient-sensitive Baltic Sea basin.

However, RAS is also technologically complex and highly dependent on stable energy supply, specialised equipment, operational expertise and internationally sourced inputs such as feed and juveniles. Evaluating RAS for Estonia therefore requires more than a description of system components; it requires a structured assessment of sustainability and resilience across technological, operational, supply-chain and environmental dimensions. Sustainability concerns the long-term viability of resource use, ecological impact and circular performance. Resilience concerns the ability of RAS infrastructures and supply chains to maintain essential functions under internal failures, external shocks or systemic disruptions.

This report provides a comprehensive evaluation of the sustainability and resilience of RAS technologies, RAS operational systems and RAS-related supply chains in Estonia, with particular attention to the industrial and infrastructural context of Ida-Viru County and the Auvere area. The analysis integrates water, energy, sludge, nutrient, land-use and ecological

assessments with evaluation of technological performance, redundancy, automation dependencies, biosecurity protocols, and the robustness of input chains. The study also examines Estonia's exposure to external suppliers of high-protein aquafeed, fingerlings, oxygenation components, sensors, spare parts and temperature-control systems, and evaluates how these dependencies shape systemic risk.

Findings indicate that RAS can deliver high environmental sustainability when integrated with efficient energy systems and designed to minimise water discharge and nutrient release. Opportunities for industrial symbiosis—such as the reuse of waste heat, process water, carbon dioxide or nutrient-rich sludge—significantly enhance performance, particularly in regions undergoing economic transition such as Ida-Viru. When supported by diversified energy sources, robust backup systems and strong biosecurity management, RAS systems demonstrate the capacity to maintain operational continuity during external stresses.

At the supply-chain level, however, vulnerabilities persist. Estonia remains dependent on imported feed components, imported juveniles, globalised equipment manufacturers and foreign maintenance expertise. These dependencies introduce critical risks that must be mitigated through supplier diversification, local hatchery and feed-processing development, strategic stock-holding and stronger regional cooperation with Baltic and Nordic partners. Energy system stability is similarly pivotal; abrupt fluctuations in electricity prices or grid disturbances pose direct threats to RAS continuity.

Scenario analysis shows that RAS can contribute meaningfully to Estonia's food-systems resilience if certain enabling conditions are met. These include: access to stable and affordable energy; development of local hatchery capacity; improved logistics for domestic distribution; integration of RAS into industrial clusters to optimise thermal and resource synergies; and improvements in permitting, regulatory coordination and long-term investment frameworks. Under these conditions, RAS represents not only a technological solution but an infrastructural asset that enhances national food security, supports circular-economy goals and contributes to structural economic transformation, particularly in former oil-shale regions.

The report concludes that RAS can become a cornerstone of a sustainable and resilient aquaculture sector in Estonia when implemented within a coherent strategy that connects technology, system design, supply-chain fortification and territorial integration. The transition from experimental to stable, scalable RAS capacity requires coordinated investments, technological reliability, supply-chain restructuring and clear governance. With these elements in place, Estonia can reduce its vulnerability to external disruptions, strengthen domestic production of high-value fish, and establish a new generation of environmentally responsible aquaculture infrastructure.

Chapter One

Introduction, Objectives and Methodology

The development of a sustainable and resilient aquaculture sector has become a strategic priority for Estonia as structural shifts in global supply chains, energy markets and regional security dynamics expose the vulnerabilities inherent in small, import-dependent food systems. Domestic reliance on externally sourced high-value fish, combined with the cold climate of the Baltic region and the ecological fragility of coastal waters, restricts the expansion of traditional aquaculture models and intensifies the need for controlled, land-based production technologies. Recirculating Aquaculture Systems (RAS) emerge in this context as an advanced technological solution capable of delivering stable year-round output while maintaining strict control over environmental interactions and resource flows. The potential of RAS to support Estonia's food-security architecture, however, depends not only on technological performance but on the sustainability and resilience of the wider systems and supply chains that enable continuous operation.

The purpose of this report is a comprehensive evaluation of RAS technologies, RAS operational systems and the critical supply chains that support them, using Estonia as the applied context. This evaluation responds to the need for a deeper understanding of how RAS can contribute to sustainable domestic fish production while remaining operationally robust within the energy, climate, and geopolitical conditions of the Baltic region. The analysis recognises that RAS is neither environmentally neutral nor inherently resilient. The high degree of technological control that characterises RAS introduces substantial dependencies on energy, automation, specialised inputs and uninterrupted operational continuity. These dependencies must be evaluated alongside the environmental performance of the system to determine whether RAS can deliver stable, sustainable aquaculture capacity at national scale.

1.1 Context and Analytical Rationale

Estonia's aquaculture landscape is shaped by a set of interacting physical and structural constraints. The Baltic Sea, while supporting marine capture fisheries, is highly sensitive to nutrient loading and exhibits long retention times that intensify eutrophication risk. These conditions limit the feasibility of expanding open-water marine aquaculture installations, particularly for species that require high feed inputs and generate nutrient-rich waste. Freshwater resources suitable for large-scale flow-through aquaculture are limited, and climatic conditions impose long periods of cold temperatures, variable hydrological regimes and substantial icing that reduce the viability of extensive systems. At the same time, domestic demand for high-value fresh fish remains high, and imports have become a structural component of the national fresh-food supply chain.

The emergence of RAS as a land-based alternative aligns with Estonia’s environmental constraints while also offering potential synergies with industrial infrastructure such as waste-heat flows, reclaimed land areas, high-capacity grid nodes and process water systems. Yet the suitability of RAS cannot be determined solely by conceptual or technological appeal. It must be evaluated through a structured, multi-dimensional assessment that considers environmental performance, energy demand, operational reliability, biosecurity, supply-chain dependencies, regulatory integration and location-specific feasibility. The overarching rationale for this report is therefore to provide a decision-relevant evidence base that clarifies the conditions under which RAS can serve as a sustainable and resilient component of Estonia’s future aquaculture sector.

1.2 Objectives of the Evaluation

The evaluation pursues three interlinked objectives that correspond to the main elements of the report’s title.

Objective 1: Evaluate the sustainability of RAS technologies and RAS systems.

This involves assessing water recirculation efficiency, nutrient discharge control, energy intensity, thermal management options, land-use compatibility, sludge and waste-stream management, environmental risk mitigation and opportunities for circular resource integration. Sustainability is evaluated at both the technological level (e.g., filtration performance, treatment efficacy, oxygenation systems) and the system level (e.g., water source and discharge dynamics, energy configuration, integration with industrial symbiosis).

Objective 2: Evaluate the resilience of RAS technologies, systems and supporting supply chains.

Resilience is defined as the capacity of RAS infrastructures to maintain critical functionality under stress conditions. This includes resilience to energy interruptions, climatic extremes, water-supply constraints, equipment malfunction, disease emergence, feed-supply disruptions, logistics instability and geopolitical disturbances. The evaluation addresses both internal system resilience (e.g., redundancy, automation reliability, fail-safe mechanisms) and external resilience (e.g., energy-system stability, supply-chain diversification, secure access to juveniles and feed).

Objective 3: Assess the performance of Estonia's critical fresh-food supply chains and the potential contribution of RAS to supply-chain stability.

This objective requires evaluating the structural weaknesses in current fresh-fish supply chains, including import dependence, perishability, cold-chain vulnerability and logistic exposure. The analysis investigates how domestic RAS production could mitigate these vulnerabilities and how the sustainability and resilience of RAS itself influence national food-system resilience.

Together, these objectives guide the examination of how RAS technologies and systems can be positioned within Estonia's environmental, industrial and energy landscape to provide long-term, reliable aquaculture capacity.

1.3 Analytical Scope

Current technical report focuses on the technical, operational and supply-chain dimensions of RAS that materially influence sustainability and resilience outcomes. The analysis encompasses brooding, juvenile and grow-out stages as relevant to system design; technological elements including water treatment, solids removal, denitrification, oxygenation, heating, cooling and monitoring; external infrastructures including energy supply, water sources, land availability and industrial synergies; and critical input chains including feed, juveniles, equipment, disinfection chemicals, spare parts and specialist maintenance expertise.

The geographical focus is the Estonian national context, with particular attention to Ida-Viru County and the Auvere industrial area, where existing energy and industrial infrastructure provide opportunities for resource integration. Broader Baltic Sea Region dynamics are considered where they influence supply-chain resilience, energy-system stability or regional market access.

The evaluation excludes aspects unrelated to sustainability and resilience performance such as detailed financial modelling, species-specific optimisation protocols, or operational staffing models that lie beyond the scope of a technical sustainability–resilience assessment.

1.4 Methodology and Analytical Approach

The methodology integrates several evaluation frameworks to generate a comprehensive understanding of sustainability and resilience outcomes. Sustainability evaluation uses a systems-based analytical approach that incorporates water and nutrient flow analysis, energy-use characterisation, carbon-intensity indicators, land-use suitability, sludge treatment pathways and alignment with circular-economy opportunities. This includes assessment of water intake and discharge regimes, identification of pollutant streams, evaluation of biosecurity controls and quantification of energy requirements for filtration, oxygenation, pumping, aeration and climate control.

Resilience evaluation applies infrastructural and supply-chain resilience principles to assess the capacity of RAS systems to withstand operational disturbances. The approach includes failure-mode identification, redundancy analysis, dependency mapping, sensitivity analysis to energy and feed disruptions, and evaluation of system response under shock scenarios. Special attention is given to Estonia's energy context, including grid configuration, regional interconnectors, renewable integration and the vulnerability of energy-intensive operations to price volatility.

Supply-chain assessment evaluates the integrity, diversity and vulnerability of RAS-relevant input chains. This includes mapping essential materials and components, examining supplier concentration, transport dependencies, lead-time characteristics, cold-chain requirements and exposure to international commodity and logistics disruptions. Dependencies on imported feed, juveniles and specialised equipment are examined with respect to both availability and resilience.

Scenario analysis is used to test the robustness of RAS systems under varying conditions. Scenarios include energy-price fluctuation, feed-import disruption, juvenile-supply interruption, equipment replacement delay, climatic stress events and changes in environmental regulations. These scenarios are used to determine system thresholds and identify required resilience strategies.

This methodology employs a principle of triangulated evaluation: sustainability, resilience and supply-chain criteria are not assessed independently but analysed in relation to one another. For example, energy-source diversification affects both sustainability (through carbon intensity) and resilience (through redundancy and reliability). Likewise, water-discharge management affects environmental compliance while influencing operational stability. This integrated approach ensures that the evaluation captures the multi-dimensional nature of RAS performance in Estonia.

The subsequent chapters are structured into ten chapters, beginning with an overview of the study's aims, context and methodology, followed by an examination of the regional, environmental and policy landscape shaping RAS development. It then reviews RAS technology and infrastructure, assesses system sustainability and resilience, and maps the full logistics chain from investment to distribution. Subsequent chapters explore future scenarios, risks and mitigation pathways, consider Germany as a reference model for complex cold-chain systems, and analyse how Big Data analytics support dynamic market adaptation in the Norwegian salmon industry. The report concludes with targeted recommendations and a synthesis of key findings.

Chapter Two

Regional, Environmental and Policy Context (Estonia & Ida-Viru / Auvere)

The performance, sustainability and resilience of RAS in Estonia are shaped fundamentally by the environmental conditions, industrial landscape and policy frameworks that define the regions in which such systems may operate. In the context of Estonia, and particularly Ida-Viru County, RAS development intersects with ecological constraints, climatic factors, industrial-resource flows and regulatory structures that either enable or restrict system performance. The national strategy emphasizes increasing the resilience of critical energy infrastructure, taking into account hybrid threats, including identification, prevention, response, and restoration of the situation. Understanding these contextual elements is essential for evaluating the long-term viability of RAS technologies and supply chains in the country. Table 1 summarizes the dual role of geopolitical context in RAS resilience planning.

Table 1: *Geopolitical factors influencing RAS resilience in Ida-Virumaa.*

Factor	Influence on RAS viability	Resilience capacity affected	Strategic implication
Border proximity (Russia)	High security risks; diminished investor attractiveness.	Preparedness, transformation	Mandates reliance on public funding (JTF) and stringent security protocols.
Logistics vulnerability	Loss of key export market (St. Petersburg); risk of transport disruption (rail/road).	Adaptation, absorption	Requires reorientation of supply chains toward Western/BSR markets.
Hybrid threats (sabotage)	Direct risk to energy and digital infrastructure stability.	Absorption	Mandates N+1 redundancy, system hardening, and inclusion in national critical infrastructure protection.
National defenses needs	Restricts renewable energy expansion (e.g., wind farms conflict with radar requirements).	Adaptation, transformation	Limits local green energy options, increasing dependence on symbiotic heat from existing Enefit complex.

2.1 Regional Characteristics of Northern Estonia and Ida-Viru County

Ida-Viru County presents a unique territorial profile compared to the rest of Estonia. The region is characterised by decades of oil-shale mining, thermal power generation and heavy industrial activity, which have created extensive reclaimed landscapes, engineered plateaus, artificial lakes and large contiguous areas of post-industrial land. These areas often consist of compacted soil and modified terrain shaped through excavation, deposition and land recovery processes.

These reclaimed zones possess several physical characteristics relevant to RAS development. The land parcels are typically large and continuous, reducing fragmentation and enabling the design of integrated aquaculture and water-treatment facilities. Surface stability is generally sufficient for heavy-infrastructure foundations, although localised geotechnical assessments are required where subsidence risks remain from earlier mining voids. Unlike agricultural or residential zones, these areas exhibit low land-use conflict and fewer community-impact constraints, supporting the siting of industrial-scale aquaculture infrastructure without competing with food crop production or sensitive landscapes.

Proximity to major transport routes enhances the logistical potential of Ida-Viru County. The Tallinn–Narva transport corridor supports inbound flows of feed, juveniles and equipment, as well as outbound flows of processed fish or live-haul transport. The region is also positioned near the eastern EU border, where geopolitical conditions influence supply-chain planning. These logistics considerations shape RAS resilience by determining the speed, stability and reliability of critical supply flows.

The geographic reality of heavy infrastructure concentration in Ida-Virumaa transforms what might otherwise be poor land for agriculture into a high-potential symbiotic development zone, contingent upon managing external geopolitical and environmental pressures.

2.2 The Auvere Industrial Zone as a Strategic RAS Location

The Auvere energy-industrial area is one of the most relevant RAS-compatible locations in Estonia due to its unique combination of land availability, energy proximity, water resources and existing industrial infrastructure. The area sits within a complex of modern power-generation assets, reclaimed oil-shale extraction zones and associated process-water systems.

A. Land Suitability

The terrain around Auvere consists largely of industrially modified land with minimal agricultural or ecological value. This makes the area suitable for placing large, enclosed RAS facilities that require controlled drainage, soil stability, and protection from environmental contaminants. The lack of residential neighbourhoods helps avoid social conflict issues often associated with agricultural or industrial developments. The ability to construct on reclaimed mining land also aligns with broader circular-economy principles that prioritise reuse of post-industrial areas.

B. Energy Infrastructure

One of Auvere's most strategic assets for RAS is its extensive and resilient energy infrastructure. The presence of high-capacity grid nodes and multiple high-voltage transmission lines reduces the risk of energy bottlenecks, while offering opportunities for RAS facilities to benefit from stable power delivery. The energy-intensive nature of RAS, particularly for temperature regulation, pumping, oxygenation and filtration, makes this proximity essential. Additionally, the thermal output of the energy complex creates a potential symbiosis pathway through which low-grade waste heat can be reused to support fish-growth temperature regimes, thereby improving sustainability and reducing operational costs.

C. Water Resources

Water availability in Auvere is shaped by a combination of the Narva River, quarry lakes, groundwater-influenced basins, and industrial cooling-water systems. The Narva River, Estonia's largest river by discharge, provides a reliable freshwater source from which carefully regulated abstraction may be permitted. At the same time, industrial cooling circuits create separate water streams whose characteristics (temperature, suspended solids, chemical composition) may support specific RAS pre-treatment systems. These water sources cannot be used without advanced purification; however, their stable volumetric availability enhances resilience, especially during seasonal fluctuations. Table 2 summarizes the critical geographic characteristics of the Auvere location and their corresponding influence on RAS viability and resilience planning.

Table 2: *Geographic characteristics of Auvere/Ida-Virumaa and their influence on RAS resilience.*

Geographic Feature	Description/condition	Influence on RAS sustainability/resilience
Location	Ida-Virumaa, proximity to Narva/Auvere industrial complex.	Essential geographic prerequisite for Industrial Symbiosis (IS). Mitigates high operational costs (OpEx) via waste heat exchange.
Water Source	Proximity to Narva River and utilization of reclaimed Narva quarry areas.	Ensures high-volume water supply (Narva River). RAS water recycling (*>95%*) mitigates risks associated with poor local groundwater quality.
Geopolitical position	Bordering the Russian Federation (Narva, Narva River).	Major vulnerability: diminishes investor attractiveness, loss of key export markets (St. Petersburg), and national defence needs restrict local renewable energy expansion.

Geographic Feature	Description/condition	Influence on RAS sustainability/resilience
Energy infrastructure	Presence of Auvere Power Plant and 330 kV substation.	Supports large-scale energy projects; provides critical resource stability for IS (heat, CO_2), enhancing Absorption capacity during energy market volatility.
Topography / Land Use	Reclaimed oil shale surface mine (1,500 ha), poor soil.	Land availability for large-scale development (EISAP); high potential for ecological restoration via agroforestry integrated with RAS/greenhouses.

2.3 Climatic and Meteorological Factors Affecting RAS

Estonia's northern climate imposes strict operational demands on land-based aquaculture. Winters are long, with temperatures routinely below freezing for extended periods and frost depths that affect buried pipeline installations. In RAS facilities, where water temperature is a critical growth parameter, winter conditions substantially increase thermal-energy demand. This makes the integration of waste-heat sources or renewable-hybrid energy systems particularly valuable.

Temperature volatility in shoulder seasons (spring and autumn) creates additional challenges. Rapid changes in external temperature can introduce differential heat loads on facilities, requiring precise climate-control management. Ice formation on nearby lakes or water channels further restricts the ability to source water from surface bodies in winter without prior heating or controlled intake structures.

Wind strength and winter storms influence logistics reliability, especially for feed imports, equipment delivery and transport of live fish where continuous cold-chain conditions are mandatory. Storm disruptions, road closures or port delays can disrupt supply chains that are time-sensitive, particularly for live fry or juvenile transfers. While RAS itself is protected from weather variability by being enclosed and artificially regulated, its operational resilience remains linked to these external climatic factors.

2.4 Ecological Constraints: Baltic Sea Basin and Freshwater Regulation

The Baltic Sea is one of the most sensitive marine ecosystems globally due to its semi-enclosed structure, slow water turnover and high nutrient load from riverine inputs. Estonia's marine areas are particularly vulnerable to eutrophication and harmful algal blooms. These ecological constraints severely limit the expansion of marine cage aquaculture along Estonia's coastline.

Land-based RAS is therefore the only pathway for expanding aquaculture production without contributing to nutrient pressures in the Baltic which is due to RAS' ability to capture, treat and reuse nutrient-rich effluent streams before discharge. Estonia's water-management rules specify strict conditions for effluent temperature, nutrient composition and allowable discharge rates into natural receiving waters. RAS facilities must incorporate multi-stage filtration and denitrification processes, stable sludge handling, and continuous monitoring to maintain compliance.

On the other hand, freshwater regulation also influences intake limits. River abstraction is subject to environmental-flow protection rules, requiring RAS operators to design systems with high water-recirculation efficiency to minimise extraction. These regulatory conditions reinforce the appropriateness of RAS relative to other aquaculture models, while placing technical obligations on system design.

This is why the assessment of RAS sustainability in Ida-Viru County must confirm regulatory compliance by verifying the high efficiency of nutrient removal and the robust implementation of compensatory measures for any unavoidable nutrient flow. Figure 4 synthesizes the key environmental characteristics defining the sustainability and compliance challenge in Ida-Viru County.

2.5 Industrial and Circular-Economy Dynamics

Ida-Viru's industrial transition creates a favourable environment for integrating RAS into circular-resource frameworks. Waste heat from energy conversion processes provides opportunities for climate-control synergies. Meanwhile, RAS sludge, once stabilised and treated, can serve as a nutrient resource in horticulture, greenhouse operations or soil-regeneration projects. The region's extensive industrial-water systems offer pathways for creating semi-closed water loops, reducing freshwater abstraction through pre-treated reuse.

The availability of industrial CO_2 streams also introduces possibilities for coupling RAS with greenhouse horticulture, where carbon enrichment enhances plant growth efficiency. Although such integration requires strict environmental and health controls, the potential for industrial-scale symbiosis is significant. These resource exchanges can strengthen both sustainability and resilience by reducing dependence on external energy and fertiliser inputs.

2.6 Regulatory, Spatial and Permitting Framework

RAS development in Estonia must conform to a multi-layered regulatory structure that governs land use, environmental impact, water abstraction, discharge, construction and operational monitoring. Environmental permits define allowable abstraction volumes, discharge conditions and required treatment levels. Spatial-planning instruments determine permissible land-use classes, and industrial zones such as Auvere typically provide the most favourable conditions for siting RAS due to reduced conflict potential and existing infrastructural capacity.

This why permit holders are required to maintain strict biosecurity standards, including control of pathogen transfer, species containment, treatment of intake water and sampling protocols for effluent. Additionally, the construction of RAS facilities on reclaimed industrial land often requires geotechnical evaluation, contamination screening and drainage management to ensure long-term structural stability.

2.7 Strategic Implications of the Estonian Context for RAS

The combined environmental, climatic, hydrological and industrial characteristics of Estonia create a highly specific context for RAS sustainability and resilience. Water is available but highly regulated; energy is abundant but undergoing structural transition; land is plentiful in post-industrial zones yet requires careful engineering; and supply chains are efficient but globally exposed. These factors shape a landscape where RAS can thrive only when designed with integrated energy systems, advanced water treatment, robust supply-chain buffers and precise regulatory alignment. The Ida-Viru region, in particularly Auvere offers a rare combination of conditions capable of supporting RAS systems that are sustainable, resilient and scalable, but only when embedded carefully within the region’s industrial ecosystem.

Chapter Three

RAS Technology and Infrastructure Assessment

The performance, sustainability and resilience of RAS depend fundamentally on the interaction between technological components and the physical, industrial and environmental context in which these systems operate. In Estonia, where climatic conditions impose significant heating demands and where regulatory constraints require rigorous water treatment standards, RAS technology must be assessed not only for its generic engineering properties but for its fit with local conditions. The resilience of RAS facilities positions them as critical nodes within regional food supply networks, necessitating their treatment as Critical Infrastructure (CI). Figure 1. illustrates the indispensable role of RAS in ensuring fresh food security within the broader context of Baltic Sea environmental degradation and energy transition.

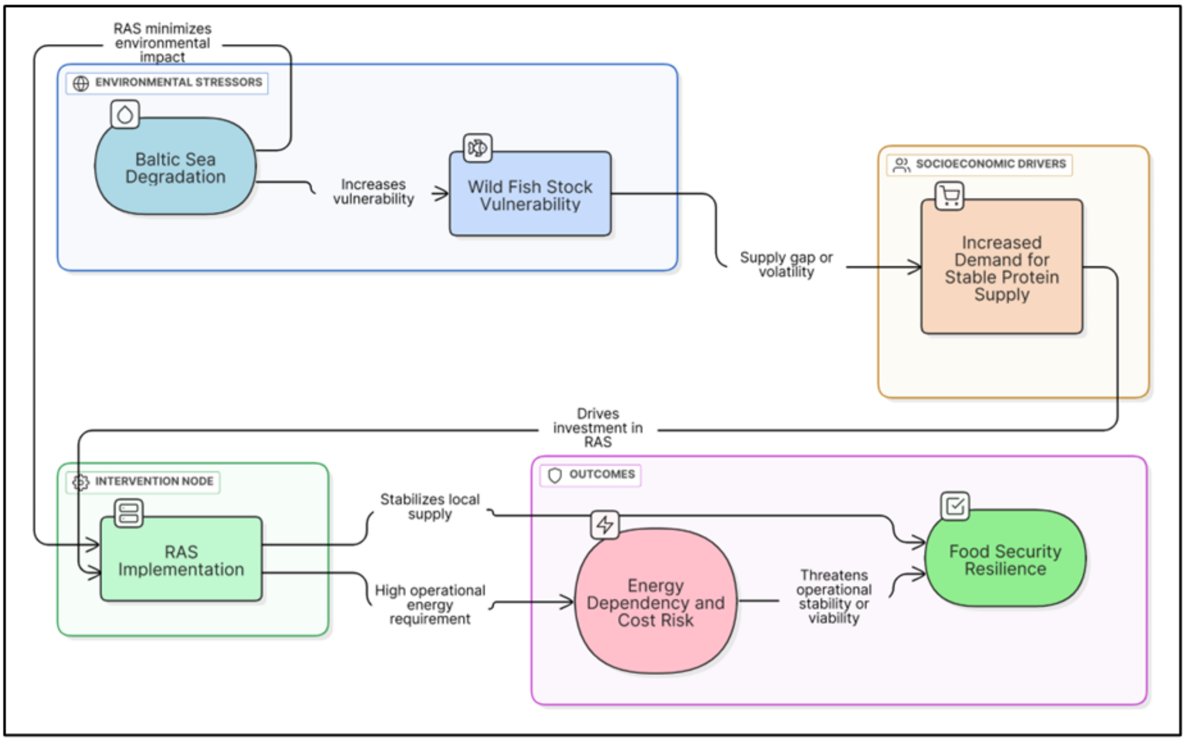

Figure 1. *RAS infrastructure as a critical node in the BSR resilience network.*

3.1 Core Architectural Features of RAS Technology

Modern RAS relies on a closed-loop architecture in which water continuously circulates through a series of physical, biological and chemical treatment stages before being returned to culture tanks. The system is built around a multi-stage water-treatment sequence incorporating solids removal, biofiltration, carbon dioxide stripping, oxygenation and temperature control. In Estonia's climatic setting, each of these stages must be designed with high redundancy and efficiency to maintain water quality under variable operational loads.

The central element of RAS operation is the culture tank unit, where fish biomass is held at controlled stocking densities. These tanks are engineered to maintain consistent hydrodynamic conditions that allow uneaten feed and solids to be transported efficiently to mechanical filtration units. In cold climates such as Estonia's, tanks often require insulation layers and reinforced floors to maintain high thermal stability and prevent conductive heat loss to sub-zero ambient temperatures. The Figure 2 below details the energy distribution in typical intensive RAS configurations, highlighting the critical points for efficiency interventions pertinent to cold climate operations like Ida-Virumaa, Estonia.

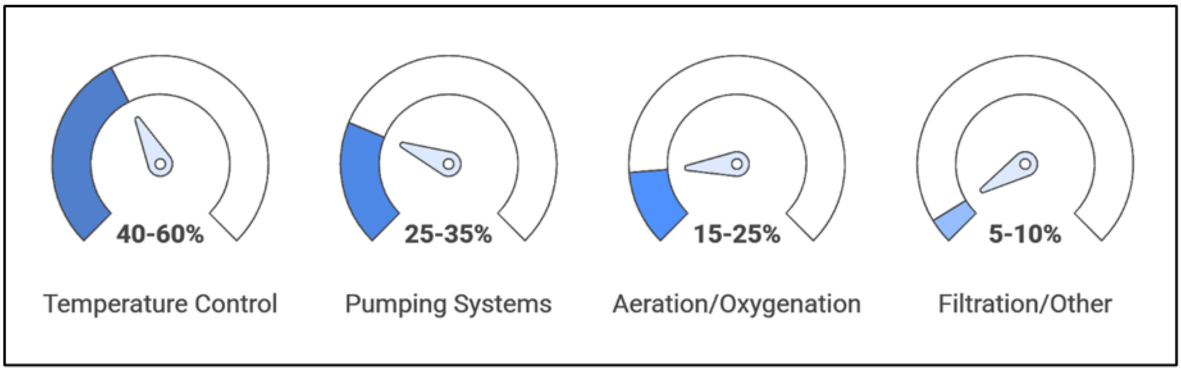

Figure 2: *Energy consumption distribution by RAS component in intensive systems.*

Mechanical filtration removes suspended solids through drum filters or microscreens. This step is crucial to reducing organic loading on downstream biofilters, especially given Estonia's regulatory expectations for effluent quality. Biological filtration is achieved through nitrifying biofilters, either moving bed bioreactors (MBBR) or fixed-bed configurations, that convert toxic ammonia and nitrites into nitrate. Given the strict nutrient discharge standards in the Baltic basin, biofilters must be sized conservatively to ensure high nitrification rates, especially under cold-water conditions where microbial activity is slower.

Beyond biological treatment, RAS employs carbon dioxide degassing to prevent hypercapnia. Degassing towers or low-head oxygenation systems are used to strip CO_2 from the water column. These systems also integrate closely with oxygen-supply infrastructure, which may be sourced from liquid-oxygen (LOX) tanks or on-site oxygen-generation units. In Estonia, where energy and oxygen supply stability is a core resilience issue, the choice between LOX and oxygen generators carries significant operational implications.

Temperature regulation forms a particularly demanding subsystem in Estonia's northern climate. RAS requires stable thermal regimes that do not fluctuate with ambient weather patterns. Thermostatic control is typically achieved through heat pumps, heat exchangers or direct integration with industrial waste-heat flows. Estonia's long, cold winters and the thermal conditions of the Ida-Viru region make waste-heat symbiosis technically attractive, reducing operational costs and improving sustainability by lowering energy demand for water heating. However, integration requires precise engineering to ensure stable heat-delivery conditions and to prevent thermal overshoot.

The control architecture of RAS relies on digital sensing networks that continuously monitor dissolved oxygen, ammonia, nitrite, nitrate, pH, temperature, turbidity, biofilter performance and flow rates. These systems typically use programmable logic controllers (PLCs), supervisory control and data acquisition (SCADA) platforms and distributed sensor units. Estonia's advanced digital infrastructure supports high-quality control systems, but the region's cyber-threat exposure increases the importance of designing SCADA units with cyber-resilience features, including local fail-safe modes, offline override capability and redundant sensor arrays.

3.2 Water Infrastructure Requirements and Treatment Architecture

RAS water requirements are characterised not only by high recirculation efficiency but by the need for reliable sources of clean intake water and stringent discharge control. In Estonia, where the Narva River and quarry-lake systems form major water bodies near industrial energy sites, RAS installations require intake configuration that complies with hydrological protection rules.

A typical RAS intake in Estonia draws pre-filtered surface water which is treated before entering the recirculation system. Pre-treatment often includes sand filtration, ultraviolet (UV) disinfection or ozonation to eliminate pathogens present in natural waters. Intake systems must be frost-protected and buried below seasonal freeze depth, given the climatic conditions of northern Estonia. The Combination of ozonation and UV irradiation has been demonstrated to effectively reduce total heterotrophic bacteria and coliform counts to near-zero levels, performing better than UV alone, which can be limited by bacteria embedded in particulate matter. Figure 3 illustrates the dual strategy of source water sterilization and in-system microbial control using these physical disinfection methods.

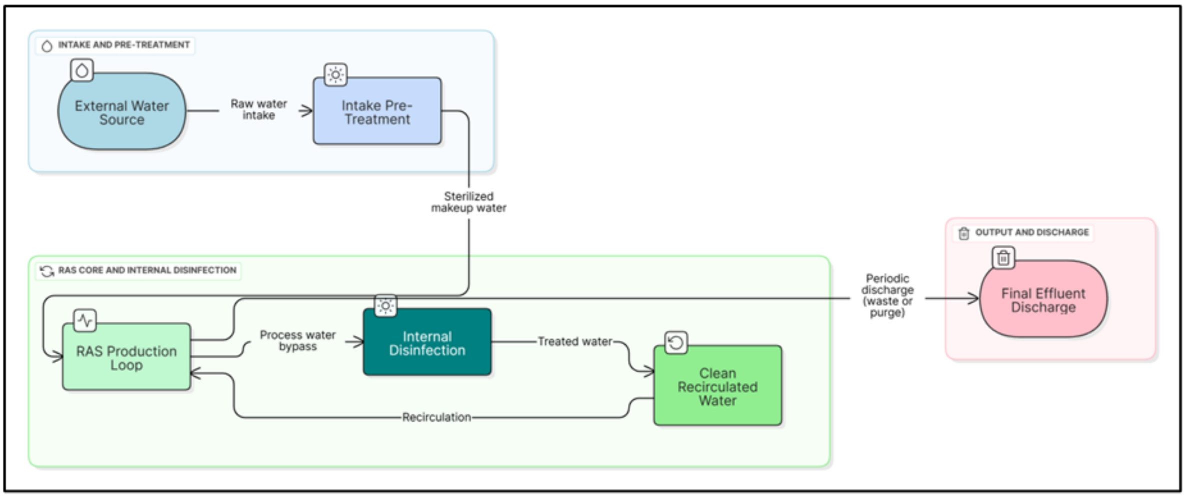

Figure 3: *Disinfection placement in recirculating aquaculture systems*

Discharge from RAS must comply with nitrogen, phosphorus, suspended solids and temperature standards. Multi-stage effluent treatment—incorporating solids capture, fine filtration, denitrification, pH correction and disinfection—is mandatory for large RAS installations to meet Baltic Sea protection thresholds. Estonia's discharge regulations also impose limitations on temperature differentials, meaning that thermal energy must be recaptured, dissipated or exchanged in industrial processes prior to discharge.

The sludge generated from solids removal and biofilter backwashing represents a nutrient-rich resource stream with potential for biofertilizer production or anaerobic digestion. In Ida-Viru, where industrial symbiosis is encouraged as part of the region's transition away from oil shale, sludge processing can be integrated with biological-waste treatment facilities or agricultural co-products. However, these synergies require regulatory alignment and quality assurance, especially concerning heavy-metal concentrations, pathogen load and nutrient profiles.

3.3 Thermal and Energy Subsystems: Requirements and Integration Potential

Energy constitutes one of the highest operational demands of RAS, especially in northern climates. Pumps, blowers, oxygenation systems, recirculation units, heating equipment and digital control systems operate continuously, and any interruption can cause rapid declines in water quality with severe biological consequences. Estonia's energy environment therefore plays a decisive role in RAS feasibility.

RAS heating requirements are intensified by ambient winter temperatures that often range between –10°C and –25°C, with wind chill and extended frost periods. Heat pumps used in isolation face efficiency challenges at such low temperatures; thus, hybrid-combined energy strategies become essential. One of the most compelling advantages of siting RAS in the Auvere industrial environment is the availability of large, stable waste-heat flows from power-generation operations. These flows can be channelled through plate heat exchangers or integrated into RAS heating circuits to maintain stable water temperatures.

Electrical energy is another critical factor. Pumps, drum filters, blowers and oxygen generators require reliable power supply. Estonia's grid is well-developed in Ida-Viru, with high-voltage lines and multiple redundancy options connected to national transmission corridors. However, Estonia's ongoing energy transition, phasing out oil-shale power production introduces uncertainty in long-term baseload stability. RAS installations must therefore incorporate:

- dual electrical feeds
- automatic transfer switches
- on-site backup generation
- uninterruptible power systems (UPS) for critical sensors and oxygenation systems

While these redundancies increase capital expenditure, they are central to resilience in cold climates where pump failure or heat loss can cause rapid fish mortality.

Carbon intensity is another dimension of sustainability. RAS depends heavily on electrical and thermal energy, and the environmental footprint is strongly influenced by the energy mix. Integrating RAS into industrial zones with waste-heat opportunities and future renewable-energy potential (e.g., wind-hydrogen hybrids) can substantially reduce carbon intensity and improve sustainable performance.

3.4 Oxygenation, Degassing and Gas-Exchange Systems

RAS fish require consistent dissolved oxygen levels, typically maintained above 7 mg/L for salmonids. The oxygenation system must therefore match biological demand and ensure stable delivery even during peak feeding or biomass density expansion.

Liquid-oxygen storage offers stable oxygen supply but depends on reliable delivery from external suppliers, creating logistical vulnerability during winter storms or international supply disruptions. In contrast, on-site oxygen generation provides autonomy but increases energy consumption and requires robust compressor maintenance. Estonia's supply-chain exposure suggests that hybrid configurations with both LOX and on-site generators enhance resilience.

Degassing systems prevent CO_2 buildup, which can impair fish growth and biofilter efficiency. Low-head oxygenation systems and cascade degassing columns are commonly employed. In colder climates, gas-exchange equipment must be designed with frost protection, insulation and condensate management to ensure continuous operation.

3.5 Automation, Monitoring and Digital Control Infrastructure

Control reliability is non-negotiable in RAS due to the narrow tolerances for dissolved oxygen, temperature, ammonia and flow rate. Estonia's digital infrastructure provides strong foundations for advanced SCADA systems, remote monitoring, machine-learning-based process optimisation and predictive maintenance. However, the region's heightened exposure to cyber risks requires enhanced cybersecurity protocols, segmentation of control networks, encrypted sensor communication and physical override capability. Critical parameters monitored include:

- dissolved oxygen
- temperature stability across tanks and system loops
- ammonia and nitrite concentration
- pH and alkalinity
- flow uniformity
- turbidity and solids load
- biofilter oxygen consumption
- sludge accumulation rates

These monitoring systems must remain functional during outages or cyber interruption. Emergency fallback modes, such as manual oxygen injection or bypass circuits, are essential components of resilience architecture.

3.6 Site Integration and Infrastructure Layout Considerations

RAS facilities require large, stable foundations due to heavy tank loads and the dynamic stresses generated by circulating water. The reclaimed mining plateaus in Ida-Viru provide suitable platforms if reinforced appropriately. Frost-resistant piping infrastructure is essential, especially for intake and discharge circuits that must cross open ground exposed to winter winds.

Proximity to roads and logistic corridors influences feed deliveries, spare-part stocking and harvest transport. Ida-Viru's access to major east–west and north–south corridors supports supply-chain resilience but must be complemented by on-site feed storage and emergency stock redundancy due to winter logistics risk.

Water treatment buildings, mechanical rooms, oxygenation towers and heat-exchanger housings must be located to minimise pipe run length and heat loss. In Estonia's climate, exterior equipment must be enclosed or insulated to prevent freezing and maintain operational integrity.

3.7 Engineering Interdependencies and System: Level Performance Implications

The effectiveness of RAS in Estonia is determined by the interplay between technology choices and contextual constraints. Heating loads, oxygen demand, pump energy, recirculation efficiency and sludge removal must all be engineered holistically. Poor integration of thermal systems can undermine sustainability even when water quality is stable; similarly, underestimating flow redundancy or energy backup requirements can compromise resilience even in systems with strong environmental performance. RAS sustainability in Estonia improves when:

- heating systems are efficiently coupled with industrial symbiosis;
- advanced treatment reduces nutrient discharge to sensitive waters;
- energy systems draw from stable, diversified sources;
- sludge is valorised within a circular-resource pathway.

RAS resilience improves when:

- redundancy is built into pumps, blowers and oxygen systems;
- energy supply is secured through hybrid feeds and backup generation;
- automation systems include robust fail-safe modes;
- supply chains for feed and spare parts are diversified and buffered.

These sustainability–resilience trade-offs mentioned form the foundation for the deeper analysis in subsequent chapters.

Chapter Four

Sustainability and Resilience Analysis of RAS Systems

The sustainability and resilience of RAS in Estonia depends on a combination of engineered system performance, environmental compatibility, energy configuration, operational continuity and supply-chain robustness. This particular analysis focuses on key sustainability domains such as water, energy, land, nutrient flows, sludge management and circular-resource synergies followed by a detailed resilience evaluation covering operational stability, redundancy, biosecurity, supply dependencies and vulnerability to external shocks.

4.1 Water Use, Treatment and Discharge Sustainability

RAS systems rely on continuous water recirculation, typically exceeding 95% reuse, which substantially reduces freshwater abstraction compared to flow-through facilities. In Estonia, where water bodies such as the Narva River are ecologically significant and regulated for thermal impact and nutrient release, high-efficiency reuse is essential for environmental compliance. Water abstraction from surface sources in the Auvere–Narva region is feasible, but the ecological rules governing flow stability, sediment transport and seasonal water quality impose limits on intake volumes. RAS operators must therefore incorporate multi-stage treatment including drum filtration, protein skimming, biological nitrification, UV disinfection and solids-removal units to ensure that discharge meets strict nutrient thresholds and temperature limits.

The efficacy of solids removal for example (Figure 4) is maximized when tanks are designed with optimal hydraulic characteristics, such as circular or octagonal tanks utilizing dual drains (a main side wall drain and a central bottom drain for concentrated sludge). This separation allows the highly concentrated sludge stream to bypass the main treatment loop and be sent directly for disposal or valorisation (e.g., fertilizer or biogas production), minimizing nutrient discharge to the Baltic Sea environment.

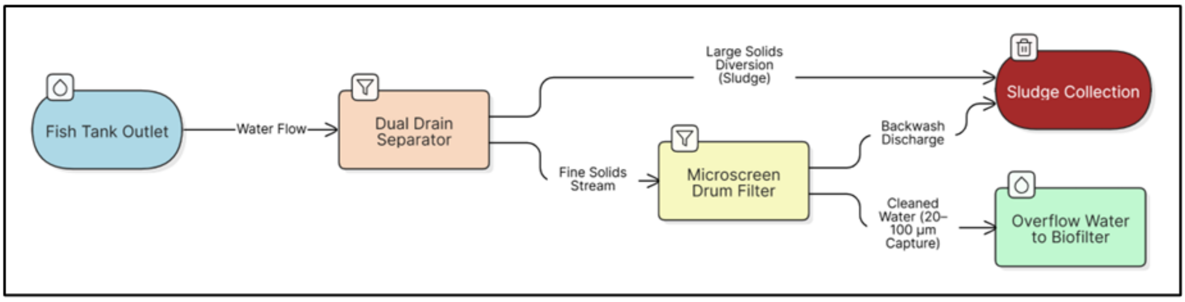

Figure 4: *Mechanical solids removal process in intensive RAS.*

Discharge is particularly sensitive because the region includes Natura 2000 sites and fish habitats vulnerable to thermal stress. Estonia's discharge regulations require temperature moderation before release, which in turn shapes energy-use dynamics. The more efficiently heat is recovered within the system, the lower the ecological burden at the discharge point.

4.2 Energy Demand, System Configuration and Decarbonisation Potential

RAS energy profiles are dominated by heating, pumping, oxygen generation and control-system loads. Estonian climatic realities increase the significance of thermal-energy management: low ambient temperatures and significant seasonal fluctuations demand continuous water-heating for many species. If powered exclusively by grid electricity, this results in high energy intensity and elevated operational costs, making sustainability dependent on energy-source diversification and efficiency improvements.

The Auvere energy industrial zone presents specific advantages because of its stable waste-heat output from thermal generation processes. Waste heat can support:

- pre-heating of intake water,
- maintenance of optimal rearing temperatures, and
- reduction of heating loads during winter.

These interactions substantially reduce the carbon intensity of RAS operations and strengthen resilience by decreasing dependence on external energy supply variations.

Operational resilience also depends on the continuity of power supply. RAS failure during power outages can cause catastrophic stock losses within minutes. Systems positioned in high-capacity grid nodes with redundant substation connectivity such as those available in Ida-Viru benefit from reduced outage risk. Additional measures such as on-site generators, UPS-supported sensor networks and secondary oxygenation systems strengthen operational continuity.

4.3 Land, Site Stability and Environmental Footprint

RAS facilities require stable construction platforms capable of supporting heavy tanks, filtration units and piping networks. Reclaimed mining lands in the Auvere area provide expansive surfaces with low competing land-use value, minimal residential proximity and pre-existing industrial drainage. These characteristics minimise both direct ecological disturbance and indirect social impacts.

The environmental footprint of RAS systems is further reduced by their ability to operate independently of natural water bodies. Unlike coastal aquaculture, land-based operations eliminate risks of escape, eutrophication hotspots, seabed degradation and interactions with wild fish populations. Their waste streams can be fully captured and integrated into controlled treatment processes, allowing nutrient and sludge flows to be directed into circular agriculture

4.4 Waste, Sludge and Circular-Resource Integration

RAS processes generate nutrient-rich sludge composed of uneaten feed, faecal matter and biofilm residues. In Estonia, sludge can be directed into:

- biogas digesters
- composting systems
- agricultural fertiliser production
- integrated greenhouse systems

The regional circular-economy ambitions in Ida-Viru County create opportunities for sludge valorisation rather than disposal. Sludge integration with greenhouse horticulture, in particular, can support controlled nutrient cycling and alignment with Estonia’s waste-reduction goals.

Similarly, potential synergies exist for reusing treated RAS effluent for industrial processes or irrigation of controlled-environment agriculture. Each such synergy reduces freshwater demand and enhances sustainability.

4.5 Operational Resilience and System Redundancy

RAS systems are engineered for continuous operation, and operational resilience is a function of robustness, redundancy and early warning feedback. The core vulnerabilities include pump failure, oxygenation disruption, filtration overload, sensor malfunction, biofilter collapse and thermal-system malfunction. To mitigate these risks, resilient RAS systems incorporate:

- duplicate pumps and blowers
- independent oxygenation sources
- multi-layered sensor networks
- fail-safe shutoff valves and bypass loops
- real-time water quality alarms
- compartmentalised production units

In Estonia's context, where external threats include harsh winter storms, potential grid instability and logistical delays, operational safeguards must be reinforced by on-site backup power, oxygen reserves and critical spare parts. Resilience also depends on operator expertise, rapid response protocols and the availability of local maintenance capacity. Given Estonia's limited domestic supplier base for specialised equipment, reliance on foreign technicians increases vulnerability, underscoring the need for enhanced local technical training and cross-industry maintenance partnerships.

4.6 Biosecurity and Disease-Resilience Capacity

Biosecurity is a core dimension of resilience because disease outbreaks in RAS, although less likely than in open systems, can spread rapidly in enclosed environments. Estonia's cold climate strengthens environmental barriers against some pathogens, but reliance on imported juveniles increases risk pathways. Effective biosecurity requires:

- controlled intake-water treatment
- compartmentalised fish cohorts
- strict disinfection of equipment and personnel
- quarantine protocols for new stock
- stable water chemistry to reduce fish stress
- sealed facility envelopes limiting external contamination

RAS facilities benefit from the ability to entirely eliminate contact with wild fish populations and to manage water quality with high precision, reducing disease exposure. However, the technological density of RAS also means that any failure in filtration or recirculation can compromise biosecurity rapidly.

4.7 Supply-Chain Resilience: Inputs, Dependencies and Vulnerabilities

RAS in Estonia relies on several externally sourced input chains that present structural resilience challenges.

A. Feed Dependencies

High-protein feeds are imported primarily from Nordic and Western European producers. Feed supply is vulnerable to fluctuations in global commodity markets, port delays and transport interruptions during northern winters. Storage strategies and multi-supplier agreements are essential for resilience.

B. Juvenile Supply

Estonia lacks extensive domestic hatchery capacity for salmonids at commercial scale. Dependence on imported juveniles introduces fragility due to border delays, health certification issues and transport stress on live fish.

C. Equipment and Spare Parts

RAS components such as oxygen cones, filtration membranes, pumps, UV lamps and sensors originate from international manufacturers. Long lead times for replacement parts pose a major resilience challenge. Facilities in Estonia must maintain a critical inventory of spare components.

D. Logistical Corridors

RAS relies on road-based movement of feed, juveniles, oxygen cylinders and harvested product. Winter storms, port closures and regional geopolitical tension introduce variability into transport reliability.

Each of these supply-chain vulnerabilities affects system-level resilience and must be integrated into long-term planning.

4.8 System-Level Integration of Sustainability and Resilience

The sustainability and resilience of RAS are deeply interdependent. Heat reuse improves environmental performance while strengthening thermal resilience. Efficient water recirculation reduces ecological impact while enhancing operational stability during water-intake interruptions. On-site energy diversification decarbonises operations and provides fallback capacity during grid disturbances. Circular sludge utilisation improves sustainability while reducing waste-handling risks. RAS becomes most resilient when supported by a robust supply chain and embedded in a well-designed industrial ecosystem.

For Estonia, achieving this integrated sustainability–resilience performance requires:

- strengthening energy redundancy
- expanding domestic juvenile capacity
- diversifying feed suppliers
- deepening industrial symbiosis in Ida-Viru
- consolidating operational backup systems.

Chapter Five

RAS Logistics Chain

The supply chain associated with RAS-based fish production begins with the procurement or internal production of eggs and fry. Hatchery sections maintain strict control of temperature, oxygen levels and hygiene to ensure proper incubation and early development, after which fish are transferred to grow-out sections where they remain for fattening under automated feeding regimes and continuously stabilised water parameters. Throughout the production cycle, water quality and fish health are monitored as part of routine management.

When fish reach commercial size, harvesting and processing are coordinated with cooling, packaging and storage routines adapted to the specific market destination. Facilities may sell live fish, chilled whole fish, processed fillets or fry for further rearing elsewhere. The chain concludes with transport and distribution, which may involve cooperation with retail networks, restaurants or export channels, and relies on well-functioning cold-chain infrastructure to preserve freshness.

The operational lifecycle of a modern aquaculture or Recirculating Aquaculture System (RAS) facility follows a sequential chain of activities through which technical capacity, biological production, and market value are gradually built. This progression begins with financial commitment and conceptual planning and moves through system design, infrastructure development, active farming, product transformation, and market delivery. Each stage is interdependent, with decisions made early in the chain determining the efficiency, reliability, and sustainability of all downstream outcomes. Understanding this flow—from Investment → Design → Construction → Farming → Processing → Distribution → Service/Development—provides a comprehensive view of how aquaculture systems function as integrated production environments and how value is generated, preserved, and expanded across the full lifecycle of the operation shown in Figure 5

Economic considerations arising in this chain are tied to the cost structure of RAS. High investment and operating costs create sensitivity to competition from imported fish, and market actors must weigh these pressures against the quality advantages that controlled-environment production provides. Because feed quality has a direct influence on fish health and growth, producers depend on stable supply relationships and consistent formulations. Technological improvements in biological filtration, feeding equipment and overall system automation offer opportunities to strengthen cost efficiency and production stability. Consumer awareness of production methods and transparency regarding fish origin can contribute positively to demand for products originating from closed, environmentally controlled systems.

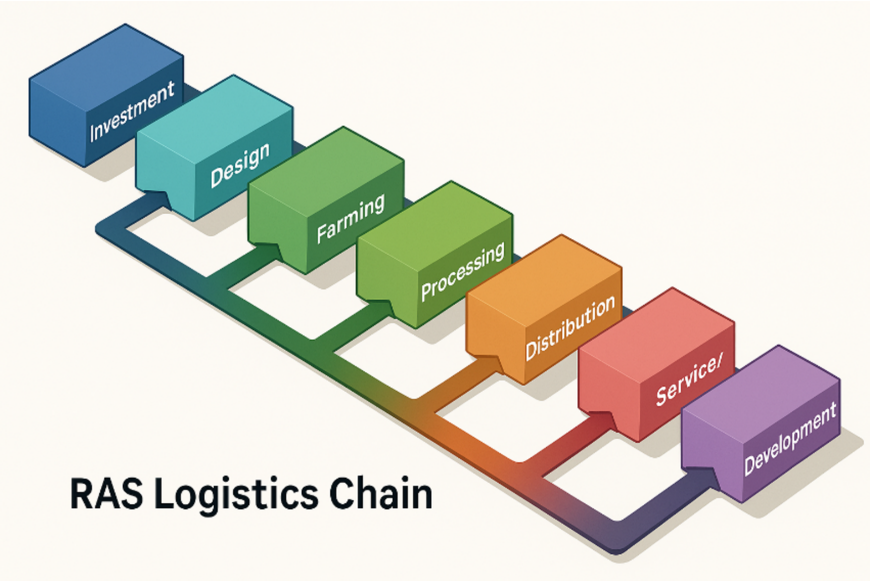

Figure 5: *RAS Logistics Chain*

5.1. Timeline and Process of the RAS Logistics Chain

A. Preparatory (Investment) Stage — 3 to 9 months

The goal of this stage is to establish project feasibility and secure investment.
Key activities include the following:

1. Market research – 1–2 months
   Analyze demand, prices, and competitors.
2. Financial and business planning – 1–3 months
   Define CAPEX, OPEX, ROI, and risk analysis.
3. Species and production model selection – 1 month
   Choose target species (e.g., trout, salmon, sturgeon) and production cycle.
4. Permitting and environmental assessments – 3–6 months
   Obtain water-use permits and environmental impact approval.

Total: ~6 months average (can extend to 12 if permits are delayed).

B. Design and Technological Stage — 4 to 8 months

Goal is to develop detailed design and build physical infrastructure.

Key activities include the following:

1. System design (RAS layout, hydraulics, filters) – 2 months
2. Component selection and procurement – 1–3 months
   (Includes tanks, filters, oxygenation, sensors, control systems)
3. Construction and installation testing – 3–6 months

Total: 4–8 months depending on project scale and import logistics.

C. Operational Stage (Fish Production) — 12 to 24 months

Goal is to begin and stabilize production.

Phases include:

1. Stocking / incubation – 1–2 months
   Introduce eggs or fry.
2. Rearing / grow-out – 8–18 months
   Continuous feeding, monitoring, and water quality control.
3. Harvesting / grading cycles – ongoing from month 10–12.

First harvest typically after ~12–18 months; system stabilizes in year 2.

D. Processing and Distribution Stage — Continuous (after month 12)

The objective if this stage is for the conversion of harvested fish into market products and deliver to customers.

Key activities are:

1. Processing / packaging – ongoing after harvest (batch-based)
2. Distribution – refrigerated transport to wholesalers or retail chains.
3. Sales & marketing – continuous market engagement.

Operational in parallel with production once first fish reach market size.

E. Maintenance and Development Stage — Continuous (year 2 onward)

Goal is Optimization, scaling, and production sustenance.

Key activities are:

1. Monitoring and biosecurity – daily/weekly routine.
2. Equipment servicing & system upgrades – every 6–12 months.
3. Training and staff development – annual cycles.
4. Cost and efficiency reviews – quarterly to yearly.

Long-term operational phase; ongoing throughout facility's lifespan (10–20 years).

The overall overview is presented in the Figure (6) and Table (3) below.

Table 3: *Overall Timeline Overview of the RAS Logistics Chain*

Stage	Duration	Cumulative Time (approx.)	Key Milestones
Preparatory	3–9 months	0–9 months	Business plan, permits
Design & Tech	4–8 months	4–17 months	Construction completed
Operation	12–24 months	16–41 months	First harvest (~Month 24)
Processing & Distribution	Continuous	After Month 18	Sales begin
Maintenance & Development	Continuous	Year 2+	Optimization, scaling

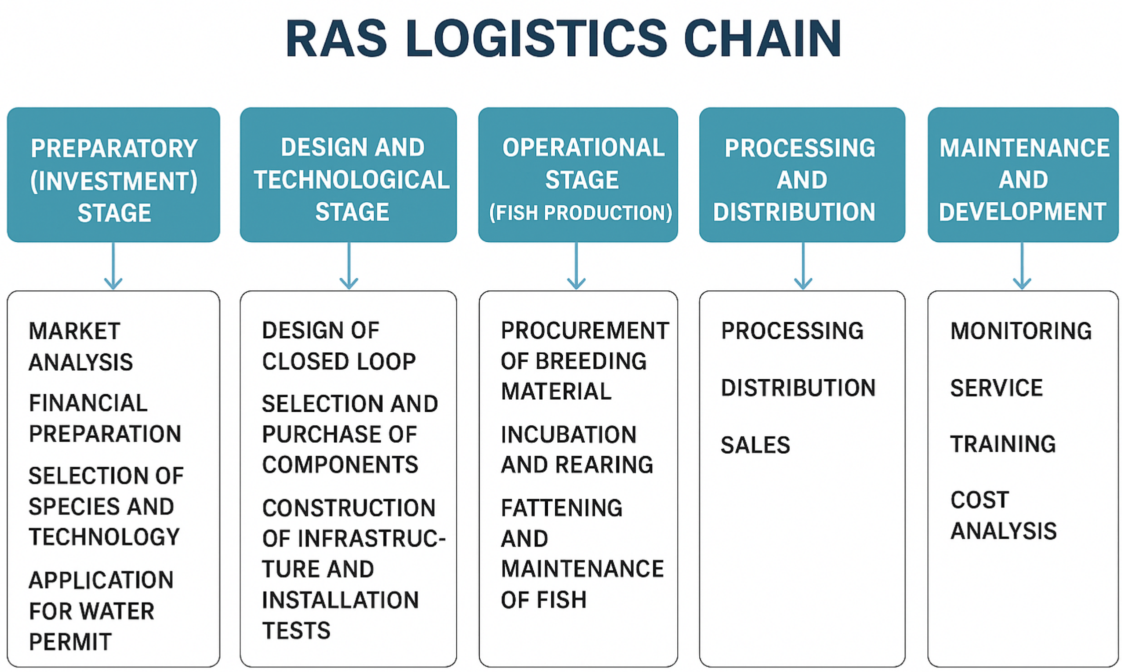

Figure 6: *RAS Logistics Chain*

5.2 The choice Between Closed vs. Open Systems

A. *Environmental Aspects of Closed vs. Open Systems*

Open Systems: Farming in open waters carries the risk of environmental pollution through the release of excess nutrients (nitrogen, phosphorus) into aquatic ecosystems, leading to eutrophication and habitat degradation. Additionally, open farms are exposed to external factors such as climate change, pollution, and diseases transmitted by wild populations.

Closed Systems RAS systems enable water recirculation and purification, significantly reducing water resource usage and pollutant emissions. Water is continuously monitored and filtered both mechanically and biologically, maintaining optimal conditions for fish around the clock. Moreover, RAS farming offers better biosecurity, reducing the risk of pathogen transmission and environmental impact.

B. Health Aspects of Fish Farming in Closed vs. Open Systems

Deep Groundwater as a Clean Water Source: RAS systems often use deep groundwater, which is free from pathogens, parasites, and harmful bacteria. This results in fish being less exposed to infections and diseases, improving the health quality of the final product.

Reduced Use of Antibiotics and Chemicals: In closed systems, the use of antibiotics is highly limited due to the risk of damaging the biofilter, a key component of biological filtration that maintains microbial balance in the water cycle. Antibiotics can destroy beneficial bacteria, destabilizing the system and causing serious farming issues. As a result, RAS farmers implement strict preventive and biosecurity procedures, significantly reducing the need for pharmaceutical treatments.

In contrast, open systems use antibiotics and other chemicals more frequently, which poses risks of residues in fish meat and the development of bacterial resistance. Despite existing regulations and withdrawal periods, control over the use of these substances varies.

Impact on Fish Health and Product Quality: Fish raised in RAS systems exhibit better health quality, lower susceptibility to disease, and reduced risk of antibiotic and chemical residues. This makes products from closed systems potentially healthier and safer for consumers.

C. Economic and Technological Challenges

Production Costs: RAS systems are characterized by high investment and operational costs, mainly due to energy-intensive water purification and oxygenation processes. Competition with cheaper, mass-scale open systems and imported fish poses a serious challenge for local producers.

Quality Requirements: Closed systems require high-quality feed that does not pollute the water or overload biological filters. Collaboration with ichthyologists and nutrition technology specialists is essential for optimizing fish growth and health.

Technological Innovations: The greatest development potential in RAS lies in improving biological filtration and optimizing energy consumption. Integrating RAS systems with renewable technologies (e.g., photovoltaics) and developing waste management solutions (e.g., aquaponics, CO_2 utilization) are key directions for future research and investment.

5.3. Development Perspectives

1. Fish farming in closed systems is a forward-looking direction for aquaculture development, enabling sustainable animal protein production with minimal environmental impact.
2. RAS-farmed products are characterized by higher health quality and lower risk of antibiotic residues, which can be a significant marketing advantage.
3. Economic challenges, including high costs and global competition, require a comprehensive approach to optimizing production processes and marketing strategies.
4. Consumer education and transparency about fish origin can increase demand for RAS products.
5. Technological innovations—especially in biological filtration, energy management, and integration with renewable systems—are key to improving the efficiency and profitability of closed-system farming.
6. Investment in RAS systems is a long-term process that requires careful planning, considering environmental, legal, and economic aspects.

Table 4: *Summary of the key environmental differences between closed (RAS) and open fish farming systems.*

Aspect	Open Systems	Closed Systems (RAS)
Water Pollution Risk	High – excess nutrients (nitrogen, phosphorus) can pollute natural ecosystems.	Low – water is filtered and reused, minimizing discharge and pollution.
External Vulnerabilities	Exposed to climate change, wild diseases, and external pollutants.	Controlled environment reduces exposure to external threats.
Environmental Control	Limited – difficult to regulate water quality and temperature.	Full control – continuous monitoring and adjustment of water parameters.
Resource Efficiency	High water usage and potential habitat degradation.	Efficient use of water and energy; reduced environmental footprint.
Biosecurity	Lower – higher risk of pathogen transmission from wild populations.	Higher – isolated systems reduce disease transmission and ecological impact.
Sustainability	Less sustainable due to environmental risks and resource use.	More sustainable with lower carbon and water footprint.

5.4. The Value Chain in RAS and Modern Aquaculture

The value chain in RAS shows how economic value, knowledge, and competitive advantage accumulate as inputs move through a highly integrated sequence of activities. Each stage builds on the previous one, transforming scientific knowledge and engineered systems into high-quality food products. The chain is therefore more than a linear movement of goods: it is a strategic process through which biological, technological, and commercial components are aligned to support efficient, resilient, and sustainable aquaculture operations.

D. *Research and Development (R&D)*

The value chain begins with scientific research, which provides the foundation for improvements in breeding, feed formulation, and system performance. Biological studies refine understanding of species-specific growth requirements, health characteristics, and environmental tolerances. Technological research, meanwhile, contributes innovations in automation, water-treatment efficiency, system control, and biosecurity. Together, R&D activities form the knowledge base that determines the productivity potential of all downstream stages.

E. *System Design and Technological Know-How*

Specialised engineering and technical expertise convert research outputs into practical and operational system designs. This stage includes planning hydraulic layouts, selecting biological-filtration technologies, integrating oxygenation and feeding systems, and specifying monitoring equipment. Design choices define the stability, efficiency, and operational flexibility of the entire facility. In RAS, where environmental conditions must be tightly regulated, the quality of system engineering plays a decisive role in production outcomes.

F. *Component Delivery and Construction*

The value chain becomes tangible when equipment and structural components are procured, delivered, and assembled. Civil works, tanks, piping networks, pumps, filters, sensors, and control systems are installed according to the engineered plan. This stage translates technical specifications into an operational facility and involves coordination among suppliers, contractors, and technical specialists. The accuracy of construction and the proper installation of equipment lay the groundwork for system reliability and long-term performance.

G. *Farm Management and Production Optimization*

Once operational, the farm shifts into continuous production management. This stage encompasses daily monitoring of water quality, operation of filtration and oxygenation systems, feeding routines, health assessment, and maintenance tasks. Managers and technicians optimise biological and technical processes to maintain stable conditions, improve growth rates, and reduce resource inputs. Production optimisation is an iterative process, relying on data feedback, operational experience, and ongoing refinement of practices.

H. *Equality Control and Processing*

After harvest, fish enter a structured quality-control and processing workflow. The emphasis is on ensuring that products meet required standards for freshness, safety, and consistency. Processing may include slaughtering, filleting, cooling, packaging, or preparing fish for specific market formats. The reliability of this stage affects product shelf life, consumer trust, and the ability to meet distribution timelines. Rigorous quality control reinforces the advantages of RAS, where stable production conditions support predictable product characteristics.

I. Branding, Marketing, and Distribution

Strategic communication and branding become central once products enter the marketplace. Producers differentiate their fish based on quality, provenance, production methods, or sustainability attributes. Marketing activities connect products with the appropriate market segments—retail chains, restaurants, wholesalers, or export partners. Efficient distribution networks ensure timely delivery, preserve product integrity, and align supply with demand. Strong market positioning strengthens competitiveness and supports higher value capture.

J. Customer Service and Sustainable Development

The final link in the chain combines customer engagement with long-term sustainability commitments. Customer service includes maintaining reliable supply relationships, responding to market needs, and integrating feedback into future production planning. Sustainable development encompasses environmental stewardship, responsible resource use, product transparency, and alignment with broader societal expectations regarding food production. In RAS, the emphasis on environmental responsibility becomes a competitive asset, reinforcing consumer confidence and supporting long-term industry viability.

Across these stages, the value chain transforms scientific input and technical capacity into a high-quality food product delivered to consumers. Value accumulates at each point, through knowledge creation, technical precision, biological performance, product quality, branding, and responsible resource management, forming a coherent framework that supports the competitiveness and long-term resilience of modern aquaculture shown in Table (5). and in Figure (7) below.

Table 5: *Value chain of RAS*

Stage	Main Added Value	Example
R&D / Innovation	Knowledge, technology	New filtration solutions, automated feeding systems
Design and Construction	System integration	RAS project tailored to species
Production (Farming)	Biological efficiency	Fast growth, low mortality
Processing	Product quality	Filleting, MAP packaging
Marketing and Sales	Brand and premium pricing	“Local, eco-friendly RAS fish”
Service and Development	Long-term customer relationship	Training, consulting, new system versions

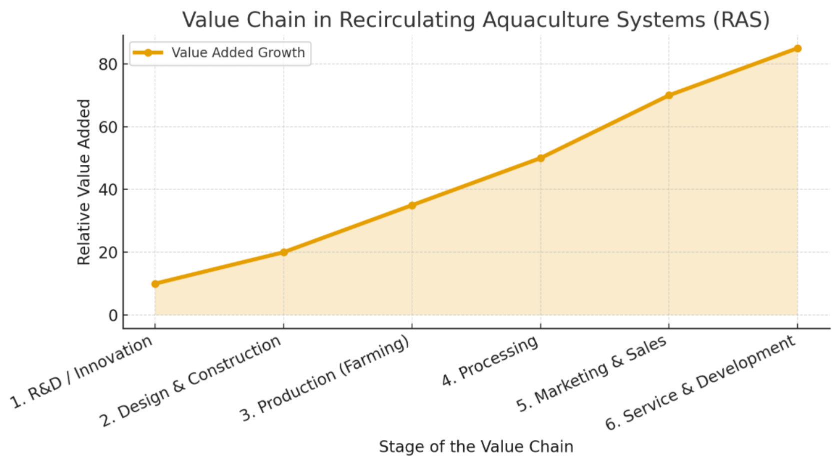

Figure 7: *Value chain of RAS*

Chapter Six

Expanded Scenarios, Risks and Mitigation Pathways

Evaluating the long-term viability of RAS in Estonia requires an integrated understanding of how these systems respond not only under normal operating conditions but under disruptions, stress environments and future changes in energy, climate, logistics, regulatory and market systems. Scenario analysis provides a structured way to test the sustainability and resilience of RAS technologies, operational systems and supply chains across multiple plausible futures. Rather than predicting a single pathway, the purpose of scenario analysis is to identify vulnerabilities, strengths, adaptation requirements and system thresholds that determine whether RAS can maintain continuous operation under destabilising conditions.

The scenarios assessment examines the performance of RAS under several categories of stress conditions that are materially relevant for Estonia: energy-price volatility and interruptions; feed-supply disruption and cost escalation; juvenile-supply instability; technological failure; logistics and cold-chain disruption; environmental and climatic stress; and regulatory-policy shifts. Each scenario reveals different dimensions of system fragility or robustness, and together they illustrate the dynamic environment in which RAS must operate to qualify as a resilient part of Estonia's critical fresh-food infrastructure. The mitigation pathways outlined at the end of the chapter translate scenario insights into actionable structural and operational measures.

6.1 Energy Shock and Energy-Price Escalation Scenario

Energy security is the single most decisive factor shaping the resilience of RAS in Estonia. Because RAS requires continuous electricity for circulation, oxygenation, filtration, pumping and digital monitoring, even short interruptions can cause cascading system failures. In addition, Estonia's climate requires extensive thermal regulation during long winter periods, amplifying exposure to energy conditions.

A scenario in which electricity prices surge sharply, due to geopolitical tensions, market volatility or reduced regional generation, would place immediate pressure on the operational costs of RAS. High-value species with narrow thermal tolerances are particularly sensitive to reductions in heating, while oxygenation and recirculation cannot be compromised without risking biological loss. Under such a scenario, RAS operators struggle to maintain economic viability and must suspend discretionary energy uses, relying heavily on the most efficient system configurations. The risks intensify during prolonged high-price periods, especially for large facilities where thermal energy demand is significant.

A second scenario concerns temporary electricity interruptions. Estonia's partial reliance on interconnectors, the ongoing reconfiguration of grid synchronisation, and exposure to winter storms all create conditions in which short-duration outages could occur. In a RAS facility without redundant energy supply, the immediate effect is destabilisation of oxygenation and water circulation. Fish stress escalates within minutes, and mortalities can occur rapidly for species with high oxygen demand. The resilience of RAS under this scenario depends on the availability of on-site backup generation, autonomous fail-safe oxygenation and the use of thermal buffers within water volumes.

Longer interruptions lasting several hours demand a different resilience profile. Facilities must be able to decouple from the grid temporarily and maintain minimal circulation, temperature and oxygenation conditions through on-site systems. Without this, catastrophic stock losses occur. The scenario demonstrates that energy resilience in Estonia requires hybridised energy systems, grid redundancy, micro-grid capabilities and integration with industrial waste-heat sources that offer partial thermal stability even during grid fluctuations.

6.2 Feed-Supply Disruption and Feed-Cost Scenario

Feed represents the largest recurring material input into RAS and is sourced primarily through import-dependent international supply chains. A scenario involving disruption of feed shipments, caused by port delays, transport constraints, regional conflict, commodity shortages or export restrictions, rapidly impacts RAS operations. Fish cannot be left unfed for more than a short period without compromising health and growth rates, especially in highly controlled production cycles.

In the case of short-term feed unavailability, operators must ration existing feed stores, modifying growth expectations and adjusting feeding algorithms to maintain stock survival. However, sustained feed shortages render operations non-viable, as feed conversion ratios remain tightly linked to metabolic energy and waste-management balance. Under moderate disruption scenarios, limited availability of key ingredients such as fishmeal, soy protein or specialised lipid components also affects the nutritional balance required for optimal fish health, increasing stress and disease susceptibility.

A complementary scenario models a sharp increase in feed prices due to global commodity instability. RAS operations must then absorb significantly higher input costs, increasing production costs and reducing competitiveness unless domestic markets can absorb price increases. These conditions reveal the importance of localised feed blending, diversification of feed suppliers, integration with Baltic pelagic raw materials, and development of alternative-protein streams integrated into RAS-associated circular systems.

6.3. Juvenile-Supply and Broodstock Instability Scenario

Sadly, Estonia currently lacks large-scale domestic hatchery and broodstock capacity for salmonids and other high-demand species, relying instead on imports from Nordic and Baltic suppliers. A scenario involving border delays, veterinary restrictions, disease outbreaks in exporting countries or transport disruptions has immediate effects on RAS continuity. Without juvenile inflow, the production cycle becomes uneven, leading to empty grow-out tanks and underutilised infrastructure.

Short-cycle interruptions create scheduling inefficiencies and revenue delays. Extended disruptions compromise year-round production stability, which is a core advantage of RAS. Variability in juvenile supply also introduces biological risks, as operators may be forced to accept alternative genetic lines, sub-optimal sizes or less rigorously screened batches. The resilience of RAS in this scenario depends on domestic hatchery development, regional broodstock partnerships and diversification of cross-border supply chains. Figure 8 illustrates the inherent biosecurity and economic risks associated with relying on cross-border supply chains for critical RAS inputs.

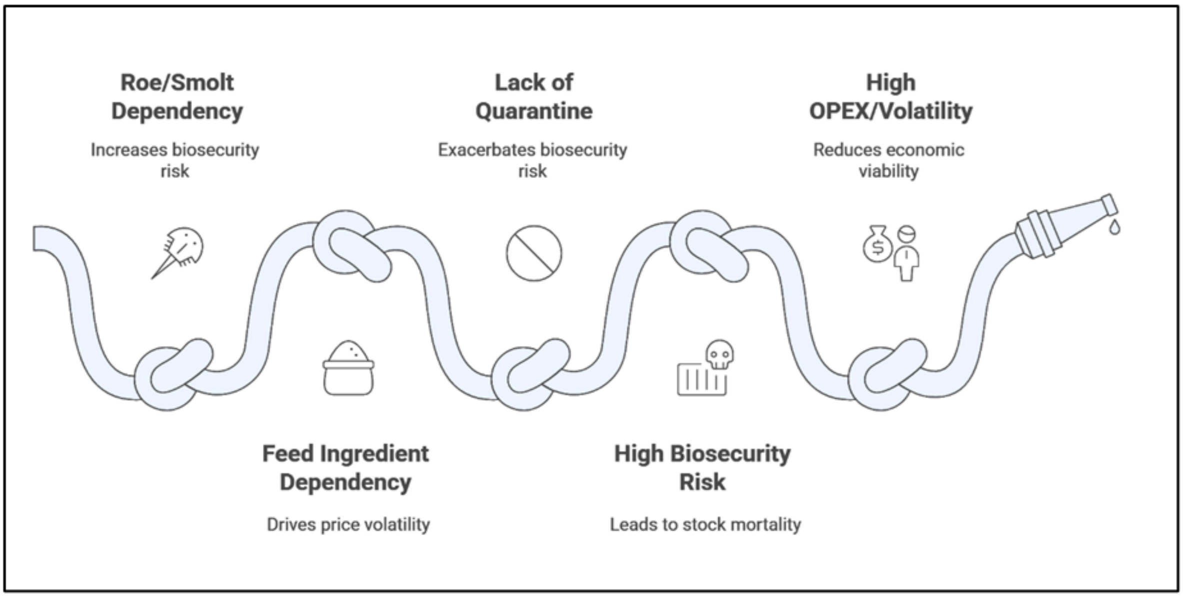

Figure 8: *RAS input supply chain: biosecurity and economic risk pathway.*

6.4 Equipment Failure and Technological Malfunction Scenario

RAS depends on a tightly orchestrated series of mechanical and digital systems. Scenario modelling of equipment failure, whether in pumps, biofilters, oxygenation units, heat exchangers or sensor networks, reveals that certain failures rapidly cascade into systemic disruption. A malfunction in one recirculation pump can lead to uneven water distribution, altered biofilter loading and increased metabolic waste. Failure in oxygen delivery or degassing systems can cause acute fish stress

Technological malfunction extends beyond hardware. Sensor failures or corrupted digital control logic can produce inaccurate readings, causing operators to misestimate oxygen saturation, pH fluctuations or nitrification efficiency. Automated dosing or alarm systems that fail silently amplify the risk. Estonia's increasingly digitised environment offers strong capabilities in cybersecurity and automation, but also increases exposure to cyber disruptions or control-system instabilities. These scenarios illustrate the need for mechanical redundancy, local manual override capacity, real-time monitoring with backup sensors and regular stress testing of digital control pathways.

6.5 Logistics and Cold-Chain Disruption Scenario

The cold chain is one of the most sensitive external systems upon which RAS depends, particularly for outbound fresh-fish distribution and inbound temperature-controlled inputs.

Scenario models that incorporate road closures due to snowstorms, maritime delays, border queue escalation, or regional rail disruptions reveal that even short-term cold-chain instability can compromise product freshness and market reliability.

For inbound logistics, delays in receiving oxygen cylinders, packaging materials or disinfection agents can throttle production. For outbound logistics, interruptions can cause unsellable stock, contract penalties or forced processing at reduced value. These scenarios reflect the need for diversified logistics partnerships, enhanced storage buffers, regionally redundant distribution hubs and improved domestic processing capacity.

6.6 Environmental and Climate Stress Scenario

Environmental scenarios centre on changes in water availability, temperature extremes, and ecological shocks. In cold winters, RAS facilities require intensive heating to maintain species-appropriate temperatures. If climate variability intensifies, more frequent cold snaps or heatwaves may strain thermal-regulation systems. Extreme rainfall events may influence abstraction points, while drought cycles could tighten regulatory limits on water intake.

In some cases, regulatory responses to environmental shifts may also restrict discharge conditions, introduce new water-quality thresholds or impose additional monitoring obligations. These factors can affect operational sustainability if not anticipated. The scenario modelling shows that resilient RAS facilities require flexible treatment capacity, adaptable thermal-management configurations and diversified water-abstraction options.

6.7 Regulatory and Policy Instability Scenarios

The regulatory environment governing aquaculture, water abstraction, discharge, sludge management, energy use and industrial integration is evolving in Estonia and the broader EU. A scenario involving accelerated tightening of nutrient-discharge standards would require upgrades in filtration and denitrification capacity. A scenario involving increased carbon-pricing regimes would raise operational energy costs unless mitigated by renewable integration or industrial symbiosis.

RAS must also anticipate changes in zoning, permitting, water-use rules, and environmental-impact assessment procedures. Regulatory shifts that affect feed ingredients, cross-border movement of juveniles, or biosecurity requirements also carry operational implications. These scenarios underline the importance of compliance planning, regulatory foresight and strong engagement with institutional actors.

6.8 Integration of Scenario Findings: System Thresholds and Structural Risks

Assessment across all scenarios reveals several structural risks that define the thresholds of RAS resilience in Estonia. Energy dependency emerges as the central pivot, with thermal and electrical stability being indispensable for continuous operation. Feed and juvenile supply present the most significant external vulnerabilities, while equipment redundancy and robust digital-control infrastructure represent internal determinants of resilience. Logistics and environmental variability create additional layers of complexity that RAS must navigate.

The scenarios collectively show that RAS can maintain continuity under moderate shocks but becomes vulnerable when multiple stressors coincide. For example, a feed-cost spike combined with an energy-price surge, or a logistics disruption occurring simultaneously with equipment malfunction. The integrated analysis demonstrates that resilience is not solely dependent on technological robustness but also on strategic design choices, supply-chain architecture, location-specific advantages and broader infrastructural integration.

6.9 Mitigation Pathways

The mitigation pathways that arise from the expanded scenario analysis emphasise structural, operational and policy-aligned measures. These include the establishment of hybrid renewable-industrial energy systems; development of domestic hatchery and broodstock capacity; diversification of feed sources and growth of local processing; strategic stockpiling of key inputs; enhancement of redundancy in critical technological systems; investment in cyber-secure automation; strengthening of domestic cold-chain infrastructure; and refinement of regulatory frameworks to support resilient, circular, and industrial-integrated RAS developments.

Collectively, these pathways enable RAS facilities in Estonia to operate with significantly higher resilience while reinforcing sustainability outcomes through efficient resource use, minimised waste, and reduced external dependency. Under such conditions, RAS is positioned to contribute meaningfully to the stabilisation of national fresh-fish supply chains and support the broader transition toward a circular and resilient food-production architecture.

Chapter Seven

Germany as a Reference Model for Cold-Chain Complexity

Germany possesses one of the most advanced refrigerated-logistics systems in Europe. Its structure illustrates the technical and operational requirements of a high-capacity cold chain capable of moving millions of tonnes of perishables annually. This provides a useful comparative lens for understanding the scale of infrastructure, redundancy, monitoring, and regulatory discipline required for resilient food logistics.

The German cold-chain system includes:

- Large manufacturers of temperature-sensitive goods (meat, dairy, fish, pharmaceuticals)
- Specialised logistics service providers with automated cold warehouses
- Nationwide fleets of refrigerated vehicles (30,000–40,000 units)
- Multimodal transport using road, rail, air and intermodal hubs
- Advanced IoT-based monitoring and HACCP-compliant processes

This system underpins a refrigerated-logistics market valued at roughly €20 billion, handling over 10 million tonnes of temperature-sensitive goods each year. Such scale and redundancy enable stability, flexibility and high throughput which are conditions that Estonia currently lacks.

7.1 Structure, Capacity and Sectoral Dynamics of Refrigerated Logistics

Refrigerated logistics in Germany is a critical infrastructure element within the national food and pharmaceutical supply chains. It enables the safe storage, handling and movement of perishable and temperature-sensitive goods such as fresh and processed food, pharmaceuticals, biologics and selected chemicals. The sector is characterised by a diverse set of actors, a technologically sophisticated asset base and a dense network of regulatory and quality requirements. As consumer expectations for freshness and convenience rise, and as the share of temperature-controlled goods continues to increase, refrigerated logistics has evolved into one of the most demanding segments of Germany's transport and supply-chain system.

1. Core Actors in the Refrigerated Logistics Sector

Refrigerated logistics involves several interdependent actors who collectively maintain the continuity of the cold chain from primary production to the end user.

Manufacturers form the starting point of the refrigerated chain. They produce temperature-sensitive goods such as dairy products, meat, fish, ready-to-eat meals, fresh convenience items, pharmaceuticals and biologics. Production schedules are designed around the availability of cold-chain capacity so that goods can be transferred into controlled environments immediately after processing. Any delay at this stage can reduce shelf life and compromise food safety or product efficacy.

Logistics service providers operate cold-storage warehouses, cross-docking platforms, distribution centres and temperature-controlled fulfilment hubs. They manage long-term storage, consolidation and redistribution for regional and national markets. Their operations increasingly rely on digital tools such as warehouse-management systems, automated storage-and-retrieval equipment, real-time temperature tracking and predictive maintenance for refrigeration assets. In many cases they act as integrators, coordinating multiple transport operators and aligning capacities with downstream retail requirements.

Retailers, including supermarkets, discount chains, specialist food stores and online grocery platforms, depend on reliable refrigerated logistics to maintain the quality and safety of products presented to consumers. They require precise delivery windows and strict temperature compliance to meet shelf-life targets, reduce food waste and comply with food-safety regulations. Retailers often impose their own quality specifications on logistics providers, adding an additional layer of control and documentation.

Transport service providers constitute the mobile backbone of refrigerated distribution. Fleet operators deploy refrigerated trucks, semi-trailers, rigid vehicles, vans and specialised pharmaceutical-grade vehicles to move goods between production sites, warehouses, distribution centres and retail outlets. Their performance is decisive for maintaining temperature integrity along the chain: delays, equipment failures or poor loading practices can result in immediate product losses.

Together, these actors form a tightly coordinated ecosystem in which failures in storage, transport or handling at any stage can have direct consequences for food quality, safety and economic value.

2. Logistics Processes Within the Cold Chain

A. Storage

Cold-storage facilities are the fixed nodes of refrigerated logistics. They are equipped with high-efficiency refrigeration and insulation systems designed to maintain constant temperatures under varying load conditions, frequent door openings and peak-season throughput. Facilities are typically located close to production plants, major ports, large urban markets or strategic transport corridors to minimise transit times and associated energy consumption.

Modern warehouses often feature:

1. Zoned temperature areas for deep-frozen, chilled and temperate goods.
2. Automated storage-and-retrieval systems that reduce handling times and limit door-open durations.
3. Integrated temperature and humidity monitoring, with alarm systems for deviations.
4. Rapid-closing insulated dock doors and air curtains that reduce thermal ingress during loading and unloading.

These sites are essential not only for short-term buffering but also for seasonal storage and for balancing fluctuations between production and demand.

<u>Transport:</u> Transport operations represent the most vulnerable part of the cold chain, as goods are exposed to external conditions and subject to potential delays. Refrigerated vehicles are specially insulated and equipped with independent cooling units capable of maintaining setpoint temperatures throughout the journey, whether for frozen, chilled or controlled-ambient conditions.

Road transport is the dominant mode due to its flexibility, dense network coverage and ability to service both full loads and smaller consignments. Heavy trucks are used for national and international flows, while medium-sized vehicles and vans serve regional and last-mile distribution. Rail transport plays a role in high-volume or long-distance flows, particularly when integrated into intermodal chains that combine rail with road for final delivery. Air freight is deployed for particularly time-critical and high-value shipments, such as premium fresh seafood, exotic fruits or biopharmaceuticals with very tight stability windows.

For each mode, maintaining load integrity requires careful pre-cooling of vehicles, correct stacking and air-circulation patterns, and strict control of dwell times at terminals and loading docks.

Distribution: Distribution networks ensure that goods reach retailers and, increasingly, end consumers while maintaining cold-chain continuity. Multi-step distribution is common: products move from production facilities to regional cold stores, then to urban distribution centres and finally to local outlets or consumer addresses. Each interface is a potential risk point for temperature deviations. Operationally, efficient distribution requires:

1. Coordinated scheduling to minimise waiting times at loading bays.
2. Clear procedures for mixed loads with different temperature requirements.
3. Standardised handling protocols for cross-docking operations.
4. Continuous monitoring and documentation of temperature conditions for quality control and liability management.

3. Technologies, Standards and Regulatory Compliance

The technical backbone of refrigerated logistics consists of refrigeration technology, monitoring solutions and quality-management systems.

Temperature-monitoring technologies increasingly use networked sensors, telematics and real-time data transmission. Data loggers positioned in trailers, storage areas and even pallets provide continuous information on the thermal environment. Deviations from the prescribed range trigger alerts, allowing operators to intervene quickly. These data sets also serve as evidence for contractual compliance and as a basis for process optimisation.

Quality standards play a central role in the design and operation of cold chains. The Hazard Analysis and Critical Control Points (HACCP) framework is widely used for food-safety risk management, identifying critical points where contamination or temperature abuse could occur and defining mitigation measures. For pharmaceuticals, Good Distribution Practice (GDP) imposes additional requirements for validated equipment, calibration routines, documentation of handling steps and segregation of temperature-sensitive products.

Environmental and safety regulations further influence system design. European regulations on fluorinated gases and energy efficiency drive the adoption of low-global-warming-potential refrigerants, high-efficiency compressors, variable-speed drives and improved insulation.

Operators are increasingly investing in alternative refrigerants such as CO_2 or ammonia systems, especially in large cold stores.

4. Challenges Facing Refrigerated Logistics

The refrigerated-logistics sector faces three overarching challenges: sustainability, cost pressure and regulatory intensity.

From a sustainability perspective, refrigeration is energy-intensive. Cold stores and refrigerated vehicles are significant electricity consumers, and many facilities operate around the clock. Rising expectations for climate-neutral operations and corporate decarbonisation commitments are pushing operators to adopt energy-efficient equipment, integrate renewable electricity (for example via rooftop photovoltaics) and use waste-heat recovery where feasible.

Cost pressures are closely linked to energy prices and capital expenditure for advanced equipment. Maintaining temperature integrity requires a continuous energy input and regular maintenance of compressors, evaporators, condensers and control systems. Skilled technicians are needed to manage refrigerants and perform repairs, adding labour costs. Logistics providers must balance these costs with competitive pressure from shippers and retailers trying to minimise logistics expenses.

Regulatory compliance is becoming more demanding as EU and national regulations evolve in areas such as food safety, greenhouse-gas emissions, vehicle standards and working time. Each regulatory shift may require investments in new equipment, additional documentation or revised operating procedures.

Despite these challenges, the sector continues to grow, driven by consumer demand for fresh products, expansion of online grocery services and a broader shift toward temperature-sensitive pharmaceuticals and biologics.

5. Volume and Vehicle Structure in German Refrigerated Logistics

Refrigerated logistics is substantial in both economic and physical terms. The sector's market volume in Germany is estimated at about 20 billion euros when storage, transport and distribution activities for food, pharmaceuticals and other temperature-controlled goods are combined. Annually, around 10 million tonnes of temperature-sensitive products move through German cold-chain networks, illustrating its strategic significance.

The vehicle fleet used for refrigerated transport comprises an estimated 30,000 to 40,000 refrigerated vehicles. This fleet is heterogeneous:

1. Long-haul refrigerated trucks and articulated vehicles for national and international routes.
2. Medium-sized vehicles for regional distribution to warehouses and retail platforms.
3. Smaller vans and light commercial vehicles for urban last-mile services and specialised deliveries such as home-delivery groceries.
4. Specialised vehicles equipped for pharmaceutical transport, with tighter tolerances, redundant cooling units and validated monitoring systems.

Sector trends indicate continued growth in vehicle numbers and technology sophistication. The rise of e-commerce and home-delivery services increases demand for smaller temperature-controlled vehicles. At the same time, digitalisation of fleets through telematics, remote diagnostics and automated reporting improves utilisation and compliance management.

7.2 Logistics of Fish Products in Germany

Fish-product logistics is a highly specialised sub-segment of refrigerated logistics, with particularly stringent requirements for temperature control, hygiene and traceability. Both fresh and frozen products are handled, each with distinct temperature ranges and shelf-life characteristics.

1. Key Actors and Product Flow

The chain begins with fisheries and aquaculture producers that land or harvest fish. Immediately after capture, fish must be chilled or frozen to arrest microbial growth and maintain sensory quality. Primary processing facilities located near landing sites or aquaculture clusters convert raw fish into fillets, gutted whole fish, smoked products, marinated goods, canned products or frozen portions. The speed with which products move from landing to primary chilling and processing is a critical determinant of final quality.

Cold-chain logistics providers then take over, offering refrigerated storage and transport capacity. They use high-performance refrigeration equipment and rapid handling processes to minimise time spent outside controlled environments. Retailers, including supermarkets, fishmongers and online seafood platforms, rely on these logistics services to maintain product quality until the point of sale. In some cases, foodservice operators such as restaurants and caterers are supplied directly from specialised fish wholesalers.

2. Technical Requirements for Fish Handling

Fish is one of the most perishable animal proteins. Frozen fish is generally stored and transported at −18 °C or lower to maintain texture and prevent rancidity. Fresh fish must be maintained in a narrow temperature band around the melting point of ice, typically 0–4 °C, often using flake ice or slurry ice in insulated containers. Deviations above these ranges can rapidly degrade quality, leading to off-odours, texture breakdown and potential safety hazards.

Transport operations for fish products commonly rely on road transport for domestic flows. Temperature-controlled trucks move products from processors to cold stores, from cold stores to distribution hubs, and from there to retail points. Air freight is employed for high-value or ultra-fresh products such as sashimi-grade tuna or fresh salmon flown from producing regions to German hubs, where they are rapidly transferred into refrigerated onward distribution.

Strict handling protocols govern loading, stacking and unloading to minimise physical damage and temperature fluctuations. Time–temperature integration is critical; even short periods of overheating can significantly shorten remaining shelf life.

3. Challenges

The short biological shelf life of fresh fish means that cold-chain integrity is non-negotiable. Any break in the cold chain can result in spoilage, histamine formation in certain species, or increased bacterial load. Regulatory frameworks place particular emphasis on hygiene controls, species identification, labelling, origin certification and traceability from source to consumer.

From a sustainability perspective, logistics operators face the dual task of ensuring stringent cold-chain control while reducing carbon intensity. This has driven interest in energy-efficient refrigeration systems, optimised routing, consolidated shipments and hybrid or alternative-fuel vehicles, especially on high-frequency routes.

Technological developments support these requirements. Temperature logging, RFID-based tracking, integrated logistics platforms and, in some cases, blockchain-enabled traceability systems are increasingly adopted to provide end-to-end visibility and document compliance.

4. Volume of Transported Fish Products

The transport volume associated with fish products in Germany is substantial and reflects both domestic consumption and Germany's role as a trading hub within Europe.

<u>Transport Volume:</u> On an annual basis, approximately 1.5 million tonnes of fish and fish products are transported within Germany. This figure includes fresh, chilled and processed forms such as smoked, canned and frozen products. The economic weight of fish and seafood is significant, with the national fish and seafood market estimated at around 3 billion euros.

<u>Volume Distribution:</u> Transport volumes can be broadly divided into fresh and frozen segments:

1. Fresh products account for a considerable share of transport, because they need to reach markets rapidly to preserve quality. These flows are often aligned with daily or multi-day delivery cycles to wholesale markets, fishmongers and retail outlets.
2. Frozen products represent another large share. Their extended shelf life allows for larger, less frequent shipments and storage in central frozen warehouses. Bulk flows of frozen fish are common in both import and export directions, with national distribution from a limited number of major hubs.

5. Trends and Developments

Demand for fish products is growing, particularly for sustainably sourced or organically certified options. This trend drives higher volume requirements for specialised cold-chain services. The expansion of online food commerce, including direct-to-consumer seafood delivery, further increases the number of temperature-controlled consignments, especially in the last-mile domain.

The combination of higher volumes, more demanding quality standards and the need for distribution flexibility makes fish logistics a demanding segment in planning, technology and capacity management.

6. International Fish Consumption Patterns

Fish consumption varies widely between countries, reflecting cultural preferences, geographical access to marine resources and the structure of national diets.

Countries with Above-Average Fish Consumption: The Table 6 below summarises selected countries with high per-capita fish consumption:

Table 6: *Countries with high per-capita fish consumption.*

Country	Annual fish consumption per capita (kg)	Special features
Iceland	80	Very high consumption, strong focus on cod and salmon
Norway	25–30	High-quality salmon and other seafood products
Denmark	25–30	Popularity of herring and other traditional species
Sweden	25	Long tradition of herring and preserved fish dishes
Finland	20–25	Consumption of freshwater species and marine fish
Estonia	15–20	Traditional emphasis on herring and Baltic species
Lithuania	15–20	Fish forms part of national dishes, often preserved
Latvia	15–20	Strong demand for smoked fish products
Poland	10–15	Fish used in specific regional and festive dishes

Cultural factors play a central role in these consumption patterns. In many of these countries, fish has historically been a primary protein source, embedded in traditional recipes and social eating habits. Geographical proximity to productive fishing grounds or aquaculture areas increases the availability of fresh fish and reinforces consumption. In some cases, sustainability objectives also shape behaviour, as in Norway and Japan, where management regimes and certification schemes support long-term resource protection.

Fish Consumption in Baltic Sea Countries:Fish consumption levels across Baltic Sea countries differ according to cultural traditions, economic factors and the availability of local fish resources.

Ranking by Per-Capita Consumption: Earlier Table (6) provides a comparative view of annual per-capita fish consumption in selected Baltic Sea countries. These figures show a clear gradient: Nordic countries with strong fishing traditions tend to have higher consumption levels, while some coastal states around the southern Baltic have more modest but still significant fish intake. Consumption is also influenced by income levels, price structures, and the availability of alternative protein sources such as meat and poultry.

7.3. Fish Consumption in Germany

In Germany, fish represents an important but not dominant component of the diet.

Per-Capita Consumption: Annual per-capita fish consumption in Germany is approximately 13–15 kg. This includes both fresh and processed forms such as frozen fish, smoked products, canned fish and ready-to-eat formulations. In European comparison, Germany occupies a mid-range position: consumption is lower than in southern European countries such as Portugal or Spain, but higher than in some Central and Eastern European markets.

Consumer Trends: Several trends shape consumption:

1. Commonly consumed species include herring, salmon, tuna and cod, reflecting a mix of domestic tradition and global supply chains.
2. Processed products, especially fish fingers, canned tuna, marinated herring and smoked salmon, account for a significant share of total fish intake. These products fit well with convenience-oriented consumption patterns.
3. Awareness of sustainable fishing and aquaculture has increased, driving demand for eco-labels and certification marks. Consumers increasingly look for information on origin, stock status and production methods.

7.4. Price Levels for Fish Products

Price levels vary considerably across countries and product types, reflecting resource availability, production costs, supply-chain structures and consumer purchasing power.

Price Level in Baltic Sea Countries: An overview of typical average retail prices per kilogram for fish products in Baltic Sea countries is shown below (Table 7):

Table 7: *Average retail prices per kilogram for fish products in Baltic Sea Countries*

Country	Average price of fish products (EUR/kg)	Special features
Norway	15–25	High quality and export orientation, especially salmon
Denmark	10–20	Strong focus on herring and cod
Sweden	10–20	Robust demand for traditional fish products
Finland	8–15	Broad availability of freshwater fish
Estonia	7–12	Competitive prices for local species such as herring
Lithuania	6–10	Many preserved and canned products
Latvia	6–10	High demand for smoked fish
Poland	5–10	Affordable prices in supermarkets and discount stores
Iceland	20–30	Higher price level due to export quality and logistics

Seasonal fluctuations can be significant. During peak fishing seasons, prices for certain species may decrease due to higher availability, while off-season imports can increase average price levels. Products from certified sustainable fisheries or premium aquaculture operations may command higher prices.

Price Levels for Fish Products in Germany: Germany exhibits a wide price range across species and product forms, as illustrated in the following Table 8:

Table 8: Price range across species and product forms

Fish species / product	Average price (EUR/kg)	Special features
Fresh salmon	20–30	High demand, predominantly from aquaculture
Cod	15–25	Prices depend on fishing area and processing method
Herring	5–10	Lower-priced, often sold in canned or marinated form
Fresh tuna	25–40	High price, especially for sushi-grade quality
Fish fingers	8–15	Processed, mass-market convenience product
Peeled shrimp	15–25	Sensitive to origin and certification
Smoked fish	15–30	Higher price due to processing and added value
Canned fish (e.g. tuna)	3–6	Low-cost, long-shelf-life products

Seasonal availability, sustainability labels and point of sale all influence final retail prices. Fresh fish is often more expensive at specialised fishmongers than in supermarkets. Certified sustainable or organic products tend to carry price premiums, reflecting additional production and verification costs.

Refrigerated logistics in Germany underpins both national food security and the availability of a broad portfolio of temperature-sensitive products. It integrates a range of actors and processes, from cold-storage and transport operations to highly specialised segments such as fish-product logistics. The sector operates under stringent quality, safety and environmental requirements while simultaneously responding to rising demand, evolving consumption patterns and increasing sustainability expectations.

Within this landscape, fish logistics represents one of the most demanding applications of cold-chain technology, given the extreme perishability of fresh fish, strict temperature regimes and the need for robust traceability. Understanding structures, volumes, consumption patterns and price levels helps identify where investments in infrastructure, technology and governance are most needed to support both economic efficiency and long-term resource sustainability.

Chapter Eight

Case of the Use of Big Data Analytics in Market Adaptation of the Norwegian Salmon Industry: A Perspective on Dynamic Production Management Under Market Volatility

The Norwegian salmon industry provides a structural lens through which the digital transformation of each stage of the RAS value chain, ranging from research and system design to production, processing, and distribution is able to generate a continuous flow of biological, environmental, and operational data. In Norway, where salmon producers operate in a highly volatile global market, these data streams underpin the development of Big Data Analytics systems that enable producers to stabilise output, anticipate market fluctuations, and optimise production decisions. Thus, the value chain forms the operational backbone for the collection, interpretation, and utilisation of large-scale datasets.

Dynamic production management, a central theme of the Norwegian case, is tightly linked to critical value-chain components such as feeding optimisation, fish health monitoring, biomass estimation, processing scheduling, and logistics coordination. In RAS and sea-cage systems alike, sensors and automated systems continuously capture information on water quality, fish behaviour, growth trajectories, and feed utilisation. Norwegian salmon companies integrate these datasets with external information like export prices, transport costs, weather patterns, and weekly demand signals to adjust feeding intensity, harvest timing, and market allocation. This demonstrates a direct functional correlation: the structure and technological requirements of the aquaculture value chain determine the points at which Big Data analytics can influence operational choices.

Moreover, the downstream stages of the value chain i.e. processing, branding, and distribution are central to how Norwegian producers mitigate market volatility. Accurate forecasting of biomass, quality attributes, and processing capacity supports flexible harvest planning that aligns with price movements and logistics availability. Market analytics, often powered by machine learning and real-time trade data, guide decisions on whether to sell fresh, frozen, whole, or processed products depending on evolving global conditions. The value chain therefore acts as the interface between biological production and market reality, enabling data-driven responsiveness throughout the production cycle.

The emphasis on sustainability and customer assurance at the end of the value chain closely aligns with Norway's reliance on traceability systems and ESG reporting. Big Data supports these functions by aggregating information on inputs, animal health, environmental performance, and product movement, which strengthens market access and consumer trust. In this sense, the structure of the value chain not only facilitates operational optimisation but also shapes the strategic use of data to adapt to regulatory expectations and shifting market preferences. The Norwegian salmon industry illustrates how a technologically integrated value chain allows Big Data analytics to transform production stability and competitive advantage under volatility.

In a nutshell, the implementation of advanced big data analytics systems in the Norwegian salmon industry, with a focus on adaptive production management strategies in response to market fluctuations. The study highlights the correlation between predictive analytics and business model flexibility, contributing to the sector's economic stability amid unpredictable global events. Using data from the European market and case studies, the report documents Norwegian salmon producers' ability to dynamically modify their value chain and product strategy in response to changing macroeconomic conditions.

8.1. Analytical Methodology in Salmon Production Management

A. Predictive Analytics in Production Planning

The Norwegian aquaculture sector uses advanced analytical models to forecast long-term market trends, which is crucial given the 5–6-year production cycle from planning to market launch. Predictive systems enable strategic decisions regarding resource allocation and product diversification.

B. Multidimensional Market Data Analysis

Analytical systems in the Norwegian salmon industry integrate heterogeneous data sources, including:

1. Historical price trends of raw materials and final products
2. Meteorological and oceanographic data affecting farming conditions
3. Consumption patterns in target markets
4. Regulatory changes in key markets
5. Macroeconomic factors such as exchange rates and economic indicators

8.2 Adaptive Production Management Strategies

A. Flexible Product Portfolio Adjustments

Norwegian companies demonstrate the ability to dynamically adjust their product offerings in response to market conditions. Empirical studies document systematic shifts between product segments:

1. During periods of high prices for unprocessed fish (whole salmon) – focus on maximizing sales of low-processed products
2. During price drops of basic products – increase production of higher value-added items (boneless fillets, consumer-packaged products)
3. In case of disruptions in major markets – geographic diversification and expansion into alternative markets.

B. Adaptation to Changing Regulatory Conditions

The introduction of a natural resource tax in 2023 created significant challenges for the industry, leading to operational restructuring in many companies. Large farming enterprises transferred their biomass and licenses to separate entities, creating specialized units for operations subject to taxation.

8.3. Impact of Technology on Increasing Market Flexibility

A. Technological Innovations in Norwegian Aquaculture

The Norwegian aquaculture sector is increasingly diverse technologically, with emerging new production systems. Innovations in closed farming systems, land-based technologies, and coastal systems allow for greater control over the production process while reducing environmental risks associated with traditional farming methods.

B. Digitalization as a Catalyst for Market Flexibility

Aquaculture is still in the early stages of digitalization, with many operations relying on manual processes. However, the digital era presents a major opportunity for the sector to develop and implement new solutions tailored to its unique challenges. Artificial intelligence (AI) and advanced production technologies are seen as the next steps for aquaculture, driving improvements in fish welfare and sustainable development.

8.4. Case Analysis: Adaptation to Market Disruptions

A. Response to the Conflict in Ukraine

The closure of the Russian market due to the armed conflict in Ukraine posed a major challenge for the Norwegian salmon sector. Market response analysis revealed a multi-layered adaptation:

1. Rapid reconfiguration of distribution channels toward alternative markets
2. Modification of product structure to match preferences of new markets
3. Intensification of processing to extend the value chain and increase unit margins
4. Use of predictive analytics to identify new consumer segments

B. Price Competition from Alternative Protein Sources

In response to competitive pressure from cheaper protein alternatives (e.g., Turkish trout), the Norwegian salmon industry is implementing diversification and premium positioning strategies based on advanced analytics of consumer purchasing patterns.

8.5. Implications of Strategic Value of Big Data Analytics

The implementation of advanced analytical systems in the Norwegian salmon industry demonstrates a paradigm shift in agricultural production management, where traditional decision-making models are replaced by data-driven approaches. Benefits include:

1. Reduction of investment risk
2. Optimization of resource allocation
3. Increased adaptability to unpredictable market events
4. Stabilization of financial performance under market volatility

Despite clear advantages, the implementation of analytical systems faces challenges, including:

1. High initial costs related to infrastructure and expertise
2. Need to integrate heterogeneous data sources
3. Requirement to adapt business models to data-driven decision paradigms
4. Differences in adaptive capacity between large enterprises and SMEs

The Norwegian salmon industry exemplifies the transformative potential of big data analytics in the food production sector. Empirically documented adaptability in the face of changing market conditions highlights the value of implementing advanced analytical systems for long-term economic stability.

Record-breaking revenues achieved in recent years, despite global economic disruptions, confirm the effectiveness of data-driven strategies. At the same time, the observed divergence between large entities and SMEs in terms of technological adaptation points to the need for dedicated initiatives supporting the digital transformation of smaller enterprises to maintain the competitiveness of the entire sector.

Chapter Nine

Recommendations

The evaluation of sustainability and resilience across RAS technologies, operational systems and supporting supply chains indicates that Estonia possesses a strong opportunity to establish a stable, environmentally compatible and strategically significant aquaculture capacity, provided that key technological, infrastructural and governance conditions are addressed systematically. The recommendations in this chapter translate the analytical findings into actionable directions, identifying the structural investments, operational priorities, institutional adjustments and supply-chain interventions needed for RAS to function as a reliable component of Estonia's food-production architecture. The analysis shows that the country's northern climate, industrial legacy and energy-transition trajectory create conditions that are both supportive and constraining. RAS offers meaningful advantages only when embedded within robust energy systems, diversified supply chains and well-coordinated regulatory frameworks. This chapter therefore integrates technical and non-technical recommendations and outlines the overarching conclusions derived from the assessment.

9.1 Infrastructure, Engineering and System Design

Ensuring the long-term reliability of RAS installations in Estonia requires strengthening the engineering and infrastructural foundations of the systems in ways that both reduce environmental burdens and enhance resilience to operational disturbances. Technical measures must prioritise energy configuration, water-treatment capability, redundancy within critical components and the circular handling of nutrient and waste flows. These technical areas represent the core determinants of continuous operation, especially during climatic extremes or external supply interruptions.

The first priority concerns the stabilisation and diversification of energy supply. RAS systems must be designed with integrated thermal-energy solutions that reduce exposure to electric heating loads during winter. Industrial symbiosis with the Auvere energy complex, or comparable sources of recovery heat, provides one of the strongest pathways toward energy sustainability. Such integration requires engineering linkages between RAS water-heating loops and available low-grade heat streams. In parallel, electrical redundancy through dual-feed arrangements, localised transformers and emergency generator capacity ensures continuity during grid disturbances. (figure placeholder: schematic of integrated electric and heat supply architecture)

The second technical priority involves advanced water-treatment configuration. High-efficiency mechanical filtration, biological nitrification systems sized for load variability, and multi-stage disinfection units enable stable water quality and compliance with discharge limits. Larger RAS facilities in the Estonian context must design their systems to accommodate fluctuations in ambient water-source temperature and seasonal turbidity, which influence treatment loads. Multi-stage treatment also supports biosecurity by reducing the probability of pathogen entry or proliferation.

A third area relates to internal redundancy. Estonia's energy and supply-chain vulnerabilities require that RAS installations embed duplicated or alternative subsystems for pumping, oxygenation and monitoring. Pump configurations should support automatic switchover modes in case of partial failure. Oxygenation systems must combine primary oxygen generation or storage with backup delivery routes. Digital monitoring and alarm systems require parallel communication channels and physical manual-override capability to maintain operation during cyber or system-control disturbances. Table 9 compares the current energy sourcing strategies relevant to RAS resilience in Estonia, highlighting the role of Industrial Symbiosis. Utilizing waste heat from industry minimizes the RAS temperature control costs, which is otherwise the highest operational expense. This symbiotic integration enhances system resilience by diversifying the heat source away from volatile electricity markets and aligning the project with circular economy principles. However, the reliability of this heat source remains intertwined with the uncertain future of the oil shale sector and investor demands for demonstrably green energy.

Table 9: Comparison of RAS energy sourcing strategies for resilience in Estonia.

Energy Strategy	Source Type	Resilience Benefit	Resilience Drawback	Relevance to Auvere Agropark
Grid Electricity (Fossil-based)	Centralized (Oil Shale, Gas)	High capacity and immediate availability (currently).	Geopolitical risk; High CO_2 footprint; Price volatility; Phase-out uncertainty.	Historically primary source; transitioning away.
Grid Electricity (Renewable)	Centralized/ Distributed (Wind, Solar)	Low carbon footprint; Aligns with EU/national climate goals.	Intermittency requiring dispatchable backup; Grid instability risks; Siting restrictions (Ida-Virumaa).	Essential for investor attractiveness; constrained by location and grid capacity.

Energy Strategy	Source Type	Resilience Benefit	Resilience Drawback	Relevance to Auvere Agropark
Industrial Symbiosis (Heat)	Waste heat (Auvere PP)	Reduces largest OPEX (heating 40-60%); Energy efficiency; Resource loop establishment.	Dependent on partner longevity (oil shale phase-out); Requires specialized thermal infrastructure.	Core design principle, essential for economic viability.
On-site Dispatchable Backup	Diesel/ Gas Generator, LOX	Guarantees operational continuity during shocks.	High fuel cost; Localized emissions; Requires routine maintenance and storage.	Mandatory minimum resilience requirement.

The last technical recommendation is the systematic incorporation of circular-resource handling. RAS sludge should be stabilised and processed for nutrient recovery through composting, digestion or co-utilisation with industrial by-products suited for soil production. Heat recovery, CO_2 capture for greenhouse integration, and the reuse of treated effluent as process water further strengthen sustainability performance and reduce operational exposure to resource price volatility. These measures reinforce the alignment between RAS and Estonia’s circular-economy objectives while promoting localised nutrient and energy loops in Ida-Viru’s transitioning industrial landscape.

9.2 Supply Chain and Input-System Recommendations

RAS viability in Estonia is strongly shaped by dependence on imported feed components, juveniles, specialised equipment and maintenance expertise. To reduce vulnerability to external disruptions and enhance systemic resilience, the supply chain must undergo deliberate restructuring. The first requirement is the development of domestic hatchery and broodstock capability. Local supply of high-quality juveniles reduces dependence on long-distance transport that is sensitive to border conditions, climatic disruptions and logistic bottlenecks. Establishing domestic hatcheries also supports biosecurity by allowing operators to maintain consistent quality standards and reduce the risks associated with transporting live fish across jurisdictions.

A second supply-chain priority is the diversification of feed sources. Reliance on a narrow set of international feed producers increases exposure to commodity volatility and logistical instability. Efforts to utilise regional pelagic fish for feed, incorporate insect or microbial protein, or establish small-scale domestic feed processing facilities help stabilise supply while reducing carbon intensity associated with long-distance transport. These developments require coordinated investment but offer long-term resilience gains.

Equipment and spare-parts availability also poses constraints in Estonia's remote northern context. Creating regional maintenance hubs, encouraging suppliers to stock critical components domestically and developing long-term service contracts with equipment manufacturers strengthens operational continuity. Reducing lead times for oxygen diffusers, pump impellers, UV components, sensors and control-system modules is essential for mitigating system downtime during component failures.

Finally, cold-chain distribution for fresh fish must be strengthened to ensure the marketability of RAS products. Enhancing domestic refrigerated-transport capacity, optimising regional distribution routes and improving storage nodes reduces losses and ensures that RAS output can reliably reach consumers even during external shocks.

9.3 Institutional, Regulatory and Governance Recommendations

Regulatory clarity, institutional coordination and stable permitting conditions are critical for supporting RAS expansion and for creating a predictable operating environment. Estonia's current regulatory frameworks for water abstraction, discharge, sludge handling and industrial symbiosis are dispersed across multiple authorities, creating fragmentation that increases uncertainty for investors. Strengthening regulatory integration begins with developing a coherent permitting protocol for RAS installations, outlining requirements for water use, discharge quality, thermal impacts, biosecurity measures and industrial co-location. Such guidelines should be harmonised at national level to reduce variation in interpretation between regions.

Governance resilience also requires establishing mechanisms that facilitate industrial symbiosis. For RAS facilities situated in industrial zones such as Auvere, coordination between energy producers, municipal land-use planners and environmental authorities should occur through structured partnership units capable of assessing and approving resource-exchange projects, such as waste-heat utilisation or CO_2 handling.

In addition to formal governance, the sector benefits from soft institutional measures such as expert networks, aquaculture innovation platforms and cross-sector working groups. These structures support knowledge exchange between operators, energy companies, researchers and regulators and accelerate the adoption of best practices. Estonia's small scale allows for rapid institutional learning if supported by the appropriate frameworks.

9.4 Strategic Inferences

The overarching deduction from the sustainability and resilience evaluation is that RAS can serve as a reliable, environmentally responsible and strategically valuable component of Estonia's aquaculture sector, but only when supported by targeted technical, infrastructural and institutional measures. Sustainability arises not simply from closed-loop water treatment but from the integration of RAS into efficient energy configurations, circular-resource flows and environmentally appropriate siting. Resilience emerges from redundancy in critical subsystems, diversified supply chains, robust governance frameworks and alignment with industrial clusters that enhance stability during shocks.

Ida-Viru County, particularly the Auvere industrial area, offers conditions that are favourable for large-scale RAS development. The availability of reclaimed industrial land, high-capacity energy infrastructure, substantial waste-heat resources and opportunities for symbiosis create an environment where RAS can achieve performance levels not achievable in isolated rural settings. These advantages, however, must be balanced against the region's exposure to geopolitical risks, dependency on cross-border logistics and ongoing energy-system transitions.

RAS presents Estonia with a viable pathway toward strengthening national food-security architecture while maintaining strict environmental safeguards. The technology is not without limitations, but these can be mitigated through strategic planning, system design refinement, supply-chain diversification and institutional coordination. If implemented within a coherent country-level development framework, RAS can contribute significantly to Estonia's transition toward resilient, low-impact and circular food-production systems.

Chapter Ten

Conclusions

The evaluation of sustainability and resilience across RAS technologies, RAS operational systems and RAS-related supply chains demonstrates that Estonia possesses the enabling environmental, infrastructural and industrial characteristics necessary to support advanced land-based aquaculture. However, the analysis also reveals structural vulnerabilities and systems-level dependencies that must be addressed for RAS to operate as a stable pillar of national food security.

10.1. Technical Issues

A. Strengthening Water and Effluent Systems

RAS facilities in Estonia require multi-stage treatment systems that meet strict temperature, nutrient and pathogen thresholds. To ensure long-term system stability, operators should implement advanced denitrification, biofiltration and disinfection processes capable of handling variable inflows and seasonal temperature gradients. Increasing the hydraulic redundancy of intake systems, diversifying abstraction points and incorporating automated monitoring technologies will reduce operational vulnerability. Facilities sited in the Auvere region benefit from consistent hydrological conditions, yet the integration of real-time water-quality controls remains essential.

B. Enhancing Energy Resilience and Thermal Integration

As RAS installations depend heavily on continuous electrical and thermal energy, a resilient configuration must include multi-source energy integration. In Ida-Viru, the availability of industrial waste heat and proximity to high-capacity substations provide opportunities for hybrid thermal strategies that balance heat recovery with insulated heat-pump systems. Incorporating on-site emergency generation, multi-point grid connections and localised storage improves continuity during external disturbances. Thermal-integration modelling indicates that coupling RAS with industrial cooling circuits is technically feasible, provided that the thermal load is matched to species-specific requirements.

C. Upgrading Automation and Control Infrastructure

RAS must rely on advanced automation systems to maintain oxygenation, pump flow, waste removal and thermal balance. To avoid single-point digital failures, operators should implement distributed sensor networks, redundant SCADA nodes and fail-safe fallback controls. The Estonian cyber-risk environment requires protective measures such as encrypted telemetry, isolated control channels and physical override mechanisms. Preventive maintenance of pumps, blowers, valves and drives should be scheduled through integrated diagnostic tools that anticipate failure modes before they threaten fish survival.

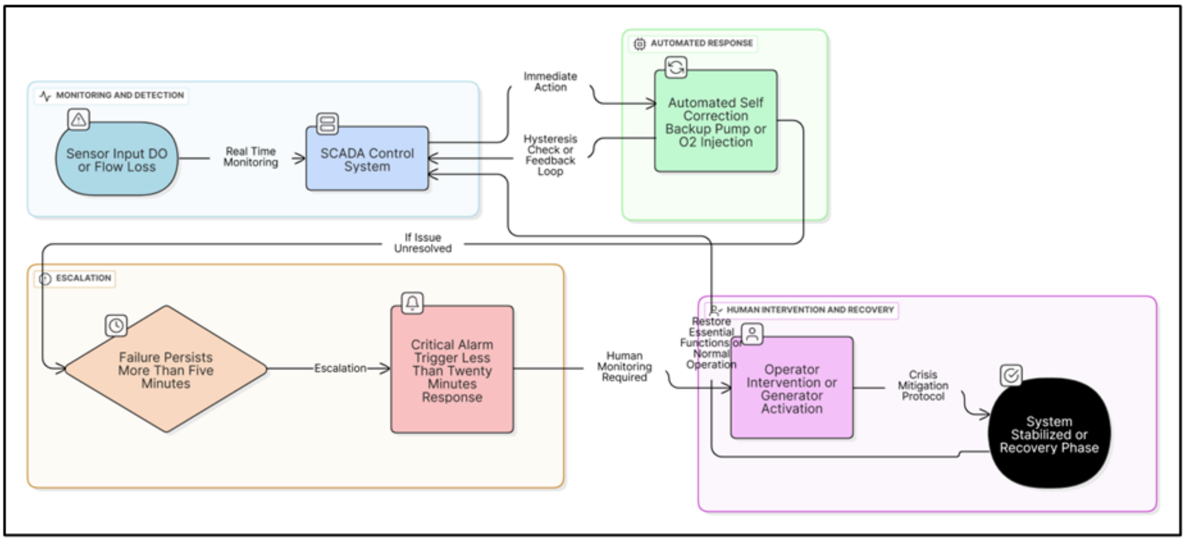

Figure 9: *Digital SCADA control hierarchy for crisis response.*

D. Developing Local Hatchery and Broodstock Capacity

The resilience analysis identifies the lack of domestic juvenile and broodstock supply as the most significant biological vulnerability. Establishing specialised hatchery capacity in Estonia reduces exposure to border delays, transport mortality and external sanitary conditions while also enabling genetic adaptation to local temperature profiles. Centralised hatchery nodes should incorporate advanced water-treatment lines compatible with RAS grow-out systems to allow for biosecurity harmonisation across the production chain.

E. Optimising Waste and Nutrient Flows

RAS sludge contains valuable nutrients suitable for anaerobic digestion, composting or fertiliser blending when properly treated. Sitings within industrial ecosystems such as Auvere create opportunities to integrate sludge streams with biofertiliser production and greenhouse operations. Technical optimisation requires dewatering stages, pathogen reduction and nutrient-quality stabilisation. Integrating such loops contributes directly to sustainability by reducing disposal volumes and improving nutrient recovery efficiencies shown in Figure 10

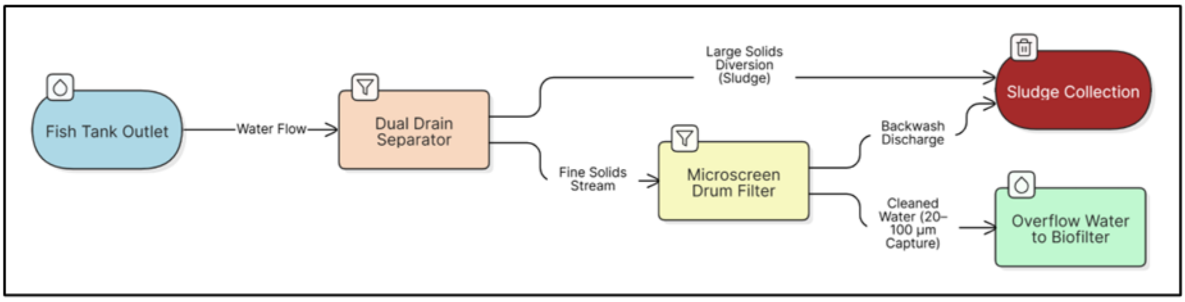

Figure 10. *Mechanical solids removal process in intensive RAS.*

10.2. Non-Technical Issues

A. Strengthening Regulatory Coordination

RAS development intersects with environmental permitting, industrial land-use regulation and aquatic biosecurity rules. Fragmentation across agencies increases lead times and introduces uncertainty for operators. Consolidating permitting pathways and developing dedicated RAS guidelines would reduce regulatory barriers. Estonia's digital governance capabilities enable the creation of a unified permitting interface where environmental, water and energy-relevant data are evaluated synchronously.

B. Positioning RAS Within National Food-Security Strategy

Given the structural import dependence of Estonia's fresh seafood supply, RAS installations should be recognised as strategic infrastructure. Integrating RAS into national food-security frameworks enables targeted investment support, clearer risk-management protocols and stronger inclusion in crisis-response planning. Establishing predefined response scenarios for energy shortages, supply-chain disruptions or disease outbreaks ensures that critical production capacity is preserved.

C. Enabling Industrial Symbiosis

The Ida-Viru region is undergoing economic transformation, and RAS can anchor industrial symbiosis clusters that combine heat reuse, water recovery, carbon-dioxide utilisation and circular nutrient flows. Non-technical support is required to formalise partnerships between energy operators, industrial tenants and municipal authorities. Creating shared-governance structures and standardised resource-exchange contracts will allow multiple actors to participate in coordinated value creation.

D. Supporting Regional Skill Development

RAS facilities require high technical competence in water engineering, biosecurity, process control and fish physiology. Establishing training modules, vocational programmes and collaborative research with regional institutions ensures the development of a skilled operational workforce. Localising maintenance expertise reduces downtime and strengthens resilience against global service disruptions.

E. Enhancing Supply-Chain Diversification

Resilient RAS operation depends on secure access to feed, specialised parts and oxygenation equipment. Estonia should promote diversification of suppliers across Nordic and Baltic markets and explore limited local production where feasible (e.g., mineral premixes, equipment assembly, oxygen production). Strategic stockholding at facility or regional level reduces vulnerability to shipping delays or border interruptions.

10.3. Integrated Conclusions

The evaluation conducted across preceding chapters demonstrates that RAS can become a cornerstone of Estonia's sustainable aquaculture sector when designed within the constraints and opportunities of the regional environment. Sustainability is achieved when RAS employs high-efficiency water and nutrient systems, integrates renewable or waste heat sources, and participates in circular-resource exchanges that minimise environmental emissions. Resilience is attainable when systems incorporate redundancy, diversified energy inputs, robust digital controls and stable supply-chain arrangements.

Estonia's unique industrial landscape, particularly in Ida-Viru, offers a rare alignment of reclaimed land availability, thermal energy integration potential, grid accessibility and emerging circular-economy infrastructure. These conditions create an enabling environment for high-capacity RAS operations, provided that regulatory coordination, workforce development and supply-chain stabilisation are strengthened in parallel.

Ultimately, RAS does not function as an isolated technological unit but as an infrastructural asset whose performance is shaped by water resources, energy networks, industrial ecosystems, governance systems and international supply flows. When these factors are strategically aligned, RAS can significantly reduce Estonia's reliance on imported fresh fish, strengthen food-system resilience, and contribute to the nation's broader economic and environmental transition.

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