A scoping study of the technical, regulatory, and economic challenges with respect to the development of the Recirculation Aquaculture System sector in England

Author(s): Keith Jeffery, Isla MacMillan, Paula Schiefer, Angela Muench, Ian Tew, Nicholas Stinton, Roland Albert.

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Project Manager:	Samuel Course
Report compiled by:	Keith Jeffery, Isla MacMillan, Paula Schiefer, Angela Muench, Ian Tew, Nick Stinton, Roland Albert.
Quality control by:	Simon Jennings
Approved by and date:	Samuel Course 28/04/2023
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Executive summary

Growth in Recirculation Aquaculture Systems (RAS) continues at pace globally. In England, RAS are currently limited to multiple small-scale operations and a few larger scale systems in early developmental stages.

Whilst RAS address many of the environmental concerns linked to other forms of aquaculture, new systems need to overcome energy challenges by dropping the energy use and cost per kilo of production. This may be achieved by use of alternate energy options, recapturing energy from waste, maximising internal efficiencies and locating RAS closer to markets to reduce carbon footprint. The efficiency of RAS in terms of spatial footprints and feed utilisation should be noted and further utilisation of Life Cycle Analysis (LCA) for emerging systems and hybrids would be beneficial to assess proposed RAS and compare efficiencies.

Operation of RAS relies on people with significant technical expertise, and skills gained in other aquaculture sectors are not fully transferable. Universities could play an increased role in solving technical challenges for the sector whilst providing graduate managers for the industry, both within England and globally.

A survey of English stakeholders revealed that the costs of establishing RAS were restricting the growth of RAS and the industry would benefit from increased financial support in R&D and early development stages through grants, tax reliefs or assistance via special development zones.

Without better incentives to invest in RAS, rapid growth in the English sector is not foreseen given economic challenges and the time to achieve a return on investment. However, establishing just 3 to 6 new farms, each producing 5 to 10 thousand tonnes per annum, could achieve the aspirations of the English aquaculture plan for producing 34,608 tonnes by 2040. This would require 20 to 30 hectares of land. RAS at this scale could produce fish as economically as open net systems, while also providing environmental benefits.

Growth of large-scale RAS would only require small areas of land, but these have proved difficult for developers to locate. Growth is anticipated on both brown field sites and on terrestrial farms, in situations where infrastructure, water supply and simplified licensing and permitting exists. Social acceptance of RAS is best achieved by early engagement with stakeholders and communities. Increased uptake of Partial RAS is anticipated by existing flow through trout farms, as this will mitigate climate change and low water flows in rivers.

Further growth in RAS for salmon (*Salmo salar*) and prawn (*Panaeus vannamei*) is most likely in England, because markets and demand for these species already exists. Producing species of lower value such as Tilapia (*Oreochromis niloticus*) or Catfish (*Clarias gariepinus)* may be economically challenging, but in the longer-term the culture of higher value fast-growing species such as yellowtail (*Seriola lalandi*), meagre (*Argyrosomus regius)* and grouper *(Epinephelus spp.)* may be viable with adequate hatcheries and supply lines.

Recommendations for government enabling actions to support sustainable development of RAS include workshops, and clarification with regulators, to address the following.

1. Clarification and updating of permitted development rights for modern RAS in England to help terrestrial farmers diversify and the provision of a set of guidelines on application for RAS development for prospective developers (as per Scotland).
2. Clarification and guidance on the ways in which environmental permitting applies to RAS, and in particular discharge consents.
3. Review of the barriers to importing prawn larvae into enclosed bio-secure RAS (considering existing Cefas risk assessments for listed prawn diseases and if government regulation via import restrictions are appropriate).
4. Clarification of hygiene rules applying to farming and processing areas to help both local authorities and operators to understand application of the rules and where separation occurs.

Other non-regulatory areas that may benefit from enabling actions include:

1. Further exploration of why RAS (a modern highly technical form of aquaculture) is excluded from enterprise zones and therefore from all the tax benefits and breaks that apply when locating to them.
2. Considering options for the most efficient food producing sectors, such as some forms of RAS, to be provided with additional or higher percentages of grant funding to support the transition towards renewables and net zero.
3. Encouragement for universities to develop engineering projects and work on technical and economic constraints for RAS sectors and the emerging semi-contained systems for deployment in deeper waters.
4. Development of a larger future workforce with a good knowledge of RAS operations, to be explored with leading educational facilities.
5. Semi-structured interviews within RAS facilities to deliver more information on non-technical barriers within the industry.
6. Research within communities of (possible) RAS facilities, to identify ways in which facilities can be built with the support of local inhabitants.

In summary, continued investment and growth in the English RAS sector is expected, despite a currently difficult economic climate. Lessons learnt and increasing knowledge and experience will reduce historic rates of business failure and the relatively low appetite for investment in England. Given the potential of RAS to increase food security while minimising the environmental impacts of production, Government and regulators may wish to address recognised barriers to growth by adopting risk-based approaches to health, hygiene, permitting and planning.

1. Introduction

There is an estimated need to increase the global protein supply from about 200 million tonnes meat and seafood to nearly 500 million tonnes by 2050 (FAO, 2020). Seafood, particularly from aquaculture, is expected to contribute significantly to meeting this need. Considering the FAO's estimates of average annual seafood consumption, the predicted demand for fish for human consumption would almost double to at least 220 million tonnes in 2050, with aquaculture expected to provide over 70% of the volume. The gap between consumption and production is predicted to be 7 million tonnes by 2050 in International Council for the Exploration of the Sea (ICES) member countries alone (Froehlich et al., 2021) and prioritising production is advised along with further studies on the effects of climate change on aquaculture.

With increasingly limited global supplies of freshwater, and suitable inshore marine sites for open system aquaculture, the development of Recirculation Aquaculture Systems (RAS) has been highlighted as increasingly important in supporting the continued and required growth of aquaculture output.

The Ukraine crisis and the increasing problems of food security prompted Minister of State, Victoria Prentis to ask if English aquaculture can grow aquatic food for the English market by developing sustainable aquaculture activities, thus contributing to wider food supply, security, and employment. Of particular interest was the potential for RAS to produce more seafood and meet the targets set out for RAS in the English Aquaculture Plan (EAP) (Huntington & Cappell, 2020).

The aims of this project were to provide a high-level holistic look at the opportunities and barriers facing the RAS sector, to identify areas that are most promising to scale up for the future. This would then enable government to take a closer look at these sectors and consider where government support should be focussed e.g., building on regulatory toolboxes and guidance documents or wider amendments to regulatory barriers if appropriate. Key policy questions to answer for Defra were:

- Which species are currently commonly cultivated in RAS.
    - The English market preferences and potential alternative species that RAS could produce.
- What types of RAS designs are available, and which may be suitable for England?
    - The practicalities of these systems in terms of location and land use, economic feasibility, infrastructure, environmental impact, workforce, and investment.
- Environmental permitting and other regulations associated with RAS.
    - Constraints and hurdles at start up.
- Identify if and where potential exists and where the difficulties would be.

The policy request was not an in-depth technical explanation of the science and workings of a RAS, or the processes for building one, but rather to provide a high-level overview of the areas above.

For this purpose, a systematic literature review & stakeholder engagement was used as described in the methodology, results, and discussion sections below.

2. Methodology

2.1. Literature review

Previously compiled information on RAS from a Cefas Seedcorn project (Tew, 2021) (including publications, grey literature and notes taken during workshops and seminars) were organised and transferred into a shared database in Mendeley. Following this, a systematic literature screening was conducted using a topic specific search in Web of Science of ‘Recirculating Aquaculture Systems’ followed by search terms including Sustainability OR Environmental Impact OR Energy Management OR Regulation OR Policy OR Economics, to identify further relevant information. Additionally, recent publications and other relevant papers were added to our review list upon discovery.

Literature on social constraints were searched separately as it was expected that we would need to broaden the search terms to find relevant results. Rather than searching for RAS specific research, we searched for research on social perceptions of aquaculture in general. We used Google Scholar and the social science and humanities database JSTOR for this purpose and scanned relevant papers. Key word searches included ‘Aquaculture AND Community’, ‘Aquaculture AND Perception’, ‘Aquaculture AND Social Acceptance’ and ‘Aquaculture AND Place’.

2.2. Stakeholder knowledge elicitation

We used stakeholder knowledge elicitation to understand which of the barriers identified in the international literature on development of RAS were relevant in England. For example, Vinci & Summerfelt (2014) claims that labour cost is only a small fraction (12%) of the overall costs for producing salmon in a RAS system, while EUMOFA (2020) identifies labour cost as one of the largest cost components to operate RAS systems, that is therefore a potential barrier for RAS development. To understand in more detail which of the issues identified in the literature are relevant for England, and whether they are specific for RAS type or species, a survey was developed as a first step to gather knowledge from stakeholders in a consistent and rapid manner.

2.2.1. Survey design

The survey was designed using elements of the hierarchical ranking approach. This approach is widely used in social science to reduce the complexity of an issue by reducing it into its main components and asks respondents in multiple stages to rank issues previously identified by the researcher. In stage 1, respondents are asked to rank the main issues. In stage 2, the respondents are asked to rank a subtheme of issues specifying in more detail the main issue from stage 1. In stage 3, respondents are then asked to choose which of the statements characterize best the subtheme identified in stage 2 as most important. An illustration of the approach is show in Figure 1 using the RAS survey as the example.

Using this staged approach allows researchers to drill into details by keeping it relatively simple for the respondents as not more than 5 options per time need to be considered or ranked. Moreover, the hierarchical ranking approach allows the researcher to filter out the most relevant issues, and aspects of these, in a timely and consistent manner. This approach therefore often serves as first step to analyse complex issues with conflicting findings.

Respondents were asked to indicate which RAS system and species they are most familiar with. We then asked them to rank which barriers, according to their experience, challenge RAS uptake in England. Findings of the literature review were presented to the respondents were determined from: (1) Regulatory burden, (2) Profitability, (3) Resource availability (Land, Water, Energy, Labour, Technology, and supply), and (4) Social barriers.

- Regulatory burden could be caused by missing, conflicting or too restrictive regulation with regards to (a) Building regulations, planning or marine licences, (b) Food and safety standards, (c) Environment and animal health regulations, or (d) Insufficient financial support/loans/grants.
- Profitability was further broken down into (e) Production cost, (f) Processing and distribution cost, and (g) Sales profit. Other facets include finding investors, high variability of outputs, and low-price premium are covered within this topic.
- Within the topic resource availability, it was further elicited whether all necessary resources are available in quality and quantity in England.
- The topic of social barriers focused on the social acceptance of RAS systems and the opposition investors may face by environmental groups or other stakeholders opposing aquaculture in general.

The process as show in Figure 1 was repeated until a full ranking of stage 1 and stage 2 was gathered from each respondent for the RAS each respondent was most familiar with. Stage 3 questions were only asked for the two highest ranked issues in stage 2 to ease the burden of cumbersome repeating. After the full ranking was achieved, respondents were asked if they are willing to go through the ranking again for the RAS, they were second most familiar with. Therefore, some respondents ranked 1or 2 systems.

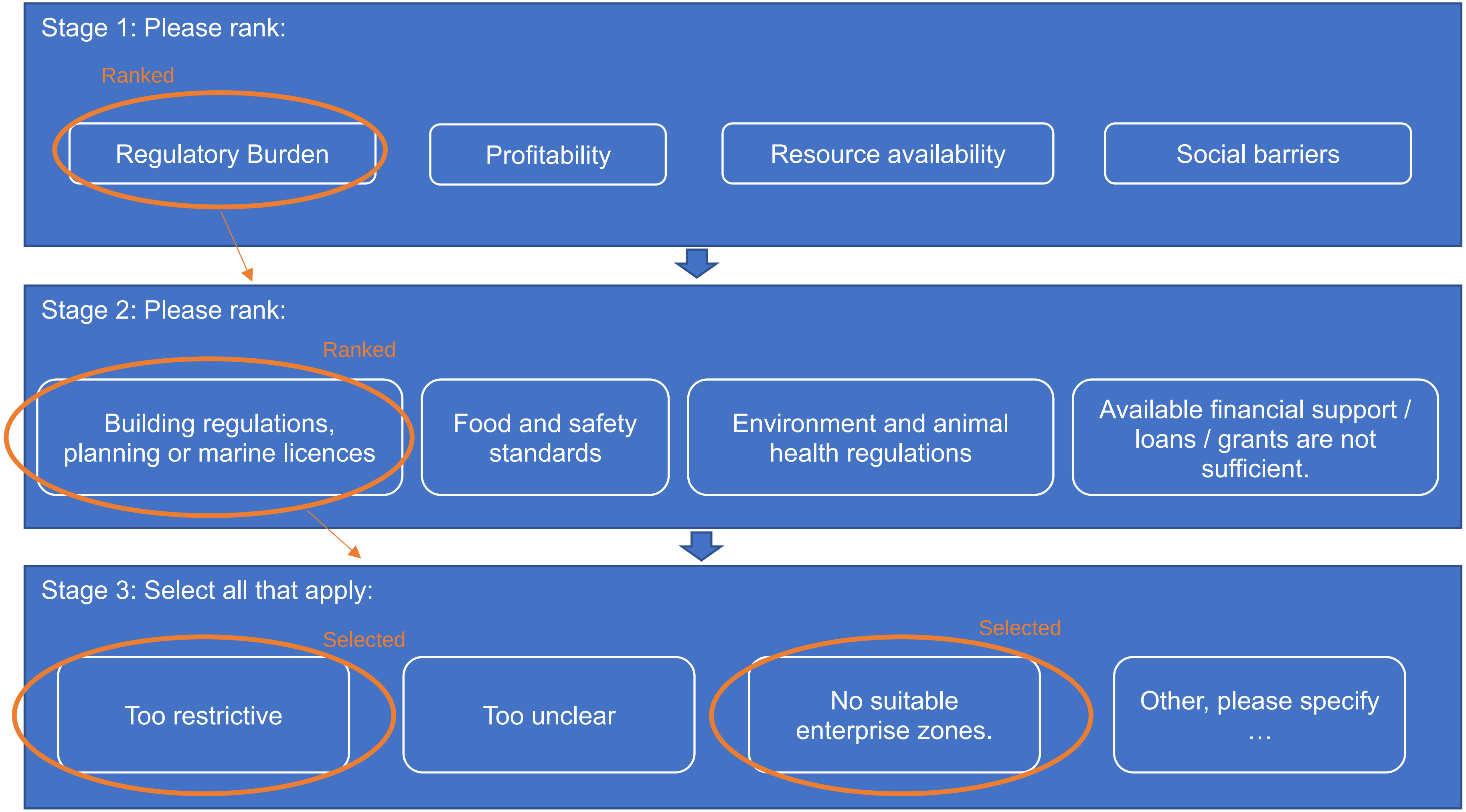
After the ranking questions, respondents were also asked to indicate the most promising RAS and species for England and whether government support would be needed to support RAS implementation. The full survey can be found in the Appendix.

The survey was implemented with the help of Qualtrics XM.

2.2.2. Participation

A list of stakeholders was collated. This included stakeholders from academia, RAS funders, operators, regulators, consultants, Non-Government Organisations (NGO), academia and representatives of trade-organisations with an interest in RAS. Current RAS operators were identified using the starfish database, as used for authorisation of fish farms by the Fish Health Inspectorate (FHI). We included some RAS system owners that had recently closed and those that are currently operating or that were in the early stages of set-up. In addition, the Dorset Coast Forum (DCF) and Local Enterprise Partnership (LEP) linked us to the Southwest Aquaculture Network (SWAN) and connected us to wider networks. Experts within Cefas then provided contact details and extended the stakeholder list further to include other RAS regulators. In addition, a BTA meeting at Cefas was briefed on the project and we subsequently received further email contacts of farms that were already using partial RAS and of another consultant with vast experience in the aquaculture area.

The identified stakeholders were firstly contacted by phone or, if unavailable, by email to request whether they would be willing to take part in the survey. All stakeholders who did not decline the request were sent an email with a link to the survey on 10th February 2023. A total of 66 RAS stakeholders were contacted in the first round. A follow up email was sent on 20th February 2023. The survey closed on the 27th of February 2023.



Stage 1: Please rank:

Ranked

Regulatory Burden

Profitability

Resource availability

Social barriers

Stage 2: Please rank:

Ranked

Building regulations, planning or marine licences

Food and safety standards

Environment and animal health regulations

Available financial support / loans / grants are not sufficient.

Stage 3: Select all that apply:

Selected

Too restrictive

Too unclear

Selected

No suitable enterprise zones.

Other, please specify …

Figure 1: Illustration of process of hierarchical ranking approached using the RAS survey as example.

3. Results from Literature Review

3.1. Overview of RAS

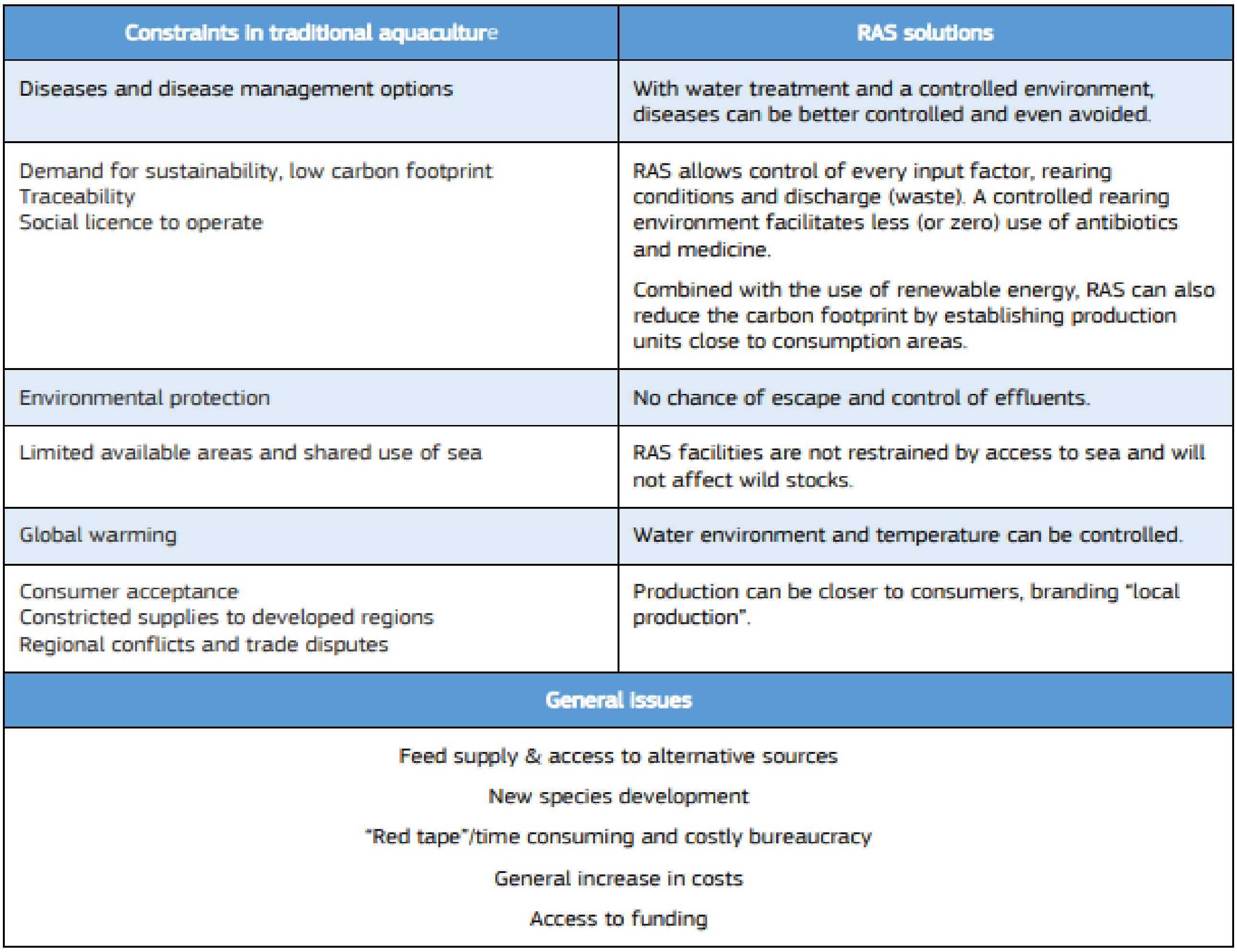
3.1.1. Historic global development and current context

Scientific research on RAS started in Japan around 60 years ago and was driven by the need to grow fish (in this case freshwater carp) in areas where water resources were limited. Concurrently, American, and European scientists were adapting technology designed for waste-water treatment (e.g., activated sludge processes, biofilters, trickling and mechanical filtration systems) for the purpose of growing fish and crustaceans in enclosed systems. Therefore, RAS technology is based principally around long-standing water treatment technology. The initial RAS systems were often small scale, laboratory based and did not have the inherent design capability to be scaled up to commercial systems.

An important concept of RAS is that they are not generally associated with adverse environmental impacts on habitats, pollution events, eutrophication of water bodies, escapees, and disease events. In addition, the growing environment is not directly affected by climatic factors such as rainfall, floods, droughts, and salinity changes (Ahmed & Turchini, 2021). RAS culture is compatible with many current sustainability goals for aquaculture. Increasingly environmental groups are supporting RAS production in lieu of production in open systems (flow through ponds or open net cage production). In addition, the perceived biosecurity and food safety benefits of RAS are more widely acknowledged, and this is also prompting more ethical investment in RAS worldwide. This is further supported by the increasingly experienced and funded providers of equipment, feeds, seedstock and technical services. Given that this sector is less than 60 years old there is a still a significant amount of research and development of RAS from practitioners, government, and private research facilities, and increasingly, within the academic sector.

Over the past 30 years these underlying technologies have been further developed to include gassing & degassing technology; water disinfection systems (ozone and UV) and innovative water filtering technologies. The aims being to maintain good water quality, extract solids and chemicals that could be harmful to the stock. In tandem with the development of the mechanical components, RAS now incorporates the use of microbes in complex biological filters to breakdown and control the levels of harmful waste products such as ammonia and nitrites. In addition, technology now also provides automatic feeding, mortality removal, control of parameters such as pH, salinity, and temperature of and provision of low energy artificial lighting. The monitoring and control technologies within RAS are of increasing importance and now provide capability to maintain the RAS aquatic environment within very specific tolerances. A recent report highlighted some constraints to traditional aquaculture and some of the solutions that RAS may provide (Table 1, EUMOFA., 2020).

Table 1: Potential main drivers of RAS and constraints for the aquaculture sector (EUMOFA, 2020).



<table>
<tr><th>Constraints in traditional aquaculture</th><th>RAS solutions</th></tr>
<tr><td>Diseases and disease management options</td><td>With water treatment and a controlled environment, diseases can be better controlled and even avoided.</td></tr>
<tr><td>Demand for sustainability, low carbon footprint
Traceability
Social licence to operate</td><td>RAS allows control of every input factor, rearing conditions and discharge (waste). A controlled rearing environment facilitates less (or zero) use of antibiotics and medicine.
Combined with the use of renewable energy, RAS can also reduce the carbon footprint by establishing production units close to consumption areas.</td></tr>
<tr><td>Environmental protection</td><td>No chance of escape and control of effluents.</td></tr>
<tr><td>Limited available areas and shared use of sea</td><td>RAS facilities are not restrained by access to sea and will not affect wild stocks.</td></tr>
<tr><td>Global warming</td><td>Water environment and temperature can be controlled.</td></tr>
<tr><td>Consumer acceptance
Constricted supplies to developed regions
Regional conflicts and trade disputes</td><td>Production can be closer to consumers, branding "local production".</td></tr>
<tr><th colspan="2">General Issues</th></tr>
<tr><td colspan="2">Feed supply & access to alternative sources
New species development
"Red tape"/time consuming and costly bureaucracy
General increase in costs
Access to funding</td></tr>
</table>

Within full on-growing RAS there have historically been more failures than successes (Jeffery et al., 2012; Prickett, 2022) and their financial viability has been questioned (Boulet et al., 2010). The cost of production needs to be competitive with that of alternative suppliers of the same species. It has been argued (Martins et al., 2010) that with technological improvements, reduction of capital costs, economies of scale and linkage with renewable energies, RAS offer much promise for the future. Further, salmon smolt production units began shifting towards RAS from 2000 onwards (Martins et al., 2010), which has continued to the point where much larger post smolts are being on-grown in RAS before stocking to open net pens. For the last few years RAS development and construction has rapidly increased with aquaculture headlines from around the world full of new RAS systems being funded and built (Arellano, 2022a, 2022b; Joensen, 2022; RAStech staff, 2022), and at scales capable of producing greater that 10,000 tonnes per farm per year. These new systems are now integrating developments and advances from the previous decades of research. In the Middle East RAS aquaculture parks and areas are being constructed for species such as salmon, sturgeon, prawns, and cobia (Arellano, 2023; Mon Chalil, n.d.)

3.1.2. Recent history of RAS in England

The commercial use of RAS within England has seen a modest development over the last 30 years. In the late 80’s and 90’s there was a spate of early design RAS built within farmers barns that were aimed at producing carp and other coarse fish at ambient temperatures. Many of these early systems existed for a few years before falling into difficulties and disrepair. By 2010 there were 18 operational RAS sites in England and Wales with an annual production of ~ 600 tonnes per year (dominated by sea bass production in Wales) (Jeffery et al., 2012). Most of these farms were based on faster growing warm water species such as tilapia and barramundi, principally located in England.

The RAS sites built in that period had a poor record for longevity, and many of the ventures failed (Jeffery et al., 2012). Reasons identified as the cause of most of the failures were poor system design, lack of attention to economic factors (e.g., electricity costs), and low demand for products (resulting in low price and sales volume). Unfortunately, most of these warm-water RAS systems are no longer operating commercially in England. Two large farms in Wales previously built for sea bass and turbot have been repurposed for culturing cleaner fish (lumpsucker or ballan wrasse) to supply the high demand for biological control of sea lice in the burgeoning Scottish salmon farming industry. In addition, the Scottish salmon industry has supported investment in other lumpsucker hatcheries in southern England.

In Scotland, there are around 12 commercial RAS facilities in operation all supplying the Salmon industry. Approximately half of these are producing salmon smolts and half are involved in the production of cleaner fish (Bostock et al., 2018). This shows a difference between the fortunes of cold-water RAS (now principally located in Scotland) and warmwater RAS (principally located in England) although it should be noted that many ornamental RAS systems have remained active for many years. It should be noted that some larger scale cold-water RAS are in planning stages for England.

3.1.3. Key types of global RAS including pros and cons

Globally, there are many variations on RAS each with many different design concepts and components. The report primarily focuses on standard fully enclosed land-based RAS systems (the majority), but we provide an overview of some of the variations and systems that are currently evolving.

Fully enclosed - full recirculation RAS

These systems make up the majority of RAS in production today and are closed within a specifically designed building (Figure 2). The technology included covers pumping, biological and mechanical filtration, oxygenation, protein skimmers, monitoring systems, feeders, and many other elements. The barriers and opportunities of these systems are discussed in more detail in later sections.

Figure 2: Picture of a fully enclosed - full recirculation RAS. Photo taken from Aquaculture Stewardship Council webpage (Anon, 2021)

Container based plug and play RAS.

These systems are frequently designed to be purchased and installed in a manner that is quick and easy, reduces both set up costs and installation time and minimises mistakes and engineering construction errors. However, they are generally most suited for either smaller scale enterprises, hatcheries, research / pilot systems, social enterprises, or educational demonstration systems. The plug and play systems can be as packages where either just the more complex filtration and operating systems are purchased for connection to holding units or combined with tanks (Figure 3).

More recently plug and play systems have been developed within shipping containers to allow easy transportation to farm locations (Neil, 2022).

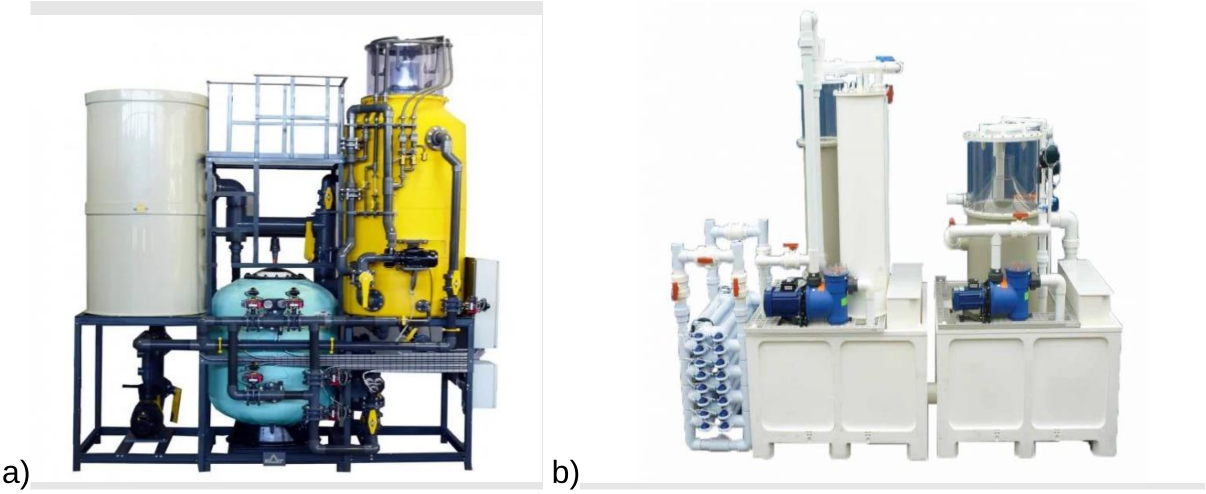


Figure 3: Picture of a container-based plug and play system taken from a) Mat-Kuling (Anon, 2023) and b) Tropical Marine Centre (TMC, 2023) webpages.

Bio-floc raceway and pond RAS

This type of aquaculture is a less heavily engineered system that provides some functions such as aeration, filtration, and circulation, but in a way that allows bacterial flocs to grow within the holding units. The rationale being that the bacterial floc helps clean the water and provides nutrition and feed for some aquaculture species. In comparison to standard RAS, positives include improved feed conversion ratios, but negatives can include increased energy requirements for mixing and aeration, increased instability of the systems for nitrification, and inconsistent seasonal performance for sunlight exposed systems (Figure 4). In addition, the understanding of microbial ecology of bio-flocs is at a basic level (Hargreaves, 2013).

Figure 4: Pictures of different examples of Bio-floc raceway and pond systems (Images taken from google images).

Partial recirculation (with limited inflow) RAS

Partial recirculation (or water reuse) systems have designed and trialled by the Freshwater Institute, Shepherdstown, Virginia (Summerfelt et al., 2004). These constitute a lower cost form of recirculation by increasing production from a limited or reduced flow of water without many elements such as large biofiltration towers. The principal of this design is to recirculate the cleaner water using gravity return and pumping and concentrating the waste to go to settlement, filtration, or discharge (Figure 5).

Disadvantages include the biosecurity risk and the need to sterilise the inflow of water.

Figure 5: Picture of a partial recirculation RAS (Image taken from Freshwater Institute Website in Virginia)

Danish model farms (outdoor semi closed system)

In Denmark, traditional flowthrough trout farms have been converted into RAS or ‘model farms. These systems reduce water requirements, capture solids, clean up nutrients in the discharge via wetlands and return any remaining flow to just below the intake point (Figure

6). These provide advantages, in that larger biomass can be farmed with a smaller discharge and footprint, and reduced impacts on river flows. This allows permission to increase feed usage thus increasing production for the site.

Disadvantages are that the systems are in outdoor semi-closed systems and thus still vulnerable to parasites and diseases from wild populations.

The ‘model farms’ system may offer increased opportunity for English trout farms, but economics must be built into reconfigurations. In Poland, significant progress has been made in installing similar lower cost RAS systems into existing farms. Within England, a small number of farms struggling with low flows and increasing temperatures have begun to move in this direction already (Fish Farmer, Dec 2020).

Figure 6: Picture of a Danish model RAS farm (Google images – Semantic Scholar

Aquaponic & Multi-trophic RAS

Aquaponics is the combined culture of fish and plants in recirculating systems where dissolved waste nutrients are recovered by plants, thus reducing discharge to the environment, and extending water use (Rakocy et al., 2006). The daily addition of the fish food provides the nutrients for the plant crops, thus replacing the need for addition of chemical nutrients as in hydroponic systems. Aquaponic filters have been shown to provide better biological performance than traditional pond filters (Varadi et al., 2009). These systems have a clean green image and have become popular among the "back-yard" community and hobbyists, producing food close to the markets. The challenge for aquaponics is to become commercially viable i.e., as competitive as either standalone aquaculture or standalone hydroponics (Taylor, 2014). It is an area where both industry and NGOs would like to see more support and encouragement (Seas at Risk, 2014). Recently, larger scale commercial systems have been built in Wisconsin, USA producing species such as salmon and trout with a range of leafy green vegetables in a form of circular production (Bostock et al., 2018). In Slovakia, a RAS system and fish production plant was built in one year to produce 1000 tonnes of Clarias catfish along with greenhouse grown tomatoes (AquaMaof, 2023). In countries such as Singapore, which has limited spatial resource, vertical growing systems for leafy vegetables have been combined with aquaculture and RAS.

Integrated Multi-Trophic Aquaculture (IMTA) systems have also been built into RAS systems, but the primary focus of IMTA is currently within mariculture at sea without the RAS element.

Pump ashore – Partial Recirculation RAS

There have historically, and recently, been systems built that pump seawater ashore and then partially recirculate before settlement and discharge. These systems are usually uncovered and open. Whilst they save on capital investment in equipment, buildings, and some other materials they have the disadvantage of being open to the elements, lower biosecurity, increased chance of ingress of pathogens, and are unable to optimise temperatures for production during colder winter months.

Marine floating RAS

Floating RAS systems have been developed in Singapore where space on land may be a limited premium. Manufacturing giant Siemens has invested in an aquaculture firm farming fish on floating platforms (Cherry, 2021). The $94 billion conglomerate will also lend technology expertise to scale and commercialise the start-up’s unique plan to bring land-based aquaculture technology to the ocean. Advantages include allowing for moving to areas where intake water is of good quality, and where risks from pollutants, algal blooms or jellyfish can be minimised (Figure 7). However, disadvantages include the need to find shelter in extreme conditions, power supply, scale of operation and supply lines.

Recently, the use of floating RAS has been proposed for the on-growing of hatchery tuna fry to develop them past the sensitive stages of their early development and to a stage where they can be stocked in open nets pens (thus removing the need for ranching of wild caught juveniles) (Fletcher, 2023).

Figure 7: Picture of a marine floating full RAS (Image from Intrafish Technology 6th August 2021)

Semi- contained (Part RAS)

In both freshwater and marine environments, a range of closed or semi-contained pens and holding systems are being developed that often include elements of RAS (Figure 8). These systems are evolving fast in Norway at CtrlAQUA, a centre for research-based innovation (SFI), conducting research on closed-containment aquaculture systems. The main goal is to develop technological and biological innovations that will make closed systems a reliable and economically viable technology. The primary focus is on critical periods in salmon post smolt sector (Espmark et al, 2020), and on reducing the impacts from open net-pens.

Frequently, closed pen systems require water to be pumped in, rather than relying on free movement of water through a mesh in open net-pen systems.

Potential benefits associated with a closed wall include both controlled water supply and discharge: capture of solid wastes, reduction and control of nutrient and chemical discharge, containment of stock, and a physical barrier to pathogen ingress and egress.

There are some other aquaculture engineers (possibly with alternative interests) who argue that they are more cost effective than full RAS, but difficulties in engineering such as mooring in strong currents and extreme weather remain.

Flexible membranes (ClosedFishCage, 2017) and rigid materials surfaces (AquaDome, 2015) have been trialled as pen walls, and another concept is large rigid walled floating tubes (Preline, 2015). The many variations of marine floating contained systems have recently been outlined (Neil, 2021; Outram, 2021).

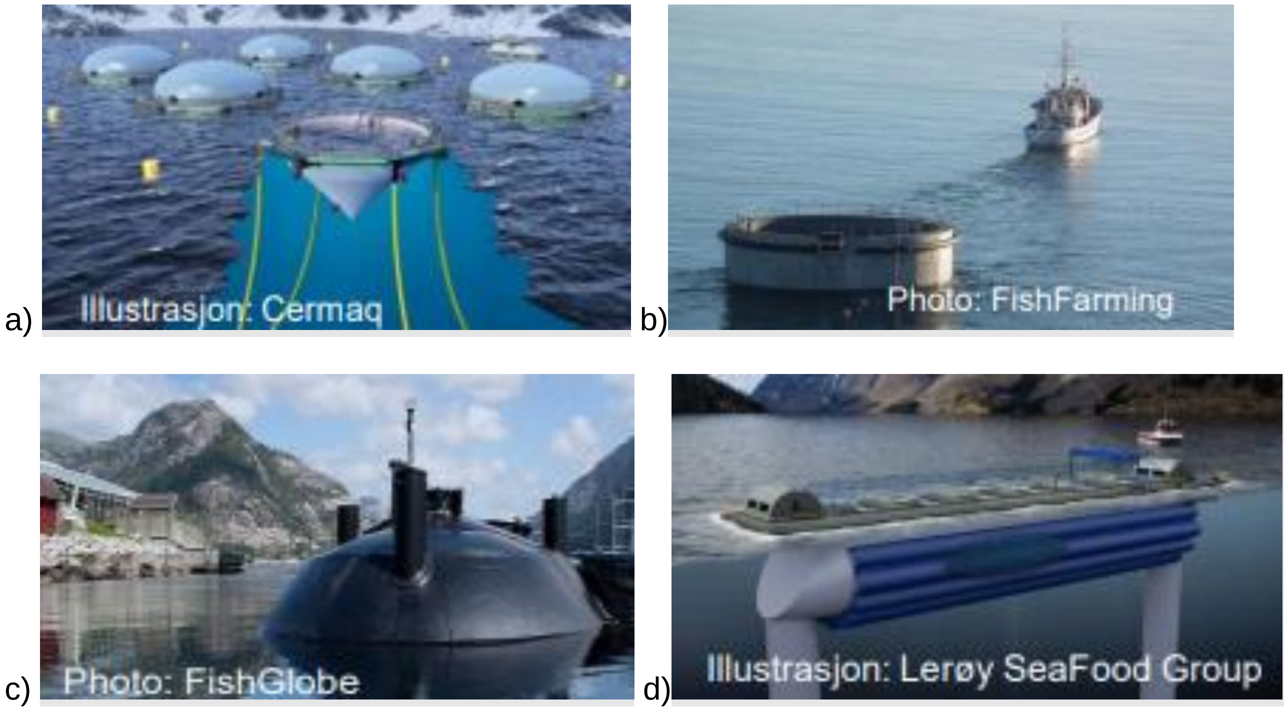


Figure 8: Pictures of different semi-contained RAS (Images taken from a) Cermaq and b) FishFarming, c) FishGlobe, and d) Leroy Seafood Group).

3.1.4. Production in RAS by species

Global

Globally, the marine species that are commercially cultured in RAS include sea bass, meagre, yellowtail, sole, white leg shrimp, grouper, and salmon. Similarly, commercial fresh and brackish water species farmed in RAS include tilapia, catfish, and barramundi. A very small proportion of global aquaculture finfish production uses RAS (estimated at < 5%) for grow-out but use of RAS in hatcheries is quite common for many species.

The global production of salmon is fairly developed in terms of RAS technology when it comes to smolt production. In Norway and Chile, the share of RAS in smolt production is somewhere between 40% and 50%, whereas in the Faroe Islands it is close to 100%. Regarding salmon full grow out production in RAS - the USA, Canada and latterly China are leading the way. Drivers for this are essentially market based. For example, the USA consumes more than 500,000 tonnes of whole fish equivalent (WFE) of salmon every year and has a 90% seafood trade deficit. (EUMOFA, 2020).

Europe

Currently, the main species cultured in RAS in Europe are finfish. Around 90% of the RAS production is in a freshwater environment, while the remaining 10% is sea and brackish water. In terms of species, the top five species accounted for 95% of the production in

2018. Rainbow trout is by far the most farmed species with approximately 15,000 tonnes annual production, accounting for 56% of total production. It is followed by North African catfish, European eel, Atlantic salmon, and Senegalese sole (Table 2 taken from EUMOFA. 2020).

RAS production is dominated by a few large producing countries, and the top 6 EU Member States accounted for 92% of the production in 2018. Denmark accounts for roughly half of the volume each year. These figures do not include figures for Norway which is one of the leading nations concerning development of RAS/ and semi closed containment systems.

In addition to the widely reported headline figures are many cases of small-scale RAS production which have not been reported to Eurostat thresholds. This may be for various reasons such as being a hatchery or for production of stock for further on-growing in aquaculture. In Belgium, a few commercial producers use RAS for striped seabass, sturgeons, pike perch fingerlings and white leg shrimp. In Sweden, the production volume in 2018 is likely above 100 tonnes and includes species such as salmon, trout, rainbow trout, Arctic charr, Nile tilapia, sturgeons, crayfish, carps, and perch.

A good indication of the current state of RAS in Europe (and beyond) can be determined by looking at the current activities and plans of some of the major RAS ‘turnkey’ project suppliers. Most of these suppliers are based in Northern Europe (Norway, Denmark, Netherlands, France, and Germany) and their technology is often based on experiences from Atlantic salmon smolt production. For example, Billund Aquaculture currently has projects totalling approximately 6000 tonnes of smolt production in Norway and over the past 8 years has supplied approximately 4000 tonnes of RAS projects in Europe including Salmon and Pike perch in Denmark, Yellowtail in the Netherlands, and trout in Finland (Billund, 2020).

Table 2: Top 5 species produced in the top 5 RAS systems in 2018 according to Eurostat (EUMOFA. 2020).

Species	Production amount/tonnes
Rainbow tout	~15,000
North African catfish	~3,000
European eel	~4,000
Atlantic salmon	~1,000
Senegalese sole	~800
Total	~23,800

England

The current situation within England is that RAS production is focussed around five or six species with several small-scale sites farming mixed species in Aquaponics or IMTA systems. There has, however, been increasing interest in RAS for cleaner fish (e.g., lumpfish and wrasse) production for use in the Scottish salmon farming industry. The following data is based on authorised aquaculture production businesses (APB's) supplied from the FHI database and therefore does not represent small scale backyard hobbyists.

Table 3: Current RAS farms authorised in England. Data provided from FHI database 24th November 2022.

Species	Number	Comments on sector
Trout / Charr	5	Recirculation built into existing farms
Clarias catfish	4	Small scale but some plans to grow
Lumpfish / Wrasse	4	Large scale farms producing significant numbers
Prawns	3	Medium sized with some plans to scale up
Red claw crayfish	1	R&D and development stages
Ornamental	2	1 large site with full production.
Aquaponics and IMTA	3	Mixed production mostly at smallish scales

Predicting the future is difficult with the current energy crisis putting some operations on hold. Some of the smaller sectors above have ambitions to grow their farms. In recent years, there have been plans to develop large scale farms close to major markets for other exotic species such as grouper and Clarias catfish. Recently, there has been interest from the Middle East in developing a 1000 tonne prawn farm in Lincolnshire and one existing site has ambitious plans for prawn production. The purpose of the large warm water prawn farming project at Exeter University is to encourage growth in this sector for terrestrial farmers (with anaerobic digestor plants providing heat and power) and to provide a model for design and application. Recent news is the announcement of plans to build a 5000 metric tonne salmon farm in Grimsby, Lincolnshire (Harkell, 2023), with a fish processing plant.

Existing trout farms have been incorporating elements of RAS within existing flow through farms and with climate change predictions it is likely that this trend may increase with reduced flows.

3.1.5. The UK's main consumption patterns for seafood

The UK is a major importer of fish and shellfish, with most of the seafood consumed in the country being imported from other countries (**Error! Reference source not found.**). This includes species such as cod and haddock, which are traditionally associated with the UK fishing industry.

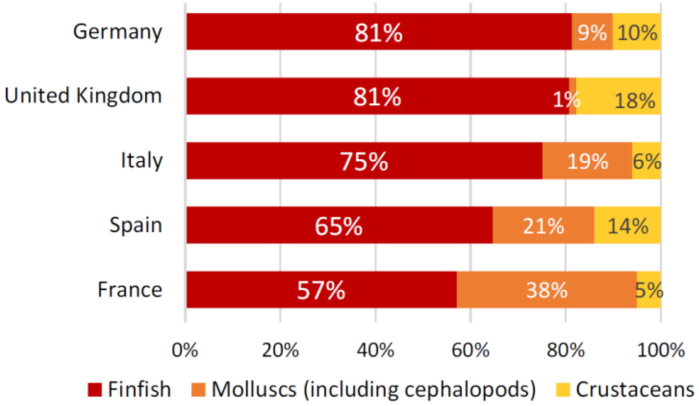


Figure 9: Unprocessed fishery and aquaculture products sold through the retail channel in 2020, shares of total volume (THE EU FISH MARKET Maritime Affairs and Fisheries, n.d.).

Most of the unprocessed seafood products sold through the retail channel are finfish, followed by crustaceans and molluscs. Salmon became the most popular fish consumed but cod, tuna haddock, prawns, and other shellfish, such as crab and lobster, are also popular.

There is however an overall decline in UK seafood consumption since 2006. The 17.3% total fall in seafood consumption from 2006 to 2018 is predominantly down to a drop in 'in home' consumption. Seafood consumption started to recover in 2019 and then received a significant 10% boost from COVID-19 increasing meal occasions. Because of the protein and large number of essential nutrients contained in fish and shellfish, many experts recommend that we try to eat at least two portions of seafood every-week (Watson, 2022).

It has been noted that to make a significant contribution to food security, English aquaculture will have to both diversify to produce species with more mainstream consumer interest and grow in volume (Huntington & Cappell, 2020). So, when comparing the top five most eaten fish in England with current RAS development we can see the following trends:

1. Salmon = Significant ramping up of RAS for all lifecycle stages
2. Prawns = Becoming more commonly farmed globally in various RAS
3. Tuna = Hatchery and R&D only (early plans for floating Marine RAS)
4. Cod = Hatchery, R&D and Pilot studies.
5. Haddock = As cod but more limited information.

3.2. Resource availability constraints

3.2.1. Spatial footprints and land requirements

England is a relatively densely populated country; therefore, the spatial footprint of RAS facilities and areas of suitable land will be of significance in achieving goals of the EAP. A previous project researched the impacts of removal of net pens in Scotland and the extent to which suitable sites were available for alternative RAS production was unclear (Franklin et al., 2012). Requirements for a RAS site were previously defined as flat land with a low pumping head to reduce energy consumption per kg growth (Kankainen et al., 2014). Similarly, low lying, flat, coastal land, rocky or gravelly with a tidal range of less than 4m springs were also identified (James & Slaski, 2009), who also suggested there was little doubt that some suitable coastal land exists on parts of the English coastline. However, both references may well have been referring to marine based RAS rather than including the opportunity for freshwater RAS. Further consideration was given to siting and locational requirements for Salmon RAS in Scotland (Bostock et al., 2018; Jeffery et al., 2015).

Table 4: Spatial footprints required for increases in RAS production in England.

	Production (tonnes)	Land Required (Ha)	Heathrow (1227 Ha) (% of area)	Hyde-park (142 Ha) (% of area)
EAP aspirations by 2040	34,608	21.6	1.76%	15.2%
Equivalent of Scottish Salmon production	160,000	124	10.1%	87.3%

Whilst it may be difficult to put a number on sites where the land is specifically available or suitable, estimates can be made for the total areas required for a significant production for RAS. In a report for the Highlands and Islands enterprise (Bostock et al., 2018), figures from Vinci et al. (2015) were used to calculate that producing the equivalent of the production of Scottish salmon (approx. 160,000 tonnes per annum) in RAS would only require 124ha of building area. Using these figures, Table 4 may help with visualisation. For comparison, in England there are approximately 8,900,000 Hectares of utilised agricultural land (Defra, 2022) with an average land holding size of 86.4ha (Dodds, 2019).

3.2.2. Water availability and requirements for RAS

RAS are considered water efficient farming methods due to low water consumption, high level of water re-use and optimization of waste management (Murray et al., 2014). The level of water reuse and replacement varies by system design. For example, the Danish model farms - outdoor semi closed systems used 1/13th of the water for traditional flow trout farming (Martins et al., 2010) However, these systems still require more water than full recirculation systems which can vary from 10% replacement per day to less than 1% replacement per day.

In a report that modelled the effects of shortening of the net pen phase of salmon farming by growing salmon to larger sizes in RAS (Jeffery et al., 2015), it was identified that marine based RAS systems needed to be near a water source (preferably good quality), with access for well boats to received pumped fish. These boats require drafts of up to 6m (Turnbull, 2014). Using a 5-10% replacement per day, producing the 160,000 tonnes per annum of Scottish salmon in RAS systems would require 43,000m^3 of water pumped per minute for RAS flow. This equates to 95,000 to 190,000m^3 water per day (Bostock et al., 2018).

Whilst these figures of water availability are unlikely to be an issue for marine units located in suitable coastal locations, this may not be the case for freshwater usage where abstractions have fallen by 30% over the last 10 years (Bostock et al., 2018). A conversation with an inspector in close contact with freshwater trout farmers (FHI, Per's Comm, 2022) highlighted that water availability and costs of abstraction and discharge licences in the period 2015 - 2016 were drivers for some trout farms to move towards RAS systems. It has been suggested that effective design of integrated multi-trophic RAS could minimize aquaculture discharges and improve disease control (Chang, 2019 In (Ahmed & Turchini, 2021)).

3.2.3. Skilled workforce requirements and availability

In 2020, the aquaculture sector employed around 1,080 persons in England, roughly ¾ on a full-time basis. Most enterprises are small-scale operations. Objectives for the English aquaculture aim to provide up to 5,000 secure jobs within the sector (Huntington & Cappell, 2020). A European-wide study (Nicheva et al., 2022) analysed socio-demographic data of the aquaculture industry in 18 countries to establish a baseline of employment structure (data from the year 2017). It asked for gender, age, education, and nationality, and divided those findings by production sectors of the aquaculture industry. The study concluded that most employers within the sector are citizens of the same country they are employed in (85%). The UK sectors employs 76% UK nationals and 10% EU-nationals, however, a rate of 13% unknown means that either rate could be higher. Rather than a lack of general workforces after the EU-exit, the RAS industry in Britain is confronted with low availability of highly skilled workers. In comparison to other aquaculture sectors and technologies, RAS in the analysed countries has the highest share of highly skilled workers, with 20% of the employees (BA degree and higher), whereas medium and low educated workers account for 44% and 34% respectively. This can be explained by the complexity of RAS, which increase the need for highly skilled workers.

This review used data from the UK that was not explicit about the distribution of education in the UK aquaculture sector, as 57% are marked as unknown (in addition to 5% low education, 27% medium education, 11% high education). More research and data collection are needed to determine if the UK workforce has skills comparable with those of EU countries.

A report published in January 2023 addresses the goal of attracting more people into land-based and aquaculture sectors in Scotland by improving learning pathways (Commission for land-based learning review, 2023). The short-term advisory group recommended to reframe the land-based sector as nature-based, therefore including the aquaculture industry. Further, it identified the need to establish clear progressive experience in nature-based learning and climate literacy across all levels as a tool to generate skills and knowledge required for the sector. The authors propose to link the value of natural environments for children with pathways for their future careers. While aquaculture and the RAS industry is part of the report, the report stays wage about possibilities to use the approach to ensure skilled labour for the future. Yet, it highlights issues relevant for the English RAS sector. For example, there is a poor understanding of the wide variety of job roles in the sector and there is likely a gender bias with young women not being encouraged enough to consider a career in the industry. The report suggests an overall need to change the perception of the aquaculture industry and other land-based sectors and connect them with environmental and social, and personal value, as well as with overall aims like sustainability and tackling the nature and climate crises. However, these would be long-term steps to recruit more labour for the sector rather than short-term solutions.

3.2.4. Energy supply requirements and emerging options

In a study of reasons for historic failures of RAS systems in England & Wales (Jeffery et al., 2012), RAS operators were asked to rank the top ten critical factors for failure. At this point (for RAS systems prior to 2012) energy costs were ranked as the fourth most significant factor behind system design, marketing, and the cost of fingerling supply. In a wider review of energy use in the RAS sector (Badiola et al., 2018) it was found that energy was of little concern for most of the industry.

It would seem logical to assume that in 2023 after the war in Ukraine with an energy crisis and rocketing prices that energy costs would now be higher in the ranking. A Foresight report for the Government Office for Science (Black & Hughes, 2017) identified that the relative costs of energy will have a very large impact on how aquaculture develops and that if energy becomes sufficiently cheap then RAS will be expected to grow.

The highest costs connected to water treatment are related to pumping and lifting of water, carbon dioxide (CO_2) removal, temperature control and oxygenation. These costs will of course vary with the different local conditions of the water source and pumping heads (EUMOFA, 2020).

On the 6th of November 2022 a RAS Virtual summit brought together experts from around the globe to discuss various aspects affecting the sectors development. The high and rising costs of energy featured prominently in the discussions. Some of the key points made during the webinar were:

- Larger producers of RAS such as AKVA and AquaMoaf are now optimising energy usage within system designs by paying greater attention to factors such as piping configurations and degassing procedures and minimising power input.
- Locations for RAS (weather and ambient temperatures) are important as any cooling or warming of water is energy intensive. This will vary with species farmed.
- The source of energy and its cost varies between countries from those still mostly reliant on traditional fossil fuel sources to countries such as the Netherlands where the energy from the grid is from renewable sources.
- Figures quoted for obtaining energy from solar panels indicated 15% to 40% recovery of operating costs (OPEX).
- More research is needed on energy recovery from waste.

The U.S. Department of Agriculture (USDA) recently awarded $10 million towards Sustainable Aquaculture Systems (SAS) (Zohar, 2023), a set of projects to make large-scale, sustainable land-based aquaculture a reality in the United States. Yonathan Zohar, professor and chair of marine biotechnology at University of Maryland, is the program leader for these projects which builds on the Recirculating Aquaculture Salmon Network (RAS-N), also led by Zohar, with the goal of connecting industry partners to develop salmon RAS. As part of this project, one area included research into treatment of captured effluent by turning it into methane (both in the lab and on real aquaculture farms) that can lead to an 8-10% recovery of energy OPEX.

Operators and constructors of RAS systems do not consider that backing away is an option but rather that greater attention be paid to achieving ambitions for Carbon neutral RAS. As an example, InfiniteSea are confident that they can shift the sectors performance average towards two kWh per kilo (Ley, 2023). This represents producing fish at a markedly lower energy to end product ratio than previously achieved where figures of six kWh per kilo have been common. Whilst these figures were previously acceptable in countries with lower energy costs before the war in Ukraine, they are unacceptable in most European countries today. So, getting from 6 kWh to 2 kWh per kilo requires a > 66% reduction in energy usage. Infinite Seas research has already shown reductions of 20-50% are possible but they have questioned some claims by other RAS producers that achieving one kWh per kilo is already possible.

Whilst the current energy crisis has made economics in this sector far more challenging (with many new developments being put on hold) there is research and development taking place e.g., at the University of Maryland (Zohar, 2023) and the Exeter King prawn project that aims to link farms with anaerobic digestor plants or other energy sources. These types of projects in combination with the industries attention to energy usage within systems can mitigate and reduce these costs significantly.

One study used LCA to look at Tilapia and Clarias culture in RAS and they found that the trade-off between energy demand and risk to the environment can be smaller than previously reported for RAS (Bergman et al., 2020). The study suggested that RAS farmed fish can contribute to more sustainable food systems.

Electricity is a far more significant energy cost than gas within RAS. **Error! Reference source not found.** shows the challenges England may face with respect to high energy costs in production when in competition with other nations.

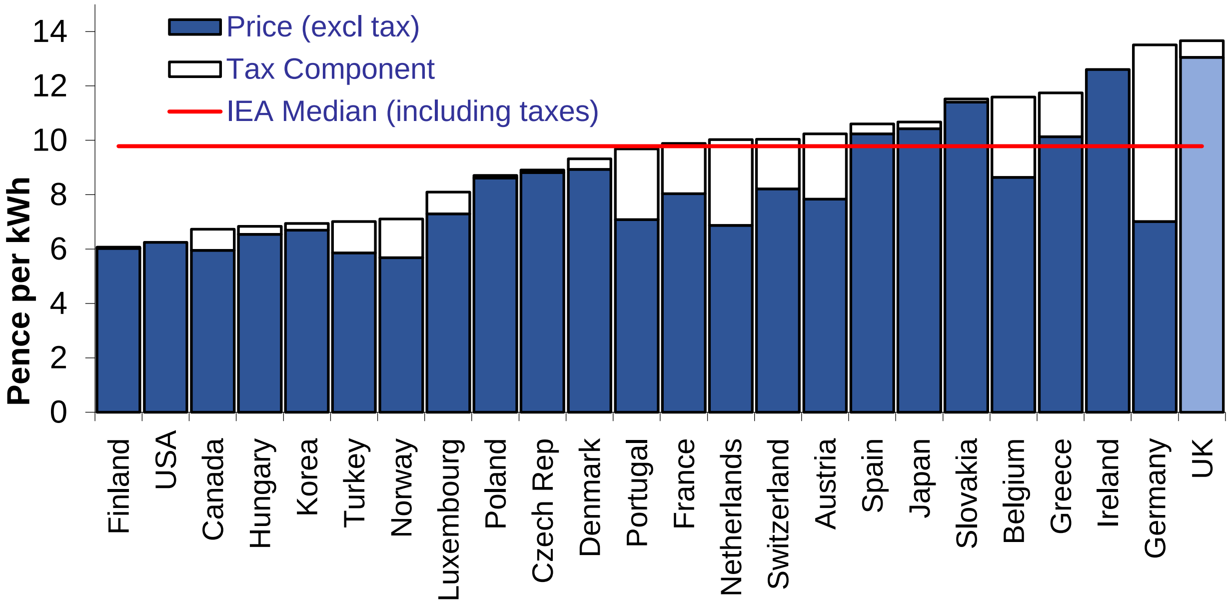


Figure 10: International comparison of industrial electricity prices in the International Energy Agency– 2021 (BEIS 2022)[1].

3.2.5. Fish food supply and emerging options

The fish food supply for fed aquaculture has historically been dominated by fishmeal and fish oil (FMFO) derived from wild-caught fish. However, as the demand for seafood continues to grow, the sustainability of this practice was called into question. This previous dependence of aquaculture on wild caught fishmeal and fish oil was responsible for increasing public concerns, based on perceived, though not consistently substantiated, negative environmental impacts on wild fish stocks, and more importantly growing economic viability issues because of the skyrocketing prices of these finite raw materials.

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[1] Source: International industrial energy prices - GOV.UK (www.gov.uk)

To address this issue, alternative protein sources have and are being explored for use in fish feed. Novel new feeds containing minimal amounts of fishmeal and fish oil, and the appropriate use of alternative and complementary raw materials, is providing several benefits. When these feeds are used in RAS (where there can be much more efficient feed management) it is evident how beneficial this is for the overall “fish-in fish-out” balance of the aquaculture sector (Ahmed & Turchini, 2021).

An emerging strategy is to use plant-based proteins, such as soy and peas, as a substitute for fishmeal. These plant-based alternatives have the potential (if grown sustainably) to reduce the pressure on wild fish populations and decrease the environmental impact of aquaculture. Additionally, insects, such as black soldier fly larvae, are being researched as a protein source for fish feed. These insects are efficient at converting organic waste into protein and can be produced on a large scale. A comparison of the nutritive value of black soldier fly larvae and fish meal can be found in Table 5.

Table 5: Nutritive value and amino acid profile of black soldier fly full-fat larvae meal (BSFL) and fish meal (FM) used in an experiment with Siberian sturgeon (Rawski et al., 2020).

Nutrient	BSFL	FM
g/1000 g of dry matter		
Crude protein	350	618
Crude fat	298	165
Crude fibre	79	0
Crude ash	53	175
Nitrogen free extract	221	42

Other options being explored include the production of microbial biomass from industrial scale production units (Jones et al., 2020) and the re-use of brewing products where experiments have shown replacement of up to 20% of traditional aquaculture feed is possible without loss of growth (Cidad et al., 2021). Another possible solution is to substitute part of the fish reduced to FMFO with fit for human consumption by-products from the food industry. Furthermore, in recent years, trimmings from commercial fisheries have increasingly been used as a replacement for FMFO.

3.3. Environmental considerations and benefits for RAS

RAS has the potential to be an environmentally sustainable solution to meet increasing demand for domestic production within the UK. RAS can be implemented to grow species where poor water quality, water scarcity, and unfavourable environmental and biophysical conditions exist (Ahmed & Turchini, 2021). Due to the enclosed nature and waste management capabilities of RAS, risk of disease outbreak, parasite transmission and genetic contamination of wild stocks, water pollution and eutrophication, biotic depletion, or captive fish escape are all greatly reduced in relation to traditional open-net pen aquaculture methods (Martins et al., 2010; Murray et al., 2014; van Rijn, 2013). Furthermore, RAS are not considered to cause habitat destruction due to self-containment of the system and the added potential to establish RAS on peri urban brown field sites, therefore utilising previously developed locations.

One of the largest concerns for the future of RAS is the use of fossil fuels. Compared to net-pen salmon farming, RAS' carbon footprint is twice that of open net pens when considering production only (Liu et al., 2016), therefore RAS are possibly more detrimental regarding their direct contribution to climate change (Ahmed & Turchini, 2021). Greenhouse gas emissions are primarily driven by energy consumption that is required for operations such as circulating water through fish tanks and treatment loops to filter and remove solids and nitrogen, lifting of the water, heating and/or cooling, oxygenation, and illumination of the facility (Ahmed & Turchini, 2021; Badiola et al., 2018). Electricity is predominantly derived from a public utility, and therefore, places limitations regarding options of energy sources (Badiola et al., 2018). However, RAS production in combination with renewable energy sources could reduce the carbon footprint of the final products, and this will become increasingly important to address environment and sustainability considerations. Research into this area is already taking place in institutes such as University of Maryland, USA.

Life Cycle Analysis (LCA) assesses a product's potential environmental impact throughout its entire life cycle (cradle-to-farm gate) and is an internationally standardised method (Song et al., 2019). LCA's consider a number of parameters such as hatchery and smolt rearing, feed manufacturing and ingredients, grow-out, energy consumption, infrastructure, transportation of feed ingredients and product to market, on-site waste, and emissions (Song et al., 2019). LCAs predominantly assess impacts on climate change (via carbon emissions of global warming potential), eutrophication, cumulative energy demand, ecotoxicity potential (human, marine, freshwater, and terrestrial), acidification and abiotic depletion/ biotic resource use.

Thus far, LCA's have almost all reported that farm-level energy consumption, and thus global warming potential, is the largest concern for RAS (Badiola et al., 2018; d'Orbcastel et al., 2009; Liu et al., 2016), with feed and feed production also recognised as key contributors (Bergman et al., 2020; Song et al., 2019). However, this is applicable to all fed aquaculture methods, given the overall impact from feed is determined by resource, emissions, farming system and pressures placed on origin ecosystems (Bergman et al., 2020; d'Orbcastel et al., 2009).

Global warming potential of RAS energy consumption has been calculated to be as high as 28,200 kg CO_2 per tonne of live weight salmon produced in Canada, whereas open net pens and land-based flow through systems produced 2,073 and 2,770 kg CO_2 per tonne, respectively (Ayer & Tyedmers, 2009). Table 6 shows the vastly different outcomes of an LCA for only one species (Atlantic Salmon) produced in aquaculture systems in North America (USA or Canada) depending on the assumptions made and aspects included.

However, LCA allows insightful comparisons of system performance. It is difficult to ascertain total electricity use at the subprocess level as most usage is reported to farm-level (Song et al., 2019). However, there have been calls for life cycle inventory (LCI) databases (Bohnes & Laurent, 2019), which will ensure better estimates of energy use in the future and allow the identification of priorities for technological advancements to further reduce environmental impacts as well as operational and economic costs.

Liu *et al*. (2016) investigated the use of renewable energy sources in Atlantic Salmon production utilising RAS versus open-net pen aquaculture. The carbon footprint of RAS was calculated to reduce from 7.41 CO_2 eq kg per head-on-gutted salmon weight at the retailer gate based in the US to 4.1kg CO_2 eq kg with the use of 90% hydropower. Comparatively, salmon transported from a Norwegian open-net pen system via airfreight to Seattle versus ship resulted in 15.22 and 3.75 CO_2 eq kg at the retailer gate (Liu *et al.,* 2016). RAS that are close to market and incorporate renewable energy sources significantly reduce the carbon footprint of RAS, however, the LCA found that open net pen systems perform better financially, and RAS would need to sell product at a premium price to break even or to be financially profitable. It is expected that economic incentives for innovations in RAS technology will decrease capital costs and afford RAS to become more competitive with open net pen systems.

Table 6: Carbon emissions per 1 tonne of live weight fish produced in RAS systems (cradle-to-farm gate) compared to open net pen (OPN).

Species	RAS – Carbon (CO_2 eq./kg live weight fish)	OPN – Carbon (CO_2 eq./kg live weight fish)	Source
Atlantic salmon	16,700 (farm level electricity)	-	(Song et al., 2019)
Atlantic salmon	28,200 (production only)	2,073 (production only)	(Ayer & Tyedmers, 2009)
Atlantic salmon	7.41 (production and transport to market) but with inclusion of hydropower this was reduced to 4.1).	15.22 (production and transport to market)	(Liu et al., 2016)
Atlantic salmon	7.01 (production only)	3.31 (production only)	(Liu et al., 2016)

One analysis conducted in Sweden for Tilapia and Clarias concluded that feed and feed production had the largest impact on overall footprint (Bergman et al., 2020). However, the caveat is that Sweden already utilises renewable energy integrated into their grid energy, potentially reducing the impact of energy consumption compared to that of countries that utilise fossil fuels as their main energy source. With utilisation of renewable energy, energy consumption can be much more sustainable.

The source and transportation of feed has implications for overall RAS carbon footprints. Feeds consist of plant-based ingredients such as maize gluten feed, wheat, and soybean meal (Bergman et al., 2020). Soy production contributes to substantial environmental impacts and greatly increases GHG emissions of RAS due to land transformation (e.g., deforested land in Brazil), therefore, resource origin of feed can greatly influence the environmental impact of RAS. However, RAS are typically characterised by significantly increased feed efficiency and better Food Conversation Ratio’s (FCRs), and thus, can substantially reduce feed related GHG emissions compared to other aquaculture methods (Ahmed & Turchini, 2021). Additionally, due to increased growth rates and superior FCRs, RAS energy savings related to feed use may partially compensate for increased energy costs associated with pumping and water purification.

Innovative advancements such as biofloc technology (BFT) can improve wastewater recycling and thus reduce water wastage, improve water quality and recycling of nutrients, improve biosecurity/ biocontrol, provide feed supplement and probiotic sources for cultured species, and therefore improve species health whilst improving FCRs (Ferreira et al., 2015; Nisar et al., 2022; Panigrahi et al., 2018). Essentially, fish waste is converted to a microbial protein (biofloc) which serves as a source of dietary proteins for the species within the RAS, therefore, reducing feed consumption and improving water quality and supporting higher stocking density (Nisar et al., 2022). Additionally, energy consumption can be reduced by using innovations such as a microaerophilic assimilation reactor that can significantly reduce energy consumption (up to 75%) and can help RAS to be more environmentally and economically sustainable (Yogev & Gross, 2019). By reducing feed and energy consumption, and advancements in technologies such as BFT, RAS profitability and environmental sustainability will be increased (Nisar et al., 2022; Yogev & Gross, 2019).

Waste from RAS consists of highly concentrated sludge, containing fish excrement and feed which was not consumed, and must be treated prior to disposal (Mirzoyan *et al*., 2010). Utilising the waste sludge from freshwater RAS for fertiliser or compost in agriculture (van Rijn, 2013) reduces unwanted nutrient releases and further improves the ‘circular economy’ approach. However, options for marine RAS sludge disposal are more limited. Furthermore, RAS waste reduction and utilisation include innovative suggestions such as anaerobic digestion of sludge waste products for biogas production which can be implemented as an alternative energy source and water savings strategy, thus improving RAS sustainability (Mirzoyan et al., 2010). Furthermore, integrated systems such as aquaponics can further reduce waste from RAS through nutrient uptake by plants (Gichana et al., 2018).

A note-worthy and major concern regarding the growth of the RAS industry is the fact that freshwater is scarce. This scarcity poses future challenges for resource users, including agriculture, public water supplies, power and industry sectors and environmental protection (Environmental Agency, 2020). Demand for water supply in a changing climate, where droughts are becoming more frequent, will continue to increase and further deplete natural water resources and therefore, additional water demands for RAS and production of aquatic foods will further drive pressure on this resource. Once supplied with water however, RAS can recycle up to 95-99% of water (EUMOFA, 2020) and are not prone to major water losses. However, a major constraint on future aquaculture is the availability and accessibility of quality water (Tom et al., 2021), therefore, with increased development of RAS facilities in the UK, freshwater scarcity, and thus supply, will require careful management.

Lastly, eutrophication potential of RAS is 38% lower than flow through systems (FTS) and 40% lower than open net pens (ONP), although RAS are not normally associated with eutrophication or water pollution due to filtration, extraction, and concentration capabilities of waste nutrients (Ahmed & Turchini, 2021). However, this may be specific to location of the farms and the waste treatment processes. An LCA conducted for a commercial-scale RAS farm for Atlantic salmon smolt grow-out in northern China identified grow-out effluent treatment as a key contributor to the marine eutrophication of RAS (Song et al., 2019) which could be a cause for concern. Eutrophication risk is an important consideration in the UK because eutrophication zones leading to dissolved oxygen depletion, and hypoxia, are predicted to become more frequent under future climate change scenarios (Mahaffey et al., 2023).

Four main certification bodies address the aquaculture sector: GlobalGAP, the Global Aquaculture Alliance-Better Aquaculture Practice (GAA-BAP), Friends of the Sea (FoS) and the Aquaculture Stewardship Council (ASC). These bodies develop agreed international standards for Aquaculture facilities. Based on promoting ‘continuous improvement’, compliance threshold limits set on a wide range of environmental indicators are likely to become increasingly stringent in future standard revisions. Together these observations point to ‘metrics based’ certification schemes (i.e., specifying threshold performance limits) such as the ASC standard becoming important drivers of a transition to future shore-based production. GAA-BAP standards are similarly metrics-based (Bostock et al., 2018). Additionally, ASC have introduced an eco-certification specifically for RAS farms, which describe the requirements for stringent responsible farming practises and includes energy monitoring and support for the development of strategies to reduce emissions. This will further drive environmental sustainability standards of RAS facilities for the UK.

Despite being valuable tools to assess system design trade-offs, LCA results are species and location specific (Ghamkhar et al., 2021), Proximity to market, incorporation of renewable energy to reduce carbon footprints, biofloc technologies and by-product utilisation have been identified as ways in which to reduce environmental impacts of RAS facilities (Bergman et al., 2020). Lastly, it must be acknowledged that LCA frameworks do not encompass all environmental interactions that are highly relevant within aquaculture, whereby in most cases, open net pen systems are outperformed by RAS (Bergman et al., 2020).

3.4. Regulations, Environmental Permitting and other constraints and barriers

3.4.1. Regulation applying to RAS systems.

In England, as with traditional aquaculture, production authorisations, permits and permissions are necessary to establish a RAS facility. One of the substantial drivers for moving production on land and into RAS is the decreasing availability of suitable, regulated coastal areas and the ability to obtain licenses for cage-based aquaculture which are difficult and expensive to obtain. In this respect, it is thought that these licencing issues will impact on the continued growth of near shore open system marine culture in Europe and provide a greater impetus for the development of RAS.

This section provides a shortened overview of the key regulatory areas as identified in the Cefas regulatory toolboxes (hosted by Seafish) where relevant documents can be downloaded with more detail depending on aquaculture system and location (e.g., marine, or freshwater RAS). An initial indication has been added to Table 7 below, to highlight consenting areas that may be acting as barriers to growth from experience of the FHI and previous assessments of regulatory burdens, and further detail is provided on these barriers in subsequent sections. In addition, the stakeholder survey provides information on known and potential barriers.

Table 7: Cefas regulatory toolbox RAS (short - summary)

Consent required	Regulatory / Authorising remit	Regulator /contacts
Planning permission (might not be required for internal adaption of existing farm buildings, rules on permitted development should be explored). Charges apply. Target times = 8 weeks minor, 13 weeks major or 16 weeks if EIA / HRA required.	Granting of development consents for land-based fish farms under the Town and Country Planning (Local Planning) (England) Regulations 2012 as amended	Local Authorities See relevant local authority https://www.gov.uk/find-your-local-council https://www.gov.uk/planning-permissions-for/farms/when-you-need-it
Planning permission is likely to be required for large scale RAS developments and advice should always be sought from local authorities. ***However, there may be a requirement for clarification of permitted development rights*** *for farmers wanting to adapt existing buildings for the purpose of RAS. See expanded section* ***3.4.2*** *below.*		

Water Abstraction & Discharge Licences (Either or, may not be required for small scale set ups using tap water and discharging to sewers) Charges apply Target time = 13 weeks subject to exceptions	Abstraction and Discharges under Environmental permitting regulations (England & Wales) 2010 Water Act 2003 may also be applicable for abstracting and discharging water	Environment agency 03708 506 506 enquiries@environment-agency.gov.uk https://www.gov.uk/environmental-management/water
***This may be an area for RAS that could benefit from further exploration with permitting officers in the EA**. RAS offers opportunity for increased production with less water footprint. However, appropriate methods of discharge and proportionality of costs may be worth exploring further. See expanded section **3.4.3** below.*		
Authorisation to operate an Aquaculture Production Business APB (An authorisation in principle may be available before the APB is up and running) No charges Target time = 90 days including consultation	Authorisation of aquaculture production businesses (APBs) under the Aquatic Animal Health (England & Wales) Regulations 2009 N.B. Authorisation for APB, Import & Permitting of Alien species may all be dealt with as one by FHI in many cases.	Fish Health Inspectorate (FHI) 01305 206700 FHI@cefas.co.uk https://www.gov.uk/fish-and-shellfish-farm-authorisation-and-registration
This area is unlikely to be a barrier to development of RAS systems. It is only unobtainable if higher permissions such as planning permission has not been granted in advance.		
Authorisation to import livestock Required if seed stock is to be sourced from anywhere outside England, Wales or Scotland No charges Target time = 15 to 90 days	Authorisation to import livestock for aquaculture from EU or third countries under Aquatic animal health Directive 2006/88. N.B. Authorisation for APB, Import & Permitting of Alien species may all be dealt with as one by FHI in many cases.	Fish Health Inspectorate (FHI) 01305 206700 FHI@cefas.co.uk https://www.gov.uk/fish-and-shellfish-farm-authorisation-and-registration
*This is an area **that is likely to require attention** and could be acting as a barrier to growth when sites are unable to obtain suitable seedstock for no apparent health reason. See expanded section **3.4.4** below.*		
Permitting farming of alien species. (FHI provide advice and carryout inspection to ensure that the facility can be classed as fully enclosed and be exempt from permitting under ASR) No charges (If a system is deemed not to be fully enclosed and a Risk Assessment is required then can costs fall to the applicant and can be significant) Target time = 15 to 90 days	Permitting under the Alien and Locally Absent Species in Aquaculture (England & Wales) Regulations 2011. N.B. Authorisation for APB, Import & Permitting of Alien species may all be dealt with as one by FHI in many cases.	Fish Health Inspectorate (FHI) FHI@cefas.co.uk https://www.gov.uk/introduce-or-keep-non-native-fish-and-shellfish
Providing the system is fully enclosed and can be classed as such by the FHI then this area should not be a barrier to the development of non-native species in RAS systems.		
Fish supplier permitting (live fish) No charges Target time = 10 to 20 days But most can be issued on day of request	Permission to supply and introduce fish into Inland waters. The Keeping and Introduction of Fish (England and River Esk Catchment Area) Regulations 2015 Conditions are laid out and issued under the fish supplier permit	Environment agency 01480 483968 fmapplications@environment-agency.gov.uk

	(e.g. a fish health check might be required where consultants charges would apply)	https://www.gov.uk/permission-to-move-live-fish-to-or-from-a-fishery
This mostly applies to restocking farms that are mostly in extensive low stock density ponds. It will not be a barrier for food production RAS systems.		
Approval to manufacture medicated Feed Required where veterinary medicines are to be mixed into or onto feed for feeding to the farmer's own fish. Charges apply, Conditional approval available Target time = 10 working days to validate the application + 30 working days for on-site approval inspection	EC Directive 90/167 laying down the conditions for the preparation, placing on the market and use of medicated feeding-stuffs. EU Regulation (EC) No 183/2005 laying down requirements for feed hygiene Protects animal health, human health and the environment.	Veterinary Medicines Directorate 01932 336911 inspections@vmd.defra.gsi.gov.uk https://www.gov.uk/government/organisations /veterinary-medicines-directorate https://www.gov.uk/guidance/manufacturing-and-supplying-veterinary-medicines-for-animal-feed
Unlikely to be applicable or required for many RAS systems although may be required if more existing flow through farms switch to RAS. Unlikely to a barrier and farming has been moving away from using antibiotics towards vaccination.		
Transporter authorisation Animal Transport Certificates (ATC) (ATC can be covered by FHI records)	Welfare in Transport. The Welfare of Animals (Transport) (England) Order 2006 Type 1 transporter authorisation for journeys over 65km up to 8 hours Type 2 transporter authorisation required for journeys over 8 hours	Animal and Plant Health Agency (APHA) See link for relevant area. https://www.gov.uk/government/organisations/anim al-and-plant-health-agency/about/access-and-opening. https://www.gov.uk/farm-animal-welfare-during-transportation
Unlikely to be a major barrier for RAS table production and only a minor administrative task		
On Farm welfare	Welfare of fish on farms is required by European Council Directive 98/58/EC and is covered by The Animal Welfare Act 2006, The Aquatic Animal Health (England and Wales) Regulations 2009. Welfare at slaughter is defined in European Council Regulation No. 1099/2009 and is currently implemented in England and Wales by The Welfare of Animals (Slaughter and Killing) Regulations 1995.	Animal and Plant Health Agency (APHA) https://www.gov.uk/government/organisations/animal-and-plant-health-agency/about/access-and-opening FAWC advice on farmed fish welfare - GOV.UK (www.gov.uk)
Currently unlikely to be a barrier for growth of RAS although excessive stock densities may cause problems for accreditation schemes.		
Disposal of mortalities	Disposal of fish mortalities under Council Regulation EC 1069/2009 on animal by-products. Fish which died from disease are defined as Category II material, which must be disposed of in accordance with Article 13 of EC 1069/2009	Regulation via Local authorities https://www.gov.uk/managing-your-waste-an-overview

This area unlikely to be a major barrier for growth of a RAS system although difficulties may increase with greater scale of production.

3.4.2. Permitted development application to RAS.

Certain types of work can be performed without needing to apply for planning permission. These are called "permitted development rights". They derive from a general planning permission granted not by the local authority but by Government. These rights are more restricted in 'designated areas' such as conservation areas or national parks. The Planning Portal's general advice is that you should contact your Local Planning Authority and discuss proposals before any work begins[2].

There have been, and continue to be, initiatives to get agricultural farmers to diversify into producing aquatic products within existing farm infrastructure such as barns or in spaces next to sources of alternative energy [3]. An earlier section (3.2.1) highlighted that the spatial footprint of RAS is relatively small for the large quantities of fish that can be produced, at approximately 1ha for a 1000 tonne unit. Consequently, under The Town and Country Planning (General Permitted Development) (England) Order 2015 it is worth exploring if these permitted developments apply for aquaculture businesses wanting to use variations of RAS systems in existing barns.

Under Class B – agricultural development on units of less than 5 hectares

Permitted developments include the following:

- The carrying out on agricultural land comprised in an agricultural unit, of not less than 0.4 but less than 5 hectares in area, of development consisting of— the extension or alteration of an agricultural building.
- the installation of additional or replacement plant or machinery.
- the provision of a hard surface.
- the carrying out of any of the following operations in connection with fish farming, namely, repairing ponds and raceways; the installation of grading machinery, aeration equipment or flow meters and any associated channel; the dredging of ponds; and the replacement of tanks and nets,"

Development that are not permitted by Class B include:

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[2] https://www.planningportal.co.uk/permission/responsibilities/planning-permission/permitted-development-rights

[3] https://thefishsite.com/articles/uk-land-based-shrimp-farming-initiative-scoops-2-million-funding

- it would consist of, or involve, the carrying out of any works to a building or structure used or to be used for the accommodation of livestock or the storage of slurry or sewage sludge where the building or structure is within 400 metres of the curtilage of a protected building.
- it would relate to fish farming and would involve the placing or assembly of a tank on land or in any waters or the construction of a pond in which fish may be kept or an increase (otherwise than by the removal of silt) in the size of any tank or pond in which fish may be kept; or
- any building for storing fuel for or waste from a biomass boiler or an anaerobic digestion system would be used for storing waste not produced by that boiler or system or for storing fuel not produced on land within the unit.

Therefore, under the above, it may be complicated and difficult for agricultural farmers to use permitted development rights under The Town and Country Planning (General Permitted Development) (England) Order 2015 to diversify into aquaculture.

The Scottish Government have provided guidance on permitted development rights for fish farming[4] .

3.4.3. Environmental permitting for abstraction and discharge

Within England, the Environment Agency (EA) are responsible for the permitting of abstraction of water and the discharge of water/waste into the environment. The EA is an executive non-departmental public body, sponsored by the Department for Environment, Food and Rural Affairs (Defra). Its primary role is to protect the environment and, as such, depending on the location of a site, the water quality of the source or discharge point, the EA will set target limits of amounts of water that can be abstracted from a source supply and water quality parameters that discharges must not exceed.

Abstraction

If water is to be taken from a surface source (such as a river, stream, or canal) or from an underground source, and the plan is to take more than 20 cubic metres (20,000 litres) a day, you are likely to need an abstraction licence from the EA and will need to apply prior to doing so. There are different types of water resource licences that can be applied for:

- full licence – for most types of water abstraction over 20 cubic metres a day
- transfer licence – to move over 20 cubic metres of water a day from one source to another without intervening use.
- temporary licence – to abstract more than 20 cubic metres of water a day over a period of less than 28 days.

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[4] https://www.gov.scot/publications/permited-development-rights-guidance/

- impounding licence – to create an impoundment structure such as a sluice, weir, or dam.

Abstraction licences may have a time limit linked to a common end date. This will be dependent on the abstraction strategy for the area and the business need. When the Environment Agency grants a licence for the first time, it is likely to be for between 6 and 18 years. When they renew a licence, it will normally be for another 12 years. They may also grant short duration licences where they think there may be issues with the licence or water availability in the longer term, or if the user only needs water for a short time. In certain circumstances, they will consider granting licences for up to 24 years, these will require a business case to demonstrate need. In this case, it is likely an environmental impact assessment is required as is demonstration of the need for the service throughout the duration of the licence.

Any investigations into groundwater sources of water will also require a “consent to investigate a groundwater source”. This includes investigations into amounts of available water, water quality, and effects on the environment. Upon application, the EA will discuss and direct any required environmental surveys on a range of local water features and any conditions of the permit. Once the survey is complete and submitted to the EA, they will review the survey and assess if a consent to carry out the investigation will be given. If a suitable source is identified and its use licenced, an abstraction licence will also be required.

A charge is payable to apply for a new licence, or to change (vary) an existing licence. In addition, a business will usually need to pay an annual charge (also called a ‘subsistence’ charge) once it holds a full licence.

Discharge

An environmental permit is required to discharge liquid effluent or wastewater:

- into surface waters, for example, rivers, streams, estuaries, lakes, canals, or coastal waters – known as ‘water discharge activities.
- into or on the ground, for example, discharging treated sewage effluent to ground through an infiltration system – known as ‘groundwater activities.

A permit is not required to discharge to an enclosed lake or pond. This means a lake or pond in which all the following apply:

- it contains water throughout the year, other than in extreme weather conditions.
- it does not have an outfall that connects it to a watercourse or has an outfall that only discharges in extreme weather conditions.
- it is sealed or lined to prevent water draining into the ground or soaking into the surrounding soil.

It is preferred if discharge of wastewater can be made to the public foul sewer whenever it is reasonable to do so. This would need to be checked with the local water company to ensure this is possible. An environmental permit is not required discharge via this route. A permit is charged based on the nature of the discharge and activity.

Potential barriers under environmental permitting.

In terms of potential barriers to the development of a RAS farm, there are several areas that could possibly by investigated in more detail with regulators. A previous project (Jeffery et al., 2012) identified that discharge of solid waste from RAS systems was not treated in the same way as terrestrial animal waste (use on fields). This would require further investigation with RAS farmers to see if it's still an issue or if alternative uses and solutions have been found. Increases in abstraction and discharge costs for fish farmers over the last decade have driven more farms towards increasing use of RAS (FHI, Per's comm). It would appear, that some charges for a permit to discharge waste (not requiring specific substances assessment) are not much below that of sewage facilities that include combined sewer overflows (CSO) operated by water companies. However, it is unlikely that a RAS would require a discharge permit like this for its concentrated solid waste as it can be dealt with either to sewers or by contractors. But with ever increasing size of RAS builds it may be that a permit is required for exchange of clean water that has been through the filtration systems to stop build-up of certain organic nutrients like nitrates.

It is understood that abstraction and impounding licensing were managed separately to discharge permitting but will be integrated into the Environmental Permitting Regulations in 2023. The aim being to create a proportionate, risk-based regulation, dynamic water management and permit consolidation across environmental regimes. This will be combined with a future digital service where customers can manage all their Environmental Permitting Regulations permits in one place.

3.4.4. Authorisation to import livestock.

All imports of live aquatic animals (fish, mollusc, crustacean) must meet the appropriate requirements. For all imports this starts with gaining authorisation to import from the Fish Health Inspectorate (FHI), if the species is not native to England, they will handle these requirements in tandem. They will advise on the creation of a bio-security measures plan for a potential RAS to help keep disease out and the site running smoothly. Information about the import process is provided at authorisation. Once authorised businesses must adhere to the conditions of authorisation and where applicable any licence issued in respect of non-native species. It is a requirement of authorisation that these conditions are followed including sources approved and appropriate health certification obtained and presented. The countries currently listed for supplying aquatic animals to England can be found in Europe[5] and rest of the world[6]. England's high aquatic animal health status requires that animals arriving meet equivalent or higher health status. As a result, listing does not mean that all scenarios will be possible from all sources in the listed countries. During the authorisation process the FHI will provide advice and validate the status of initial sources to ensure they meet the required standards before commitments are made to importing. They will then approve any subsequent sources as they arise.

The list of source countries for the import of aquatic animals was inherited via retained EU legislation[7]. The list was originally drawn up by the EC as part of the implementation of Directive 2008/88 with the listed countries reflecting trade with the EU at the time. The EC planned to audit the listed countries to ensure equivalence in the following years. However, to date, only a handful of audits have taken place and very few changes made to the listing. The UK retained the legislation and Annex III of listed countries EU Member States, EFTA Members and the Faroe Islands were added, via withdrawal legislation[8], to ensure any trade established while the UK was in the EU could continue. Since the UK's EU-Exit the EU has moved onto the Animal Health Law which continues to use an equivalent list in Annex XXI of Commission Implementing Regulation (EU) 2021/404[9].

Given that most listed countries, including EU Member States, have not been audited by the EU or by the UK since EU-Exit, confidence in the listed countries is based on historic trade being successful i.e., being carried out in accordance with legislative requirements and not having had a negative impact. The addition of new countries or the addition of commodities such as mollusc and/or crustacean to a country's listing require the assessment of the country's aquatic animal health controls as appropriate to the application.

As an example, if we take the import of prawn larvae for RAS farms, they can currently be sourced from the USA, EU, Iceland, Norway, or the Faroe Islands, but in reality, this list is more likely to mean only the USA as importers in Europe will be constrained by their 'equivalent' list when sourcing initial stock. Farms in England will need to provide the FHI with as much detail as possible about the planned source site e.g., species on site, source of stock introductions, water supply, sample and result history, the competent authority monitoring the site. This is then validated by the FHI and approval to use the source given as appropriate. Only a few sites have been presented to the FHI and approved as sources, to date. This is very limiting to the growth of a crustacean production industry in England, especially with some of these sites being in areas prone to hurricanes. Industry is keen to expand their options, however, listing new countries is a complex and lengthy process.

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[5] Aquaculture+Products.pdf (amazonaws.com)
[6] Aquaculture+Products.pdf (amazonaws.com)
[7] https://www.legislation.gov.uk/eur/2008/1251/contents
[8] https://www.legislation.gov.uk/uksi/2020/1388/made
[9] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A02021R0404-20221220

Upon EU Exit the UK Office for Sanitary and Phytosanitary Trade Assurance (UK Office) was created to ensure trading partners meet import conditions for food and feed safety and standards for animal health and welfare, roles which were previously carried out within the EC. The addition, amendment and removal of countries, territories, zones, compartments, and establishments from UK listings, including for aquatics, is now handled by the UK Office in consultation with the relevant policy teams. Once an application is made to the UK Office by a trading partner they will work with agreed policy team's technical experts, such as Marine Scotland and Cefas, to validate that the applicant country has at least an equivalent aquatic animal health regime in place and sites that can meet UK requirements. This process is likely to take 12-24 months minimum to complete, depending on speed of responses and whether an in-country audit is required. Thailand has recently started this process with the UK office with regard to crustaceans.

This whole process of the retained EU list and the listing of these diseases could be reviewed by an expert group. The rationale for this review process being.

- The main reason to maintain a yellow head virus (YHV) / Taura Syndrome Virus (TSV) free status is to future proof the health status of a shrimp industry –but this argument maybe weak because RAS farms will be epidemiologically isolated. The controls need to be balanced against the constraint listing imposes on development of the industry.
- YHV and TSV do not meet listing criteria primarily because there is no threat to biodiversity. Cefas Epidemiologists provided a Risk Assessment to Defra for these diseases.
- It has been suggested that these diseases should be left to the industry to manage and there is no public good argument for government involvement.
- The industry should require freedom from important shrimp pathogens for business reasons as it may not be commercially viable to farm shrimp in recirculation systems without excluding important infectious agents.
- In some situations, farms may prefer to import larvae that are SPR (specific pathogen resistant) rather than free.

Any future review should balance the current process and the bullet points above against barriers to growth for what are effectively closed epidemiological sites. However, other scenarios such as future exports, need to be factored in as does the fact that science has shown the virus is already present in imported fresh and frozen prawns that are distributed across UK supply chains.

We have been informed that this issue has been raised with Defra aquatic animal health teams and that there is no appetite to amend the historical listings from retained EU legislation.

3.4.5. Hygiene regulations and application to RAS

Hygiene Standards relating to the processing of fish for human consumption are set in place by the Food Standards Agency (FSA). Regulations are in place to ensure food businesses and handlers must ensure that their practices minimise the risk of harm to the consumer. Part of complying with food safety is managing food hygiene and food standards to make sure that the food produced is safe to eat.

There are many considerations that must be met with strict practices, standard processes, training, and record keeping ensuring food is as safe as possible for the consumer, such as:

- Compliance with specific requirements for processors and processing facilities
- Traceability
- Cleaning schedules
- Temperature monitoring
- Management controls
- Health standards
- Training
- Monitoring

By law, food business operators must ensure that food handlers receive the appropriate supervision and training in food hygiene, which is in-line with the area they work in and will enable them to handle food in the safest way.

Although the FSA effectively ‘set the standards’ for safe food production, local authorities are responsible for enforcing food hygiene laws. Authorised officers have the right to enter and inspect premises and enforce food safety regulations to ensure food is fit for consumption. They will audit compliance with hygiene requirements on all aspects of the requirements.

That said, there is sometimes confusion as to where the local authority remit starts with respect to the processing of fish from an aquaculture facility and if the processing and aquaculture production facility are physically close to each other or part of an overall site. This has led at times food hygiene standards being applied to an aquaculture facility, which is questionable and would not be applied elsewhere in the processing of animals for food production. Measures should be in place to ensure separation, rather than subjecting an operation to standards that will be almost impossible to achieve. Unfortunately, food hygiene standards have been applied at some sites and this is clearly an area where greater education and potential specific guidance for the processing of aquaculture products would benefit local authorities and industry.

3.4.6. Enterprise zones and other opportunities

With global interest in the growth of RAS systems there is interest in how to develop the sector. There have been articles about new aquaculture parks and significant investment into the RAS sector in middle eastern countries. Funding of special development zones has been suggested, with increased costs on open net pen potentially making RAS a more attractive option (Bostock et al., 2018)

Within England, Enterprise Zones[10] (EZ) are part of the Government's wider Industrial Strategy to support businesses and enable local economic growth. The first 24 Zones were launched in 2012 and 24 new Zones were created in 2016 and 2017. Briefly, these zones provide[11] :

- Enhanced Capital Allowances (ECA), first-year allowances of 100%.
- Relief is given for investment in new plant and machinery for use in designated assisted areas within EZ.
- An investment limit is €125 million.
- ECA are available for UK resident trading companies from 1 April 2012 to 31 March 2021, or 8 years from the date the area was designated as an EZ or treated as so designated, as extended by Budget 2020.
- Business rate relief. Relief is available for businesses that move into an EZ before certain dates. Businesses receive a business rate discount of up to 100% over a five-year period.
- Simplified local authority planning, for example, through Local Development Orders that grant automatic planning permission for certain development (such as new industrial buildings or changing how existing buildings are used) within specified areas.

It would seem sensible for any potential new RAS farms to locate within one of these zones (given a suitable water source) to capitalise on the benefits provided. However, further reading reveals that certain sectors are excluded and do not qualify for expenditure. Included within the list are:

- Fisheries and aquaculture sectors.
- Primary production of agricultural products, including farm activities preparing a plant or animal for the first sale.

3.5. Key technical constraints within the RAS sector

Whilst the technical complexities and challenges linked to RAS are outside the scope of this report, it is necessary to highlight some of the general operational and technical issues that are raised within existing literature.

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[10] https://enterprisezones.communities.gov.uk/about-enterprise-zones/

[11] https://www.rossmartin.co.uk/capital-allowances-75082/802-enterprise-zones-plant-and-machinery-allowances

3.5.1. Underlying RAS principles

In RAS, it is possible to control culture conditions, collect feed related waste and maintain high levels of biosecurity. RAS are often classified by their daily water replacement ratios, i.e., the percentage of the overall system volume replaced by fresh water in a 24-hr period. A flow through system by design will have water replacement ratios of upwards of 100%, whereas by convention, intensive or full RAS will have a water replacement ratio of less than 10%/day. The most advanced RAS are capable of operating on water replacement ratios of less than 5%/day.

The key principles of a RAS are to:

- Provide a suitable physical environment for the fish with respect to space, water flow conditions, stock density.
- Protect the stock from infection by disease agents.
- Provide for the physiological needs of the fish (mainly oxygen and nutrition).
- Remove metabolic wastes from the fish (notably faeces, ammonia, and carbon dioxide).
- Remove waste feed and breakdown products (solid and dissolved organic compounds).
- Maintain temperature and water chemistry parameters within acceptable limits.

3.5.2. Operational and Technical Challenges

RAS are designed to minimise water consumption, control culture conditions, and allow effective management of waste streams. They can also provide some degree of biosecurity through measures to isolate the stock from the external environment. However, challenges remain both operationally and technically.

Operational challenges

Operational and management challenges have been identified in recent reports and papers. Some of these challenges include:

A lack of suitably experienced RAS managers and operators. Staff with existing open system skills may need a minimum of 6-10 months training on the job before they can operate commercial scale RAS fattening farms (Tew, 2021).

Management of biosecurity. Disease free RAS are impossible to guarantee, but well designed and managed RAS create very stable environments which are optimal for fish performance. Disease outbreaks are significantly reduced under such conditions but can be significantly influenced by water quality issues and by high levels of CO_2, NH_3 and particulate matter. Proper treatment of incoming water can greatly minimise the risk of pathogen entry. However, poor design and/or management of the treatment process can enable access by parasites and may create ideal conditions for disease outbreaks. Under high stocking densities the impact of such outbreaks can be significant. (Tew, 2021). The disease status of stock is obviously critical to the management of potential disease outbreaks in such systems. Aquatic animals reared in disease free RAS can be particularly naive to pathogens due to their lack of exposure and developed immune response, and so this should be considered if the animals are to be stocked into more ’open’ systems for production.

Management of stock welfare can be impacted by exposure to stressful situations in relation to high stocking density in RAS and chronic exposure to poor water quality and associated metabolic by-products due to inadequate water treatment technology or inexperienced management(Tew, 2021).

Issues with the choice of site or location for a particular species can cause problems (Russell, 2015) Examples include:

- Choosing a freshwater site with limited ability to use and discharge water.
- Building at too small a scale or in a pre-existing building, for multiple reasons.
- Locating a farm where the water requires chilling.
- Constructing in a place with no existing aquaculture and associated support industry
- Locating a site where energy supplies may be inadequate for operation.

Technical challenges

Some of the recognised technical challenges are:.

Low awareness of the broad range of water quality variables that require 24h in-line monitoring – especially in marine RAS (Tew, 2021).

The utilisation of RAS farm waste for on-site energy production. This approach is shown to be feasible in trials. However, the investment in anaerobic digesters and equipment for conversion of gases to usable energy needs to be carefully balanced against the potential savings in power consumption. Ideally, energy generation utilising RAS farm waste should be implemented on site. This option should be increasingly attractive with larger farm sizes.

Issues leading to failure with salmon in RAS have been listed as (Russell, 2015)

- Stocking the facility with live fish rather than starting with eggs, which can be disinfected.
- Skipping the use of vaccines due to the assumption that disease is not an issue.
- Pushing the limits of system carrying capacity and stocking density
- Use of continuous production models in which systems are always stocked, with no downtime for system cleaning and resetting to break disease cycles and to eliminate carriers of disease.
- Use of pressurized oxygenation systems with inadequate total gas pressure (TGP) regulation
- Inadequate degassing infrastructure for CO_2 stripping and TGP associated with warming of cold source water.

- Skipping the use of pathogen control on the source water
- Using cheaper lower quality feeds without consideration of impact on water quality

3.5.3. Future Technical developments of RAS.

Innovation and technical developments recently within the RAS sector include additional filtration via the use of electrochemical oxidation technology such as ELOXIRAS to remove build ups key pollutants such as ammonia, nitrite, or pathogens.

Other areas where RAS may well benefit in the future are around the use of gene editing and precision breeding. This technology may well provide benefits for stock held within secure RAS systems. The Genetic Technology (Precision Breeding) Bill is currently in its final stages in parliament (as at 15.2.23). When passed, this will allow the sector to benefit from the new technology via traits for faster growth and increased disease resistance, thus helping with both welfare and overall economics by reducing the energy cost per kilo of fish produced.

New RAS entrants need to proceed with caution and optimise system design, economies of scale, input costs, marketing, and sales plans. In addition, experienced staff, system flexibility and further development of surrounding industry (i.e., fry supply and technological progress) remain critical if the RAS sector is to grow. Issues that remain can be addressed through a combination of research and development and adoption of accreditation and quality labelling schemes (Huntington T & Cappell R, 2020; Jeffery et al., 2012).

3.6. Financial and economic constraints

3.6.1. Capital expenditure and operating cost.

One of the toughest challenges for RAS operations is to be found in the amount of capital expenditure (including depreciation, CAPEX) needed to start and operate RAS (de Jong, 2019; Engle, Kumar & Senten, 2020; EUMOFA, 2020). CAPEX varies widely between different systems, species, and locations. Some stakeholders state that the total investment cost of a full-cycle RAS facility for Atlantic salmon is like that of traditional farming methods in Norway, due to the high cost of traditional farming licenses (de Jong, 2019). In general, CAPEX in RAS account for about \$2 per kg fish (ca. £1.70 per kg fish) (Warrer-Hansen, 2021), however, an Atlantic salmon RAS farmer in Norway reported to have a CAPEX need of NOK 140-200/kg salmon (ca. £11-16/kg salmon). In comparison, flow-through systems CAPEX was reported to be NOK 60-71/kg salmon (ca. £4.80-5.70/kg salmon) (Ramsden, 2023b) while traditional cage-based systems reported an average CAPEX of NOK 25/kg salmon (ca.£2/kg salmon) (EUMOFA, 2020).

Operating costs (OPEX) are generally considered higher in RAS than in traditional systems. This is mainly due to the energy-demanding process of treating and transporting the water. The highest costs connected to water treatment are related to pumping and lifting of water, CO_2 removal, temperature control and oxygenation. These costs will of course vary with different water sources. Naturally, the costs will be reduced if the inlet water can flow into the facility (reduced need for pumps), and if it has high quality and is at the right temperature (reduced need for filtering and treatment).

In all aquaculture production, feed is one of the major OPEX. For RAS. it can be a significant part of the OPEX if the facility uses specialised RAS-feed (EUMOFA, 2020; Murray et al., 2014). However, due to the controlled water temperature year-round within RAS, feed was shown to be used more efficiently compared to other systems (Engle, R Kumar & Senten, 2020). Compared to traditional sea cage production, the energy-demanding, new, and expensive RAS technology increases OPEX by almost 50%. Of this 50%, energy accounts for approximately 15% and depreciation 20% (EUMOFA, 2020). Translated into capital productivity, per dollar of capital, catfish production yielded twelve times greater volumes and trout production in raceways two times greater volumes per dollar of capital than RAS. In addition, labour productivity was shown to be substantially lower in RAS farms producing catfish and trout in the USA than in conventional systems. Economies of scale tend not to be enough to offset the differences in cost for the systems irrespective of the species under consideration (Bailey & Vinci, 2019; Engle, Kumar & Senten, 2020).

Lately, OPEX (before interest and tax) reached about NOK45 per kilogram salmon produced in traditional aquaculture production systems in Norway, while flow-through systems reported to produce a kilogram salmon for NOK 31-34, and different RAS operators reported their OPEX to be NOK 36-54 per kg salmon (Ramsden, 2023b).. The difference in OPEX between flow-through system and other production methods were explained by the lower electricity usage per kilogram salmon production. While flow-through systems show lower OPEX at times of high electricity prices, RAS water use can be a substantially lower than the daily new fresh water used in flow-through systems (Gaumet, Haegh, Ulgenes, 2013; Olsen, 2014).

Liu et al. (2016) compared the economics of two ‘typical’ 3,300mt production units for Atlantic salmon using open net pen (ONP) and land-based freshwater closed containment systems (LBCC-RAS). They calculated similar OPEX for the two production systems but very different capital costs. The estimated CAPEX for the RAS unit was $54 million which is 80% greater than the costs of the open pen system with a CAPEX of US $30 million. The financial analysis indicated that grow out in RAS would not be profitable unless a 30% price premium could be obtained (Liu et al., 2016).

Examples have shown that RAS can successfully be used to occupy abandoned brownfield sites and therewith provide new use of existing infrastructure (Mayer, 2023). RAS can also be integrated into existing infrastructure (Ramsden, 2023a). Finding such locations can significantly reduce CAPEX as well as OPEX.

In addition to higher expenditure and operating cost, incidents were reported that RAS facilities had experienced mass mortality, due to different technical errors in the recirculation flow, i.e., if something went wrong it had drastic consequences. As such RAS output is subject to high uncertainty (EUMOFA, 2020; Jaffa, 2021; Ramsden, 2023b).

3.6.2. Price premium and demand

Most promoters of RAS project higher market prices for their product, based on its sustainability credentials, localness, and associated freshness. Often this price premium is estimated to be between 5% and 20% (EUMOFA, 2020). However, most RAS products serve niche markets and need consumers willing to pay a premium for environmentally friendly produced fish in RAS (Zander & Feucht, 2018). While consumers tend to prefer wild-harvest fish compared to farm produced fish and are willing to pay a premium (Bronnmann & Asche, 2017), it is more difficult to achieve a premium price for sustainably produced fish from an aquaculture system. Consumers value sustainability aspects of production based on several criteria, for example, low level use of hormones and antibiotics, low water usage, low energy usage, or locally produced (i.e., low transportation emission). These criteria are traded-off to formulate a willingness to pay (Zander & Feucht, 2018). Thus, the willingness to pay a premium for RAS produced fish may be uncertain as the environmental benefits of RAS may be traded-off against other sustainability criteria of other food production systems. Whilst consumers are willing to pay a price premium for fish produced in sustainable aquaculture (van Osch et al., 2019), in practice it has only been observed in a few cases (Jaffa, 2021). For example, salmon produced in RAS achieved an average price of £6.90/kg in the USA compared to an average international market price of £4.10/kg. However, the same RAS operator also reported selling its salmon in Denmark for an average of £4.00/kg (Jaffa, 2021). Thus, achieving a price premium to cover the increased production cost is one of the challenges that RAS operators face. While communicating to the consumers that they are buying a premium product is one challenge, another is that, for example, Atlantic salmon produced in land-based RAS may have different eating qualities. The water flow in RAS leads to salmon actively swimming for their whole life which creates a firmer flesh structure, lower fat content (14%) and a different taste from the one consumers expect from salmon and is sometimes even referred to as “off-flavouring” (Olsen, 2014). Depuration in cleaner water tanks prior to placing on the market can remove any flesh taints from the system water.

3.6.3. The bottom line and sustainability

Achieving a positive bottom line depends upon several factors, including competition from other producers, production volume, product quality and consumer demand. Theoretically, all aquatic species can be farmed in RAS. However, not all species are assumed to perform well in a RAS environment, and not all species provide market opportunities which justify the higher production costs.

Currently, RAS economics work in favour of the vertically integrated RAS smolt units that are head starting salmon production for a company's grow-out phase and can reduce mortality of smolt significantly (Terjesen, 2014; Warrer-Hansen, 2021). It is argued that RAS technology works best for small species that are robust, high value and ideally have a short life cycle e.g., juvenile production (Prickett, 2022). However, there are RAS producers of tilapia or catfish, but due to these species being sold for lower prices, profitability is difficult to achieve (Warrer-Hansen, 2021). RAS is also potentially of use for producing higher unit-value species such as European sea bass (*Dicentrarchus labrax)*; gilthead sea bream (*Sparus aurata)*; Senegal sole (*Solea senegalensis*), turbot (*Scophthalmus maximus*) and yellowtail (*Seriola lalandi)* (Murray et al., 2014; Warrer-Hansen, 2021).

Uncertainty regarding future costs of production, including biological risks, and the long time-period between the initial investment and the revenue from RAS production, increases the need for financial flexibility. There is also uncertainty regarding the expected return on investments due to market risks. Due to RAS not reaching a break-even point as quickly as traditional aquaculture systems (Prickett, 2022), investors are harder to find, particularly in the climate of a worsening lending environment (Ramsden, 2023b). However, investors indicated that they are not totally opposed to investments into RAS (Howell, 2022).

As the demand for transparent and sustainable food is increasing, the two main drivers for RAS growth seem to be proximity to the market and reduced environmental impact. Proximity to the market is a driver for RAS growth, since recirculation of water makes facilities less dependent on water sources/location. Furthermore, RAS makes it possible to farm foreign species by adjusting the growth environment, including lighting, temperature, salinity, and water current. Near-market RAS production, and subsequent shorter transportation, reduces the carbon footprint of the products in the market compared to that of open net pen systems which are often located further away and produce fish that need to be shipped by plane to the consumer (Liu et al., 2016). On the other hand, RAS production is energy-intensive, and the environmental impact (as measured with LCA, for example) is highly dependent on the energy source. In this respect, RAS is especially interesting when combined with renewable energy sources (Fernández-López et al., 2009; Mirzoyan et al., 2010). For example, using the sludge produced in RAS to produce biogas to heat the RAS could lead to environmental and economic benefits (Mirzoyan et al., 2010). It was estimated, however, that using solar water heaters instead of electric heaters only lead to lower heating cost for indoor systems in moderate climates and the use of 50% to 100% heating strategies in the cold climate is necessary. It was previously suggested that if renewable energy is used, it would have environmental benefits rather than economical ones (Kim & Zhang, 2018) , However, these may well become economic benefits if current energy costs are sustained or increase.

Another option to increase profitability of RAS is to sell by-products such as salt from saline systems (Fernández-López et al., 2009) or valorised sludge as fertilizer (Cristiano et al., 2022). Adding the additional process of valorising sludge would not substantially impact the environmental benefits of RAS, it would, however, increase the complexity in licencing and it has not been shown to be cost-effective (EUMOFA, 2020).

3.6.4. Economic Challenges

RAS faces some additional economic challenges compared to traditional aquaculture systems, such as:

i. **Species selection**. RAS production needs to be profitable to be economic viable in the long-term and be able to compete with imported fish or domestic production in traditional systems. As such, the benefits of implementing RAS need to outweigh the costs. Species selection is a crucial component to achieve higher benefits than costs in RAS production and need to be carefully considered.
ii. **Waste management**. While RAS farms enable operators to avoid any release of particulate solid or dissolved nutrient waste into recipient waters, there are costs of implementing waste management into the production programme that traditional aquaculture production does not face.
iii. **Expertise.** Investors in RAS technology, even those with aquaculture experience, generally know little about water quality control, sea water chemistry and waste management at the industrial scale. Equally, RAS technology suppliers often know little about aquaculture and / or have a weak biological background. Expertise of both systems would improve RAS developments but are difficult to find.
iv. **Uncertainty.** Predictions about economic viability of a RAS projects are often based on assumptions and variables related to expected market prices, utilisation of the waste stream, product quality, optimal and maximum densities achievable, energy costs and costs relating to depreciation and interest on loans. These are subject to change and uncertainty. Moreover, assumptions are often based solely on small pilot or research projects as data/experience of larger scale operations are still lacking.
v. **Pricing.** The assumption that premium prices can be secured for a RAS farmed products by meeting sustainability criteria, often fails to hold true due to lack of consumer awareness. RAS is considered to serve a niche market of consumers.

3.7. Social constraints and public perception

The latest developments around RAS are not yet reflected within social science research. So aims to establish and extend RAS within the UK raises questions about perceptions and social constraints on the sector. Except for Fudge et al., 2023a, the current literature does not address RAS within a social or cultural context at the time of this study. Most reviewed papers focused on public perceptions of (an expanding) marine-based aquaculture sector and the fin-fish sector. Rather than just focusing on RAS, the literature review for this section was conducted under the research questions “what social factors influence the aquaculture industry?”. This section therefore adjusted the research scope to analyse social factors of relevance to the general aquaculture industry in England and key themes relevant for RAS were extracted in an additional step.

Overall, three key themes were identified: issues within the facilities, the public (risk) perception on aquaculture facilities, and place-attachment and local value of landscapes.

3.7.1. Issues within the facilities

Research on RAS systems often point out and seek solutions for technical challenges. However, only a few papers recognise problems related to poor management and lack of communication or knowledge exchange between the involved parties. Problems raised are for example a lack of investments in tanks, missing back-up systems and alarms, and equipment failure. Systems fail due to the solids management, biofilter operation, and overall poor management. Badiola et al. (2012) point out that there is: “no need for more information or literature on individual components, what is needed is the improvement of the overall approach to RAS system design (not just technical feasibility, but also economic feasibility) and improvements in design calculations (being more realistic and less idealistic and having in mind that the system can go wrong)” (p.30). They identify key barriers as: “poor participation by the producers; a disincentive on sharing information; and a lack of communication between different parties. The main issues are poor designs of the systems, as many had been modified after a previous approach was unsuitable; and their poor management, due mainly to an absence of skilled people taking responsibility for water quality and mechanical problems” (p.26).

Their work highlights the importance of knowledge exchange between suppliers, operators, and individual workers. This also includes a lack of documentation about system failures, outbreak of diseases, and the lack of controllability of the water quality (Bostock et al., 2018). These initial barriers suggest that system suppliers need to offer more support for less experienced operators to train them in biosecurity. While there is a need for experienced RAS operators, these cannot be trained by universities alone. Knowledge exchange within the industry is therefore a key challenge.

Overall, research on experiences and opinions from the RAS industry is rare and is certainly showing a gap within the current literature. The interview method used in the papers above showed to be useful in identifying main issues and informing (future) operators about challenges and possible improvements, especially in knowledge transfer.

3.7.2. Stakeholder perception and aquaculture

A second key theme included public perception of the aquaculture industry. Location and planning permission for RAS facilities is a possible barrier for the industry, and it is therefore necessary to understand public perceptions on these facilities. Relevant papers were found with the search terms Aquaculture AND Perception. The search results were scanned, and 22 papers were read and analysed. The literature review excluded articles which were mostly focusing on aquaculture and consumers choices, as many studies were concerned with the perceived risk of eating farmed fish. Instead, of being interested in the public perception of the industry within the communities.

Most papers included in the review focused on salmon aquafarming, accompanied by a regional focus on salmon producing countries like Norway and Chile and the perception on open-net pan systems. However, their findings indicate that RAS can be promoted as a more environmentally sustainable option to open-net pen systems. Local communities and environmental lobbyists were usually concerned with the lack of barrier between the aquaculture sites and the open sea. The global growth and intensification of salmonid production in ‘open’ net-cage systems has been accompanied by a sustained campaign, by often well-resourced civil society and other interest groups, lobbying against the environmental impacts of salmonid farms in marine and freshwater bodies. Lobbyist groups have long argued that salmon farming is damaging wild salmon fisheries, as well as the wider environment. Concerns include the escape of farmed species and their mixing with the wild population, spread of diseases and sea lice through polluted water, and other environmental impacts. Closing off the production system through RAS would minimize the perception of possible interaction between the aquafarm and other bodies of water. The literature review suggests that the negative social perception and connected environmental concerns around marine aquaculture systems might not apply to the full extent to future RAS operations (excluding the concern about animal welfare within aquaculture), yet the public perception on RAS in the UK is still to be tested. (Fudge et al., (2023a) focus on the social acceptability of aquaculture in general and the impactions for future RAS projects. Both credibility and legitimacy of the operators are key points within their studies, as is trust towards the industry as an overarching theme. They also conclude that engagement strategies between companies and communities are helpful to establish trust and acceptance.

To gain a more general insight on possible perceptions on the RAS industry, papers on integrated multi-trophic aquaculture (IMTA) were analysed. IMTA promises a balanced ecosystem approach and the prevention of potential environmental impacts from fed aquaculture. While different from RAS in its technological system, IMTA claim similar benefits compared to open-net pan farms. Together with the search term “Perception”, the search results delivered more details on possible public environmental risk perceptions. IMTA experience in Norway has shown that negative key perceptions around (salmon) aquaculture can be counteracted by positive narratives. This especially includes environmental concerns around escaping salmon, and the environmental damage to coastal landscapes. Future acceptance of IMTA must focus on communicating the (possible) benefits for communities: more jobs, increased business activities, and a better environment. Jobs could include permanent positions as well as seasonal workers to harvest and process (Ellis & Tiller, 2019).

3.7.3. Location and place of aquafarms

Only a few studies with a focus on the physical location of aquafarms are available. Next to technical considerations, the acceptance of the community in which the industry is settling is a factor to consider. A study in Norway shows that aquafarms have struggles in gaining access to space, and business stakeholders stated that they need better public acceptance and a better reputation among these stakeholders (Ellis & Tiller, 2019). Especially fruitful for a first theoretical understanding of possible RAS barriers in the implementation phase are papers which work with concepts of place attachment and the value of local landscapes. Place attachment can be defined as ways people are embedded into their socio-physical environments and can help understanding what happens if these environments are disrupted, for example through facilities.

A case study on mussel farm locations in the Baltic Sea (Germany and Denmark) explored the concerns communities have towards possible intervention in landscapes through aquafarming (Petersen & Stybel, 2022). A key finding was that local acceptance of a facility depends on historic experience with facility management in the community. Concerns include the visual disruption of the land and waterscape, competition for space, and additional waste. Overall, it became clear that former and existing facilities in the community have negative effects on the perception of new established mussel farms. More work on public perceptions of different forms of aquaculture and the impact on the environment is needed to fully understand and influence those perceptions. In addition to personal experiences, collective memories of intervention landscapes play a role, as disruption and social distrust have been generated. The authors therefore see community involvement as crucial for ensuring new facilities address local concerns.

Other comparable case studies which focus on the perception of local communities on new emerging facilities like aquafarming projects and renewable energy facilities use the concept of sense of place, which includes ideas of place attachment and place meaning. Petersen & Stybel (2022) provide a list of potential issues that can arise by new facilities and could potentially disrupt individual and communal sense of place. These include the impact in the landscape (visual, auditory, and olfactory), former/current uses and experiences of the area, risk and security, environmental impact, ownership of the area (communal or private, local or remote), local economy (threat to, interference in or contribution to local economic activities), involvement of local stakeholders and residents in planning and decisions, trust or distrust towards developer, contractor and relevant public authorities.

4. Stakeholder knowledge elicitation

To verify the findings of the literature review, an online survey was distributed to stakeholders identified as experts on RAS. This section reports the first results of the survey. The survey was distributed to 66 experts on 10 February 2023 with a reminder following on the 20 February 2023. At the closure of the survey, 29 of the approached stakeholders completed the questionnaire (i.e., response rate of 44%). Stakeholders responding to our survey identified themselves as RAS operator (past, current, potential) (14), academia (4), RAS consultant (4), RAS supplier (3), NGO (2), RAS funder (1) and representatives of a Research Technology Organisation (1).

Stakeholders were asked to rank the barriers to development of different types of RAS systems. Out of the 29 stakeholders, 14 ranked the barriers for two types of RAS and the remainder ranked barriers for one, hence the survey resulted in 43 rankings. Although all of the systems considered were mentioned by at least one of the stakeholders as being one of the top three they are familiar with, ranking on barriers was achieved for only 9 types of RAS system: (1) Aquaponic, land-based (freshwater); (2) Bio-floc raceways and pond systems, land-based (freshwater); (3) Danish model farms (outdoor semi closed system), land-based; (4) Fully enclosed (full recirculation), land-based (freshwater); (5) Fully enclosed (full recirculation), marine-based; (6) Fully enclosed, full recirculation, land based, salt water; (7) Marine floating (full RAS), marine-based; (8) Partial recirculation (with limited inflow), land-based (freshwater); and (9) Pump ashore (partial recirculation), marine-based.

From the 21 species listed in the survey, 17 were chosen as one of the top three species stakeholders were most familiar with. As such, it seems the survey reached a variety of knowledgeable stakeholders to elicit their opinion on the barriers for the adaptation of RAS in England.

4.1. Ranking of perceived barriers

The stakeholders were asked to rank barriers associated with regulatory burdens, resource availability, profitability, and social constraints for the RAS they were most familiar with (or second most familiar with if they agreed to do this). “Profitability consideration” was ranked 30 times as the top barrier and was the top barrier for most of the systems ranked in the survey. Production costs were of concern for the stakeholders, resulting in extended periods before the break-even point is reached compared to traditional aquaculture systems. Resource availability was ranked eight times as the top barrier, in particular appropriate space in the marine environment, as well as for land-based systems, were a main concern for stakeholders. The regulatory burden was ranked twice as the strongest barrier to develop RAS and 11 times as second largest barrier for the development of RAS. While some stakeholders pointed out that it is too difficult to meet the environment and animal health regulations, other stakeholders pointed towards the lack of support for RAS by providing identified development zones, hence touching on similar issues to the stakeholders that stated resource availability was the biggest concern hindering the development of RAS in England.

A summary of the rankings of the top barrier by system and stakeholder can be found in Table 8. In summary, economic concerns and regulatory barriers are perceived to be the biggest hinderance to the uptake of RAS in England.

Table 8: Summary of the barriers ranked as the biggest hinderances to investment or operation of different types of RAS. Number of responses are provided in brackets [ ].

System	Stakeholder role	Main barrier	Subtheme	Detailed Subtheme
Fully enclosed (full recirculation), land-based (freshwater) [13]	RAS consultant [2]; RAS operator [1]; Academia [3]; NGO [2]	Profitability [8]	Production cost	Extended period before reaching break-even point [8], Difficult to find investors [5], High variability in outputs [3], Risk of production success [1]
	RAS supplier [1]	Regulatory burden [1]	Environment and animal health regulations [1]	Too difficult to meet
	RAS operator [1]	Regulatory burden [1]	Available financial support / loans / grants are not sufficient [1]	No suitable enterprise zone
	RAS operator [1]	Resource availability [1]	Water	Match between location, water and labour availability and energy cost
	Academia [1]	Resource availability [1]	Energy	High cost, High cost of renewables/ability to install on site
	RAS operator [1]	Social barrier [1]	Suitability and demand of species for the UK market	Niche market
Fully enclosed (full recirculation), marine-based [10]	NGO [1], RAS operator [3], RAS consultant [1]; RAS supplier [2]	Profitability [7]	Production cost	Difficult to find investors [4], Extended period before reaching break-even point [3], High variability in outputs [2], Costs in general [1]
	Academia [1]	Profitability [1]	Sales profit	Marketing costs, Low price
	RAS operator [1]	Resource availability [1]	Water	Lack in sufficient or limited quantity, Lack of access to sufficient quality
	RAS operator [1]	Resource availability [1]	Technology and supply	Inadequate design and operation
Partial recirculation (with limited	RAS operator [3], RAS consultant [2]	Profitability [5]	Production cost	Difficult to find investors [3],Extended period before reaching break-even point [3], High

inflow), land-based (freshwater) [7]				variability in outputs [1], uncertain return [1]
	RAS operator [1]	Profitability [1]	Processing and distribution cost	There are no processors for trout, margin is too small
	RAS funder [1]	Social barrier [1]	Lack of support through local communities	Environmental risk perceptions
Danish model farms (outdoor semi closed system), land-based [5]	RAS operator [2]; RAS supplier [1]	Profitability [3]	Production cost	Extended period before reaching break-even point [3], High variability in outputs [1]
	RAS consultant [1]	Profitability [1]	Sales profit	Low price [1], Lack of consumer demand [1]
	RAS supplier [1]	Resource availability [1]	Water	High cost for water usage (abstraction, discharge, or treatment) [1], Lack in sufficient or limited quantity [1]
Aquaponic, land-based (freshwater) [2]	RAS operator [1]; Academia [1]	Profitability [2]	Production cost	Extended period before reaching break-even point [1], Difficult to find investors [1], High variability in outputs [1]
Bio-floc raceways and pond systems, land-based (freshwater) [2]	RAS funder [1]	Social barrier [1]	Lack of support through local communities	Concerns about crayfish [1]
	NGO [1]	Profitability [1]	Production cost	Extended period before reaching break-even point [1]
Pump ashore (partial recirculation), marine-based [2]	Academia [1]	Profitability [1]	Production cost	Extended period before reaching break-even point
	Representative of a Research Technology Organisation [1]	Resource availability [1]	Land	No available land sufficiently close to market/distribution, High cost, Not enough suitable space available
Fully enclosed, full recirculation, land based, salt water [1]	RAS operator [1]	Resource availability [1]	Technology and supply	Availability of appropriate/affordable feed, Availability of technology/equipment, Insufficient access to robust/reliable /larvae supplies/source stock
Marine floating (full RAS), marine-based [1]	Representative of a Research Technology Organisation [1]	Resource availability [1]	Building regulations, planning or marine licences	Too restrictive, Too unclear

Stakeholders were further asked to rank drivers of previous failures of RAS operations in England. Ranked as the strongest drivers for RAS operation failures were:

- System design [20 times ranked as one of the top three drivers],
- Energy costs [18 times],
- Final sales prices achieved [17 times],
- Technical problems [16 times],
- Disease problems [10 times],
- Lack of finance [2 times], and
- Installation going wrong or being a lot more expensive than planned [1 time]

Asked which RAS is the most likely to be successful within England based on their experiences, stakeholders saw the highest potential for land-based RAS. The following RAS were ranked according to their highest potential future as perceived by the stakeholders in the survey:

- Fully enclosed (full recirculation), land-based (freshwater) [8 times highest rank]
- Partial recirculation (with limited inflow), land-based (freshwater) [6 times]
- Fully enclosed (full recirculation), marine-based [5 times]
- Aquaponic, land-based (freshwater) [3 times]
- Danish model farms (outdoor semi closed system), land-based (freshwater) [2 times]
- Semi-contained (part RAS), marine-based [2 times]
- Bio-floc raceways and pond systems, land-based (freshwater) [1 time]
- Pump ashore (partial recirculation), marine-based [1 time]
- Land based, fully enclosed, salt water [1 time]

Questions were also asked about the species the stakeholders would expect to have the largest potential to be grown in a RAS in England. Salmonid species were rated as species with highest future potential by the stakeholders followed by the other species as listed below.

- Rainbow trout [9 times highest rank]
- Juvenile salmon [6 times]
- Shrimp [4 times]
- Lumpfish [3 times]
- Carp [2 times]
- Adult salmon [1 time]
- Turbot [1 time]
- Clarias (African Catfish) [1 time]
- Sturgeon [1 time]
- Yellowtail [1 time]

4.2. Open-ended questions

After ranking the barriers and predictions for future RAS operations in England, the survey asked two open-ended questions. These were designed to give the opportunity for stakeholders to provide additional views and information on barriers and asked for their opinions on how to support the RAS sector in the future.

Asked “Are there any challenges the survey has not mentioned and which you would like to address?”, eight stakeholders responded with a text answer. However, these answers did not highlight new challenges, an indicator that the directed questions in the survey addressed most barriers to running a successful RAS operation in England. Most of the responses to this question pointed out the complexity and linkage between the aspects separated in the survey for practicability. The stakeholders emphasized the high operational costs of RAS systems as well as the lack of available and suitable building sites. Due to the developing market, several factors are still unclear or have not been elaborated enough for (possible) operators, suppliers, and funders: among those mentioned were communication within the supply chain, barriers within marketing and demand, uncertainty around hatchery development, and potential impact of the production systems on the flavour of fish.

The second open-ended question aimed to elicit whether there are any measures, in the opinion of the stakeholders, that the government should consider putting in place to support RAS in the future. The question was answered by 15 stakeholders, who named financial support as a measure the government should consider supporting the RAS sector in future. Possible approaches suggested included financial grants for research and development, support with initial and ongoing costs, as well as financial help through tax breaks or special development zones. In addition, support with following the planning process, from training and advisors, was suggested. Stakeholders also sought practical help with finding available and suitable sites.

Within the open answer section, the stakeholders indicated that they sought financial support during the early developmental stages of RAS facilities. This was sought because there is an extended time before reaching the break-even point at a RAS facility (selected by 76% of stakeholder as a barrier within the ranking section). The findings of the open-ended questions resonate with the findings from the literature review and from the survey ranking. High production costs were identified as a main barrier, so was the lack of available land. The ask for additional training and expert advice resonates with the barrier “lack of knowledge exchange between suppliers, operators, and workers” and was ranked as the strongest social barrier by 43% of the stakeholders.

Out of 29 stakeholders, 25 (86%) answered the question “Are you happy to be contacted by Cefas as a RAS stakeholder in the future?” with “Yes”. The high number of stakeholders wanting to be part of further engagement, as well the rather high response rate, is a sign of strong industry engagement. Given the variety of stakeholder roles within the RAS sector the survey provided a good basis for further contact with the industry.

5. Discussion

Our research has highlighted that the RAS sector is developing rapidly on a global scale, but also within Europe. Within the UK, most existing development is in Scotland but recent announcements for new RAS in England (Editorial team, 2023; Jaines & Griffin, 2022) show an appetite and interest to develop this sector. New innovations and technologies allow efficient and better maintenance of water quality within the systems now available.

Recent increases in energy costs have prompted an increased focus on energy efficiency for the sector. Where some countries have access to cheap renewable energies, the increases in costs, especially across Europe, have focussed efforts to reduce the kWh per kilo of fish produced. While it is more difficult to adapt existing systems, new designs provide opportunity to build in alternative energy technologies and minimise energy usage. Currently, energy costs are high in England in comparison to the many other countries, but whilst not guaranteed are expected to fall in coming years.

Of the types of RAS system identified, the most promising for England appears to be fully enclosed RAS for either Freshwater or Marine and Brackish water. Model trout farms with partial recirculation are slowly being adopted by the existing trout farming sector to address climate change water shortages and abstraction issues. This trend would benefit from linkage with alternative energy systems to reduce the energy costs and transition towards net zero. One option would be to consider whether food producing sectors, such as RAS, can have an additional or higher percentage of grant funding when making the transition towards renewables and net zero.

Other aquaculture systems, such as plug-and-play, are currently likely to have a smaller scale impact than larger fully enclosed RAS and be used for more niche food production. Biofloc systems and Aquaponics in land-based systems would again appear to be niche, although for Aquaponics, the use of wastewater from freshwater RAS may be linked with larger new systems as in recent builds in Europe and the USA.

Floating RAS, or the development of semi-contained systems, is unlikely to be pursued in England in the short term. These systems are perhaps more suitable for integration with existing aquaculture systems in more sheltered environments (e.g., Scottish sea lochs) where they won’t experience extreme forces required to be held in place. However, any systems that can be submerged in bad weather would open potential areas of the English coastline for establishment. The future potential of this sector should not be dismissed.

RAS farming of salmonids or prawns would help fulfil market demand for species that are already the top 5 most popular choices (Barrie, 2021; Quinn, 2022) with the English consumer. There is potential to increase the small Clarias sector and produce significant tonnages (of species that are ideally suited to RAS aquaculture), but further investigation would be required into the size of the market and the economics for producing them in England. In terms of new species for the English market, species such as yellow-tail (*Seriola lalandi*), meagre (*Argyrosomus regius)* and grouper *(Epinephelus spp.)* are all potential candidates that could be farmed within secure RAS systems given access to suitable fingerling supply.

The consumption of seafood in England and the UK has seen an overall decline since 2006 despite health recommendations from government committees and agencies. Diversifying the species farmed in RAS away from the ‘big five’ eaten in England would, therefore, seem challenging to meet aspirations for growth in the EAP. However, substituting and replacement of imports of key species may offer opportunity.

The area required for the development of land-based RAS in England is small and would not seem to be a major stumbling block for increasing production, although land costs would need to be considered within business planning. Supporting the development of land-based RAS aquaculture as a diversification for agricultural farmers may well provide the land areas needed, although existing farmers would need to team up with experts in the aquaculture field for a significant period to ensure success. Some clarification around permitted development rights may help existing farmers assess this option and get permissions in place. However, examples have shown that RAS can successfully be used to occupy abandoned brownfields and provide new use of existing infrastructure.

In terms of water availability, shortages of freshwater, and both the increasing costs and difficulties of getting abstraction permits, may well continue to be a driver towards increasing RAS (partial) usage for existing flow through freshwater trout farms. However, the use of marine water sources would seem to offer the best opportunity for developing RAS, but this relies on coastal locations which often come with premium land prices or conservation designations. Some coastal options may exist in brownfield sites.

Compared to other aquaculture sectors, the RAS industry in England needs highly skilled workers. More visibility of the wide variety of job roles in the sector and training opportunities could help to recruit more workforce for a career in the industry. While RAS operations often only employ a small number of people, the recruitment of a local workforce in often rural areas can have a significant impact on local employment.

Energy costs (particularly electricity) in the last two years are the foremost of concerns for the sector and a design consideration in new builds. Whilst there have been examples of sites putting builds and development on hold owing to high energy costs, there remains a high level of interest and investment in the sector and a mindset to resolve these problems through innovation, alternative energy, and reducing the kWh per kilo produced to transition towards net zero. Despite soaring power costs in some countries creating an unfavourable investment climate, new farms or plans are being announced regularly, including in England. It may be that the lack of availability of coastal sites for open net pens has meant that there is little alternative than to push forwards and make RAS viable. Research, such as that being carried out by the University of Maryland, USA, via the Sustainable Aquaculture Systems (SAS) project and in collaboration with other institutes, is focused on reducing operating costs and solving other technical issues and will be important for development of RAS in the USA. Consideration could be given to encouraging similar research areas within institutions in England.

The supply of aquafeed for RAS systems is another challenge, particularly the increase in costs of the feed that are driven by rises in the costs of all the inputs. However, in terms of suitability of feeds for RAS, feed company research has developed foods specifically tailored for RAS and there is much substitution of marine ingredients and production and sourcing of alternatives sources underway.

In terms of environmental considerations, there are multiple benefits of producing fish in RAS such as a reduced spatial footprint per kilo in comparison to other aquaculture, control of waste, escapee reduction, biosecurity, protection against predators, more efficient use of water resources and climate resilience. Currently the biggest environmental drawbacks are the carbon footprint and greenhouse gas emissions of this sector, which are high in comparison to open net pen or flow through systems. Ironically, it may be the current energy crisis and war in Ukraine that accelerates the transition to alternative energy and reduces these drawbacks, as emissions are largely attributed to electricity production. Feed production and shipment to site also increases the carbon footprint of aquaculture, but RAS typically has better food conversion ratios and feed efficiencies than other types of aquaculture.

Future improvements in stock resilience and their performance within RAS, including through gene editing, may reduce energy costs per kilo further and thus, carbon footprint. Eco-certification is now being developed by the like of the ASC for RAS systems and energy usage. Traditional salmon aquaculture production systems were estimated to produce less CO_2 equivalent per kg live weight compared to RAS production of salmon in different studies. However, as soon as transport to the consumer was included into the calculation of the carbon footprint, RAS was estimated to have a smaller carbon footprint. This is because RAS production is often closer to the consumers than traditional aquaculture systems.

Clear proportionate regulation and permitting that adjusts for the characteristics of this rapidly growing sector will be important to prevent barriers to the growth of RAS systems in England. An initial screen of the existing regulatory toolbox for RAS by experienced Fish Health Inspectors, and with reference to previous ‘regulatory burden’ reports for Defra, highlighted little concern for APB authorisations, permitting for non-native species, fish supplier permitting, approvals to manufacture medicated feed, transporter authorisation, on farm welfare requirements or disposal of mortalities. Areas that may benefit from further exploration and clarification include permitted development rights for RAS systems, disposal methods for concentrated waste collected and charges for permits, authorisation to import crustacean larvae and the application of hygiene rules between processing units and farming units. Additionally, exploration of why modern RAS is excluded from enterprise zones and the benefits they provide would be useful for utilisation of brownfield sites.

In terms of operational challenges, one of the prominent areas is the lack of experienced managers who will have learnt lessons from previous ventures and understand the technical issues associated with running a large RAS unit. The fact that RAS are technically complex to develop and operate may well attract future graduates from aquaculture or those who want to be in developing and technical industries. Publications and papers are now available to developers and will help them to avoid some of the historical mistakes when planning and establishing a site. New technical innovations in filtration systems, such as electro chemical oxidation technology, may improve health and welfare and thus address problems previously associated with poorly designed systems.

From a business perspective, RAS requires substantially higher levels of investment than traditional aquaculture systems. Due to high investment and operation cost as well as low price premium realistically achieved, the break-even point is reached later for RAS than other systems, as such RAS is currently not always attractive for many investors. Selling by-products of RAS (e.g., saline as salt, or sludge as fertilizer) or using renewable energy to reduce operating costs, leads often to higher complexity and cost in licencing and so far, strong evidence has not been produced to suggest this would be economically beneficial.

Overall, the RAS sector is not well understood in relation to social constraints and public perception. However, research around other aquaculture systems suggest three key themes to address when considering the establishment or extension of RAS facilities within England: issues within the operation of facilities, the public (risk) perception of aquaculture facilities, and place-attachment and local value of landscapes. A main issue raised, within both the literature review and the conducted stakeholder survey, is the lack of suitable spaces for new operations. The repurposing of existing facilities such as farms or warehouses can help to minimise the visual impact on the local landscape and integrate RAS into communities. In addition, many of the social barriers marine aquaculture system usually encounter (highly visible and change the appearance of the local landscape, risk of escaping stock) are not necessarily an issue for RAS and will help to establish social acceptance for new operations (Fudge et al., 2023b). Further support can be generated if the carbon footprint due to energy consumption could be reduced (renewable energy). In addition, locations in special development zones may be used to support businesses financially. The Dorset local enterprise partnership recently provided good examples of successfully helping new RAS businesses find appropriate available sites.

Whilst there has been a poor historical track record for RAS in England, engineering and technical design has vastly improved along with understanding of economies of scale and the requirements for operating successfully and locating in the correct place. It is thought that the likely species for RAS farming are those that are in demand in the UK, such as salmon and prawns, and will fetch prices that achieve a return on investment. It is thought that cultivating lower priced white fish such as catfish and tilapia will remain economically challenging in the near future. However, higher value fast growing species such as yellow-tail or meagre should not be discounted. The current usage and development trends in England for RAS suggest an increasing move towards partial use of RAS by flow-through farms for trout and charr production, with potential larger scale systems being planned for salmon and prawns on the horizon. It may be that other species such as Clarias and red-claw crayfish will remain niche and small scale within England for the foreseeable future. Further growth in the production of cleaner fish may also be possible, but within limits of the Scottish aquaculture sector's needs.

If challenges can be overcome, then RAS has the potential become a major contributor to English aquaculture and seafood production. Investment interest in RAS internationally is currently still appears high and is likely to continue, even in the face of continued venture failures. With these failures comes experience, with new technology and operating procedures gradually reducing risk and increasing scalability. In 2020, before the Ukraine crisis and rocketing energy costs, BP's view was that long-term energy prices, one of the major cost components for RAS farms, would to be lower than previously assumed at around USD 55 per barrel. How this prediction will play out in the current environment remains to be seen. RAS will need to ensure access to renewable energy to reduce its costs and carbon footprint (Huntington & Cappell, 2020).

6. Conclusion

Growth and investment in RAS continue globally, despite increasing energy prices. Technical innovations, both within the systems and to make use of alternative energy, are either available or in the process of being developed. New RAS developments in England need to make the best possible use of these innovations to ensure health and welfare within the systems and reduce carbon footprint. Whilst energy costs are relatively high in England there is still optimism that these will drop in the future and further efficiencies within new build systems can be found. LCA results generally indicate that a closer proximity to market, incorporation of renewable energy to reduce carbon footprints, biofloc technologies and by-product utilisation can assist RAS facilities in reducing environmental impacts and becoming viable and suitable alternatives to traditional aquaculture and mariculture methods. However, stakeholders call for financial support during the very early developmental stages of the sector in England due to the extended period before reaching break-even point with RAS production. Financial support, through grants, tax reliefs, or special development zones would therefore give the industry the necessary security to develop and send signal to the sector that environmentally friendly production is politically supported. Social acceptance of new RAS facilities is best achieved by early engagement with stakeholders and local communities.

Further utilisation of partial RAS is foreseen within the existing English trout sector and increasingly larger full recirculation systems being developed in brownfield sites near to water supplies and where there is suitable infrastructure to aid the permitting and licensing process. Due to the lengthy periods of licensing, build and production cycles, approaching 5 years in length, a rapid growth in the numbers of these systems and production in England is not foreseen. However, due to economies of scale, if systems are built of 5,000 to 10,000 tonnes per annum this means that one farm of this scale could produce as much product as all the English trout farms combined. Further encouragement and funding could be given to researchers in the academic sector to develop engineering projects, and work on technical constraints for the sector, and the emerging semi-contained systems for deployment in deeper waters.

In the survey, we asked stakeholders to describe the biggest barriers to the growth of RAS in England. Most stakeholders point out that the biggest barriers for RAS in England are the high production cost and the lack of suitable space. Stakeholders suggested financial grants for research and development, support with initial and ongoing costs, as well as financial help through tax breaks or special development zones. Regulatory barriers were often seen as the second biggest barrier. To tackle the regulatory barrier, further consideration, workshops, and clarification with regulators is needed in the following areas with a view to either updating the guidance, such as the regulatory toolbox for RAS, or making amendments in processes where required.

- The potential to clarify and update permitted development rights for modern RAS in England to help terrestrial farmers diversify in England and provide a helpful set of guidelines for prospective farmers as per those in Scotland.
- Clarification of the application of environmental permitting for RAS, and in particular discharge consents to ensure clarity where required and updated guidance.
- Reviewing the barriers to importing prawn larvae into enclosed -bio-secure RAS systems considering existing Cefas risk assessments for listed prawn diseases and government involvement in enclosed bio-secure units.
- Clarification of hygiene rules on fish farms between farms and processing areas to help both local authorities and farmers.
- Whilst not regulatory, further exploration of why RAS are excluded from enterprise zones could be beneficial for start-ups.
- A greater future workforce with a thorough knowledge of aquaculture and RAS operations would be beneficial, and this area could be explored with leading educational facilities.

Growth in new larger English RAS with economies of scale will most likely be implemented for existing higher value species where hatcheries and supply chains exist. It is anticipated that economics may be difficult for lower value species, such as Clarias and tilapia, but in the longer-term other fast-growing species may be viable with adequate hatcheries and supply lines.

The initial literature review identified a lack of social research studies around RAS and the development of aquaculture facilities in non-coastal area. Furthermore, social science studies often focus on the salmon aquaculture industry and are based in salmon producing countries. Further research on possible social barriers and benefits of RAS facilities in England would therefore be recommended to help guide sustainable development of this industry. Initial research by Badiola et al., (2012) and Bostock et al., (2018) indicates that semi-structured interviews within RAS facilities can deliver more information on non-technical barriers within the industry. Research within communities where RAS facilities may be sited will also help to identify ways in which facilities can be built with the support of local inhabitants.

In summary, it is thought that investment and growth in the sector will continue despite a currently difficult economically environment within England. Lessons learnt and increasing knowledge and experience will reduce historic business failure rates along the way. Successful systems will require the correct teams of people and investment advice and will need to be built at a large enough scale to produce fish as economically as open net systems whilst using alternative energy systems and recovery from waste, thus reducing carbon footprints, and helping to move towards net zero.

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Appendix

RAS survey 2023

RAS 2023

Recirculation Aquaculture Systems (RAS) have the potential to contribute to aquatic food supply and security for the UK market and to create employment. Cefas aims to identify opportunities and barriers the RAS sector faces and seeks input from across a range of stakeholders.

Your feedback in this study is vital to understand the challenges the RAS sector is facing in England and this research aims to help decision makers to develop policies to promote sustainable aquaculture. Your responses will be available only to researchers with both scientific and ethical approvals. The data collected will be used to produce a report used by officials and policy makers to inform future RAS policy. A summary and full report will be made available publicly, but no personal information which could be used to identify you will be published or shared.
Your participation is entirely voluntary; if at any point during the survey you no longer wish to take part, please close the browser and any data you will have entered will not be stored. Due to the anonymous nature of the survey, it is not possible to withdraw your response after the survey has been submitted.
You can find out more about how we process your information in our Personal Information Charter here: https://www.gov.uk/government/organisations/centre-for-environment-fisheries-and-aquaculture-science/about/personal-information-charter

We appreciate your help in completing this survey which will take 10-15 minutes.

The survey is run by Centre for Environment, Fisheries and Aquaculture Science (www.cefas.co.uk) and funded by the Department for Environment, Food & Rural Affairs (Defra).

For further questions about this research please e-mail: ras-survey@cefas.gov.uk

Informed consent: Please indicate whether you agree with the following:

• You have read and understood the information provided.
• You have been given the opportunity to ask questions regarding your participation in this study.
• You understand that your participation is voluntary and that you are free to refuse to answer questions and can withdraw from the study at any time, without giving a reason.
• You understand that taking part in the study involves completing a survey.
• You understand that the information you provide will be used for research purposes including reports and scientific publications.
• You understand that the research data may be accessed by researchers working at the Centre for Environment, Fisheries and Aquaculture but that at all times your personal data will be kept confidential, in accordance with General Data Protection (GDPR).
• You are aged 18 years or older.

If you do not wish to participate in this research, please decline participation by selecting "disagree". By selecting "agree" you are consenting to your participation in the study.

- ☐ Agree
- ☐ Disagree

1. What is the primary role in which you are answering this questionnaire?

- ☐ Academia
- ☐ RAS funder
- ☐ RAS operator (past, current, potential future)
- ☐ RAS regulator
- ☐ RAS consultant
- ☐ NGO
- ☐ Representative of a trade association
- ☐ Other, please specify ____

2. What type of RAS system are you most familiar with? Rank up to 3 choices, with 1 being most familiar.

- ☐ Fully enclosed (full recirculation), land-based (freshwater)
- ☐ Container based plug and play systems, land-based (freshwater)
- ☐ Bio-floc raceways and pond systems, land-based (freshwater)
- ☐ Partial recirculation (with limited inflow), land-based (freshwater)
- ☐ Danish model farms (outdoor semi closed system), land-based
- ☐ Aquaponic, land-based (freshwater)
- ☐ Multi-trophic, land-based (freshwater)
- ☐ Fully enclosed (full recirculation), marine-based
- ☐ Pump ashore (partial recirculation), marine-based
- ☐ Marine floating (full RAS), marine-based
- ☐ Semi-contained (part RAS), marine-based
- ☐ Other, please specify if land-based or marine-based

3. What type of species for RAS are you most familiar with? Rank up to 3 choices, with 1 being most familiar.

- ☐ Salmon - juvenile
- ☐ Salmon - adult
- ☐ Tilapia
- ☐ Turbot
- ☐ Lumpfish
- ☐ Ballan Wrasse
- ☐ Carp
- ☐ Tench
- ☐ Rainbow Trout
- ☐ Asian Seabass
- ☐ European Seabass
- ☐ Clarias (African Catfish)
- ☐ Shrimp
- ☐ Crayfish
- ☐ Sturgeon
- ☐ Eel
- ☐ Perch

- ☐ Sole
- ☐ Zander
- ☐ Arctic Char
- ☐ Other, please specify ______________

4. Based on your experience, what do you think are the biggest barriers to invest or operate the Recirculating Aquaculture System (RAS): [highest ranked system of Q2]? Please rank the following, with 1 being the strongest barrier.

_______ Regulatory burden
_______ Profitability
_______ Resource availability
_______ Social barriers

4.1. What do you think are biggest barriers for [highest ranked system of Q2] RAS in terms of <u>**regulatory burden**</u>? Please rank the following, with 1 being the strongest barrier.

_______ Building regulations, planning or marine licences
_______ Food and safety standards
_______ Environment and animal health regulations
_______ Available financial support / loans / grants are not sufficient

4.1.1. [Only displayed if ranked 1 or 2 in Question 4.1] What are the barriers associated with **building regulations, planning or marine licences**? Select all that apply.

- ☐ Too restrictive
- ☐ Too unclear
- ☐ No suitable enterprise zones
- ☐ Other, please specify: ____________________

4.1.2. [Only displayed if ranked 1 or 2 in Question 4.1] What are the barriers associated with **food and safety standards**? Select all that apply.

- ☐ Too difficult to meet
- ☐ Too unclear
- ☐ Other, please specify: ____________________

4.1.3. [Only displayed if ranked 1 or 2 in Question 4.1] What are the barriers associated with **environment and animal health regulations**? Select all that apply.

- ☐ Too difficult to meet
- ☐ Too unclear
- ☐ Disease controls and restrictions on imports of fry/eggs hinder availability
- ☐ Cannot obtain an aquaculture production business authorisation from Fish Health Inspectorate
- ☐ Restrictions on using gene editing and GM technology
- ☐ Too expensive (for example abstraction and discharge costs)
- ☐ Other, please specify: ____________________

4.2. What do you think are biggest barriers for [highest ranked system of Q2] RAS in terms of **resource availabilty**? Please rank the following, with 1 being the strongest barrier.

_______ Land
_______ Water
_______ Energy
_______ Labour
_______ Technology and supply

4.2.1. [Only displayed if ranked 1 or 2 in Question 4.2] What are the barriers associated with **land**? Select all that apply.

☐ No available land sufficiently close to market/distribution
☐ High cost
☐ Not enough suitable space available
☐ Other, please specify: ______________________

4.2.2. [Only displayed if ranked 1 or 2 in Question 4.2] What are the barriers associated with **water**? Select all that apply.

☐ High cost for water usage (abstraction, discharge, or treatment)
☐ Lack in sufficient or limited quantity
☐ Lack of access to sufficient quality
☐ Other, please specify: ________________________

4.2.3. [Only displayed if ranked 1 or 2 in Question 4.2] What are the barriers associated with **energy**? Select all that apply.

☐ High cost
☐ Lack of access to reliable sources
☐ Insufficient supply of energy
☐ High cost of renewables/ability to install on site
☐ Other, please specify: _________________________

4.2.4. [Only displayed if ranked 1 or 2 in Question 4.2] What are the barriers associated with **labour**? Select all that apply.

☐ Lack of experienced engineers and designers
☐ Lack of available knowledge/experienced managers/operators
☐ Lack of workers available
☐ Other, please specify: _________________________

4.2.5. [Only displayed if ranked 1 or 2 in Question 4.2] What are the barriers associated with **technology and supply**? Select all that apply.

☐ Availability of appropriate/affordable feed
☐ Availability of technology/equipment
☐ Insufficient access to robust/reliable /larvae supplies/source stock
☐ Other, please specify: __________________________

4.3. What do you think are biggest barriers for [highest ranked system of Q2] RAS in terms of **profitabilty**? Please rank the following, with 1 being the strongest barrier..

_______ Production cost
_______ Processing and distribution cost
_______ Sales profit

4.3.1. [Only displayed if ranked 1 or 2 in Question 4.3] What are the barriers associated with **production**? Select all that apply.

- ☐ Difficult to find investors
- ☐ High variability in outputs
- ☐ Extended period before reaching break-even point
- ☐ Other, please specify: ___________________________

4.3.2. [Only displayed if ranked 1 or 2 in Question 4.3] What are the barriers associated with **distribution/processing costs**? Select all that apply.

- ☐ Lack of interest by retailers
- ☐ High costs for distribution and processing
- ☐ Other, please specify: _____________________________

4.3.3. [Only displayed if ranked 1 or 2 in Question 4.3] What are the barriers associated with **sales**? Select all that apply.

- ☐ Marketing costs
- ☐ Low price
- ☐ Lack of consumer demand
- ☐ Other, please specify: ______________________________

4.4. What do you think are biggest barriers for [highest ranked system of Q2] RAS in terms of **social aspects**? Please rank the following, with 1 being the strongest barrier.

_______ Lack of knowledge exchange between suppliers, operators, and workers
_______ Lack of support through local communities
_______ Problems with environmental lobbyists
_______ Suitability and demand of species for the UK market

4.4.1. [Only displayed if ranked 1 or 2 in Question 4.4] What are the barriers associated with **lack of support through local communities**? Select all that apply.

- ☐ Location of facility
- ☐ Environmental risk perceptions
- ☐ Poor perception of aquaculture products
- ☐ Other, please specify: ______________________________

4.4.2. [Only displayed if ranked 1 or 2 in Question 4.4] What are the barriers associated with **environmental lobbyists**? Select all that apply.

- ☐ Environmental concerns
- ☐ Animal welfare concerns
- ☐ Other, please specify: ________________________________

4.4.3. [Only displayed if ranked 1 or 2 in Question 4.4] What are the barriers associated with **suitability of species for UK markets**? Select all that apply.

- ☐ Niche market
- ☐ Limited market
- ☐ Other, please specify: ______________________________

5. Would you be willing to answer some additional questions on another RAS system which you are familiar with?

- ☐ Yes
- ☐ No

If yes, start from Question 4 again.

6. What in your experience drives the high rate of previous failures of RAS operations in England? Please rank the following, with 1 being the strongest driver.

_______ System design
_______ Final sales prices achieved
_______ Energy costs
_______ Technical problems
_______ Disease problems
_______ Other, please specify _______________

7. Under the current circumstances, which RAS is in your experience the most likely to be successful within England? Please rank your top 3 choices.

_______ Fully enclosed (full recirculation), land-based (freshwater)
_______ Container based plug and play systems, land-based (freshwater)
_______ Bio-floc raceways and pond systems, land-based (freshwater)
_______ Partial recirculation (with limited inflow), land-based (freshwater)
_______ Danish model farms (outdoor semi closed system), land-based (freshwater)
_______ Aquaponic, land-based (freshwater)
_______ Multi-trophic land-based (freshwater)
_______ Fully enclosed (full recirculation), marine-based
_______ Pump ashore (partial recirculation), marine-based
_______ Marine floating (full RAS) system
_______ Semi-contained (part RAS), marine-based
_______ Other, please specify if land-based or marine-based

8. Under the current circumstances, which species is in your experience the most likely to be successful for RAS within England? Please rank your top 3 choices.

_______ Salmon - juvenile
_______ Salmon - adult
_______ Tilapia
_______ Turbot
_______ Lumpfish
_______ Ballan Wrasse
_______ Carp
_______ Tench
_______ Rainbow Trout
_______ Asian Seabass

_______ European Seabass
_______ Clarias (African Catfish)
_______ Shrimp
_______ Crayfish
_______ Sturgeon
_______ Eel
_______ Perch
_______ Sole
_______ Zander
_______ Arctic Char
_______ Other, please specify

9. Are there any challenges the survey has not mentioned and which you would like to address?

____
____
____
____
____

10. In your opinion, are there any measures the government should consider putting into place to support RAS in the future?

____
____
____
____
____

11. Are you happy to be contacted by Cefas as a RAS stakeholder in the future?
    ○ Yes
    ○ No

[If yes] Please provide your email address below.

If you wish to be removed from any contact list at a future date, please email ras-survey@cefas.gov.uk.

____

Centre for Environment
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World Class Science for the Marine and Freshwater Environment

We are the government's marine and freshwater science experts. We help keep our seas, oceans and rivers healthy and productive and our seafood safe and sustainable by providing data and advice to the UK Government and our overseas partners. We are passionate about what we do because our work helps tackle the serious global problems of climate change, marine litter, over-fishing and pollution in support of the UK's commitments to a better future (for example the UN Sustainable Development Goals and Defra's 25 year Environment Plan).

We work in partnership with our colleagues in Defra and across UK government, and with international governments, business, maritime and fishing industry, non-governmental organisations, research institutes, universities, civil society and schools to collate and share knowledge. Together we can understand and value our seas to secure a sustainable blue future for us all, and help create a greater place for living.

Pakefield Road, Lowestoft, Suffolk, NR33 0HT

The Nothe, Barrack Road, Weymouth DT4 8UB

www.cefas.co.uk | +44 (0) 1502 562244