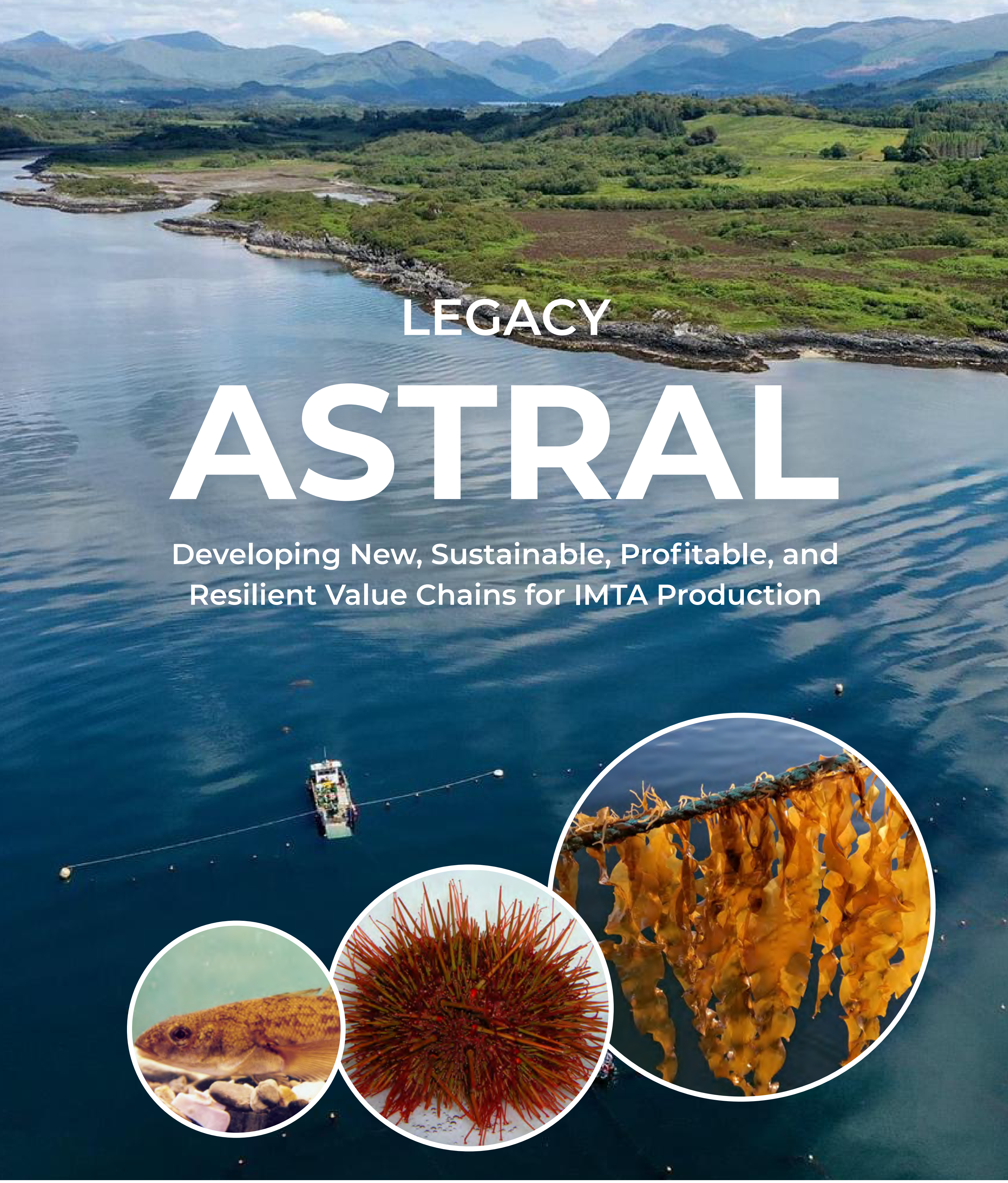
LEGACY

ASTRAL

Developing New, Sustainable, Profitable, and Resilient Value Chains for IMTA Production



All Atlantic Ocean Sustainable, ProfiTable and Resilient AquacuLture

Acknowledgement

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The 19 partners and associated partners of the project have contributed to the content.

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Coordinator's letter

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How to ensure sustainable, resilient and profitable food systems in these challenging times? Can we feed a growing population while not harming the environment? How can we achieve environmental, economic and social sustainability in aquaculture production? How can we improve Integrated Multi-Trophic Aquaculture (IMTA) production along the Atlantic Ocean?

These are some of the questions the ASTRAL project aspired to answer in the last years. Four years of intensive work, in the lab, in the field, in front of computers, at conferences and workshops, involving fellow researchers, industries, policy makers, civil society, and NGOs.

I am very proud that ASTRAL was able to answer all the questions we started out to tackle and even more. The consortium members commitment and enthusiasm were the driving force towards these outstanding achievements.

The project improved the production of four already established IMTA chains, introduced new species, assessed the environmental sustainability and the circularity, the profitability of the production and its resilience in the face of stressors like climate change, HABs and pollutants. ASTRAL has also developed relevant technologies for monitoring, prioritising cost-effectiveness.

ASTRAL established a platform where stakeholders could interact with each other as well as with researchers, and support education and the transfer of knowledge from school children to students and trainees. The Atlantic dimension of the collaboration in ASTRAL has given us the opportunity to contribute to the All-Atlantic Ocean Community, to highlight similarities and differences and create a feeling of belonging that is a key driver to progress.

This document has been created as a summary of ASTRAL's activities. More information can be found in the project's public deliverables, publications and other document mentioned in the different chapters.

It has been an inspiring, exciting and fulfilling journey for us in ASTRAL and we hope you will feel the same reading this document.

Elisa Ravagnan
ASTRAL Project Coordinator

Acronyms & Abbreviations

AI	Artificial Intelligence
AIDAP	Artificial Intelligence Data Analytics Platform
ASTRAL	All Atlantic Ocean Sustainable, Profitable and Resilient Aquaculture
CBA	Cost-Benefit Assessment
CE	Circular Economy
Chl-a	Chlorophyll A
D	Deliverable (Project reports available on the ASTRAL or Cordis websites)
DNA technology	Deoxyribonucleic Acid Technology
DO	Dissolved Oxygen
EC	Electrical Conductivity
EIA	Environmental Impact Assessment
EPV	Earnings Power Value
EU	European Union
FAN	Free Ammonia Nitrogen
FAO	Food and Aquaculture Organisation
FTE	Full Time Equivalent
FU	Functional Unit
GVA	Gross Added Value
H2020	Horizon 2020
HAB	Harmful Algal Blooms
HACCP	Hazard Analysis Critical Control Point
HMPA	Highly Protected Areas
HR	Human Resources
HUCAP	Human Capital Development Plan
ICT	Information and Communications Technology
IHHNV	Infectious Hypodermal and Hematopoietic Necrosis Virus
IMTA	Integrated Multi-Trophic Aquaculture

IoT	Internet of Things
IPCC	Intergovernmental Panel on Climate Change
IUCN	International Union for Conservation
KPI	Key Performance Indicators
LoRaWAN	Long Range Wide Area Network
MCI	Material Circularity Indicator
MEMS	Micro-Electro-Mechanical Systems
ML	Machine Learning
MPA	Marine Protected Areas
NPV	Net Present Value
OWIs	Operational Welfare Indices
sPOs	Producer Organisations
ppt	Parts Per Thousand
psu	Practical Salinity Units
RAS	Recirculating Aquaculture System
RFID	Radio-Frequency Identification
ROI	Return On Investment
RTD	Resistance Temperature Devices
SPM	Suspended Particulate Matter
SST	Sea Surface Temperature
SWOT	Strengths - Weaknesses - Opportunities - Threats
TAN	Total Ammonia Nitrogen
TSM	Total Suspended Matter
TSS	Total Suspended Solids
UAV	Unmanned Aerial/Aquatic Vehicle
WFD	Water Framework Directive
WQ	Water Quality

Contents

1. Introduction

Introduction

Consumption of seafood has grown twice as fast as the human population since the 1960s (OECD), resulting in global fishing capture reaching its maximum capacity. Aquaculture has often been the go-to source for supplementing wild capture. However, the sector, particularly in the context of intensive production, has been identified as creating a myriad of issues, such as anoxic zones, reduction in water quality, destruction of habitat, effects of antibiotic use, and so on. Controversy has also developed over the quality of aquaculture products and the threats that the sector faces from external factors such as climate change and disease. Integrated Multi Trophic Aquaculture (IMTA) is becoming an increasingly promising alternative as it has the potential to offer new alternatives and innovative solutions that avoid many of these issues. By integrating species and systems that can naturally complement and feed off one another, many challenges relating to waste management and water quality, for example, can be mitigated.

What is IMTA and Why Use This Approach?

Integrated Multi-Trophic Aquaculture (IMTA) is described as the farming of aquaculture species from different trophic levels, and with complementary ecosystem functions in the same area or at the same site. This type of integrated culturing allows one species' uneaten feed, waste, and nutrients to be recaptured and converted into fertiliser and feed for the other aquaculture species. This approach takes advantage of synergistic interactions between species. The combination of fed aquaculture species (e.g., finfish or shrimp) with extractive aquaculture species, which utilises the dissolved nutrients (e.g. seaweeds) and particulate nutrients (e.g. suspension and deposit-feeders such as bivalves, urchins, sea cucumber) enhance growth in this type of system (Figure 1 provides a visual representation of an example IMTA system). IMTA systems can be open water or land-based, marine or freshwater, with a variety of different species at differing trophic levels. IMTA aims to aid ecologically balanced systems to improve environmental sustainability, enhance ecosystem services, and boost economic stability by increasing biomass, lowering costs, providing product diversification, reducing risk, and creating jobs in rural communities while advancing societal acceptability.

According to Thierry Chopin (2019):

> ***IMTA, combines, in the appropriate proportions and scales of management areas, the cultivation of species at two or more different trophic levels, based on their complementary ecosystem functions which creates a more balanced ecosystem approach. The by-products of one cultivated species are recycled to serve as nutritional inputs for other, hence the system can reduce the ecological impact, improve social perception, and provide financial benefits for producers.***

IMTA is not a new approach, and in fact dates back 4 000 years into the late Han period, especially in Asia (combination rice and fish) (UN Department of Economic and Social Affairs (DESA), 2019; FAO, Intergovernmental Technical Panel on Soils, 2015). However, the formalised term “integrated multi-trophic aquaculture” was introduced in 2003 by Thierry Chopin » (EUMOFA, Blue economy, 2020, p. 1).

Currently, in the western world, IMTA is in a pre-commercial development phase with the number of commercial sites being limited. The approach is mostly under development, which is why IMTA experimental systems have been developed within the framework of research projects. Many initiatives exist in Norway, France, Scotland, Ireland, and in Southern countries, such as Brazil and South Africa, with several variations in the production systems (different combinations of species, etc.).

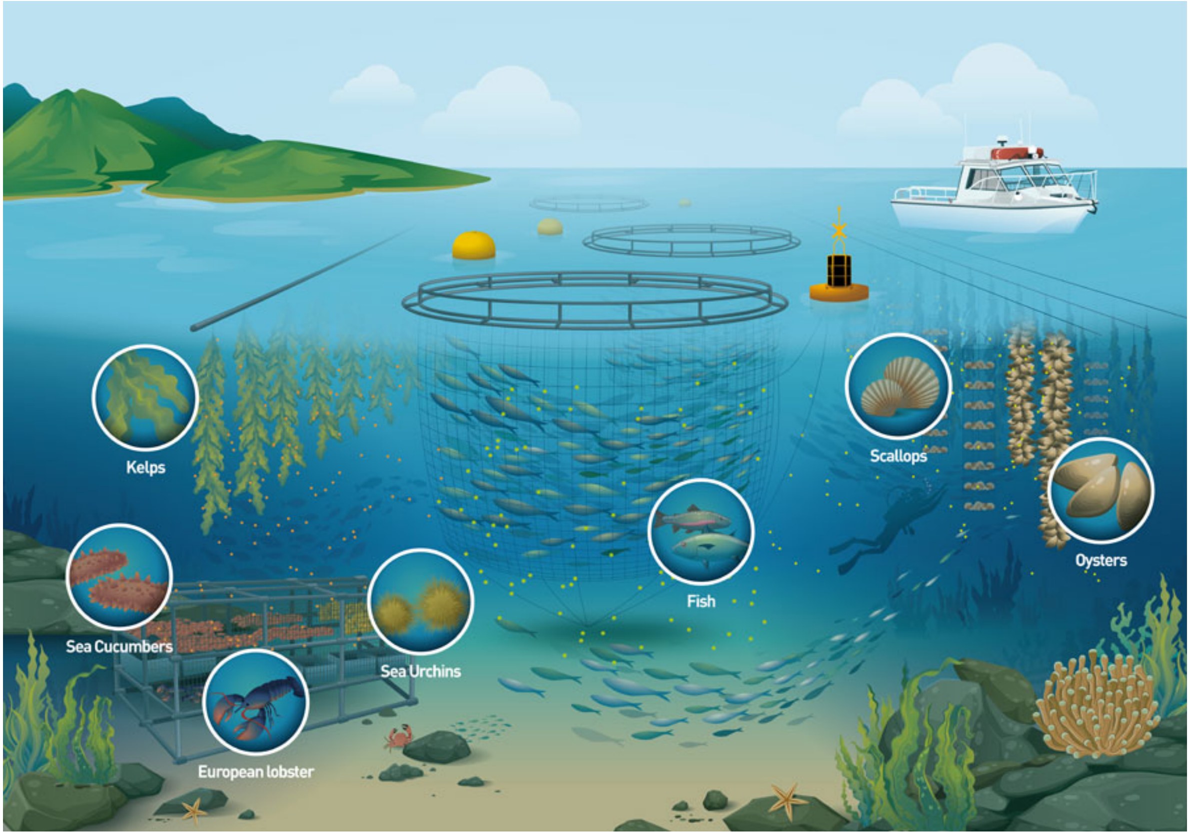


Figure 1: *Schematic of potential open-water IMTA scenario. ©Marine Institute*

The ASTRAL Project

The EU-funded ASTRAL project has developed IMTA production chains for Atlantic markets. Focusing on a regional challenge-based perspective, it brought together labs in Ireland and Scotland (open offshore labs), South Africa (flow-through inshore) and Brazil (recirculation inshore) as well as Argentina (prospective IMTA lab). The aim has been to increase circularity by as much as 60 % compared to monoculture baseline aquaculture and to boost revenue diversification for aquaculture producers. The ASTRAL consortium is proud to have fostered a collaborative ecosystem along the Atlantic through shared, integrated, and co-generated knowledge, technology and best practices.

By encompassing the principles of zero waste and circularity, while considering both potential positive and negative environmental and socioeconomic impacts, as well as potential technological solutions, ASTRAL, together with producers and other stakeholders has developed a multi-faceted and comprehensive approach to better understanding and exploiting the potential of IMTA production (see Figure 2).

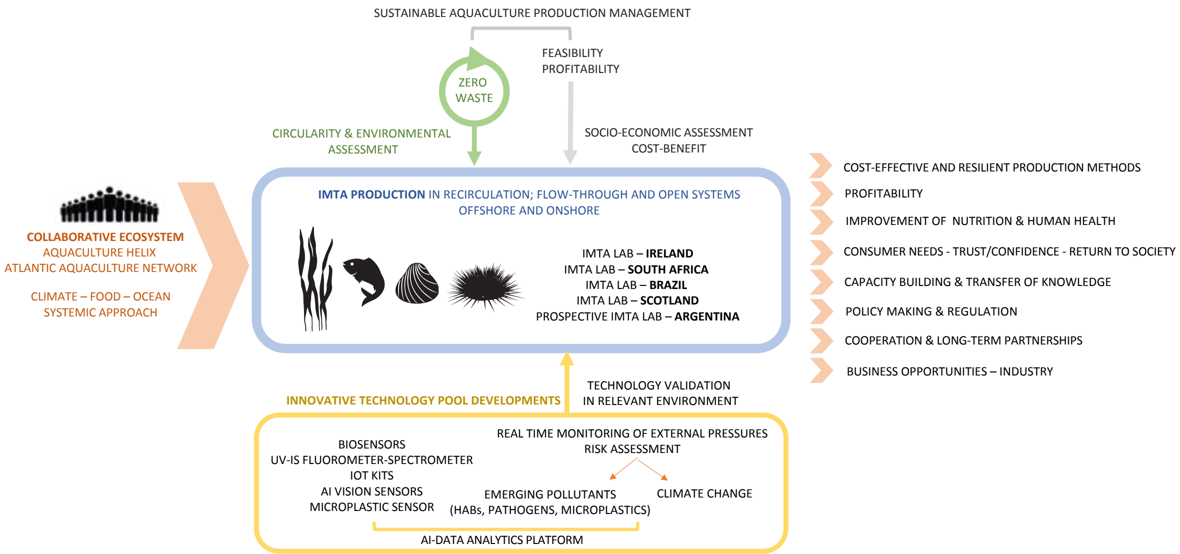


Figure 2: *Overview of the ASTRAL Project*

Overview of the ASTRAL IMTA labs

IMTA labs do not refer to a laboratory setup, but rather to the locations of the IMTA production sites of the ASTRAL project (Figure 3). The project gathers four established and one prospective (Argentina) IMTA labs using three different types of systems, namely Recirculating Aquaculture System (RAS), biofloc application (Brazil), land-based pump ashore partially recirculated (South Africa), and open-water (Ireland, Scotland). For detailed information about the IMTA production, species trialled in the project and their production, welfare and health, please refer to ASTRAL project Deliverable 2.8.

Open-water IMTA

Open-water systems refer to species production that takes place at sea, where moorings are used to anchor the growing structures to the seabed. This type of system is continuously exposed to the ambient environment.

Land-based IMTA

Within the context of the ASTRAL project, land-based IMTA refers to either RAS inshore biofloc systems or land-based pump ashore systems with partial water recirculation. These types of systems allow a certain level of control over some of the physical and chemical parameters within a production system, and provides some protection form the ambient environment – depending on the extent of the recirculation used and the location of the system.

Figure 3: *Overview of the distribution of ASTRAL partners and IMTA Labs across the Atlantic region.*

Best IMTA configurations towards zero waste

- 100% of fish meal in the shrimp diet formulation can be considered as a feasible alternative
- Reduction in crude protein levels is possible by using fish meal analogue (FMA) in shrimp diets for cultivation in biofloc systems
- Recirculation can be increased in abalone-Ulva, from 50% to 75%, as well as to 100% for short periods (3-4 days) as a mitigation strategy for harmful algal blooms
- In the 50% recirculation system, Ulva can remove ca. 60% TAN from abalone effluent
- Provision of Ulva from IMTA as feed for urchins and abalone makes the system less dependent on external feed supply and may result in a 20% cost saving on formulated feeds
- Development of a farm-scale urchin-Ulva IMTA model, as a valuable tool for environmental impact assessors, farmers, entrepreneurs, and investors to design farms, advise management practices and conduct economic, environmental, and social analyses

Environmental assessment and standards

- IMTA systems outperfom monoculture, under a life cycle perspective, considering FU as biomass harvested and craddle-to-gate perspective (more details in D.4.3)
- Eutrophication and climate change reduction 40 and 48% of the total impacts in these categories
- Other Functional Units could be potentially evaluated for IMTA
- LCA (Life Cycle Assessment) allows the evaluation of IMTA systems although limitations are identified. Moreover PEF does not provide specific recommendations for these systems (more details in D4.3)
- Certification schemes for IMTA, as yet, have not been developed, such certification however would recognise IMTA and the benefits it would bring to enhance consumer trust and improve social license to operate
- Global marketing and labelling of certified products should recognise IMTA produce thus allowing for customers to make informed purchases (more details in D4.4)

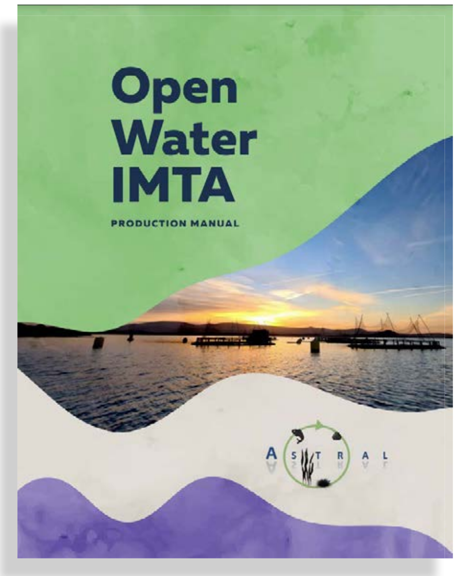
Circularity performance of IMTA

- Concepts were harmonized
  - Circularity in aquaculture (by-products, co-products, regenerative, restorative, waste)
  - Policy recommendations regarding circularity (join action with other EU projects and initiatives)
- IMTA labs were interpreted under a circular perspective
  - Complementing with the LCA approach
  - Decision tree developed to check the key actions to increase circularity in the labs
- Metrics were applied to IMTA to quantify the circularity
  - New indicators (Ireland, Brazil, South Africa IMTA Labs)
  - Adaptation of MCI (material circularity indicator) to low trophic infrastructure (Scotland IMTA lab)
- Circularity of IMTA quantified and validated:
  - Not only in terms of nutrient recycling
  - But also, regarding efficiency use of resources: water, energy, feed and materials

2. Production

2.1. Manuals

ASTRAL produced a series of production manuals to provide guidance on how to grow a selection of species and the parameters needed for their successful production, including welfare, health and biosecurity.

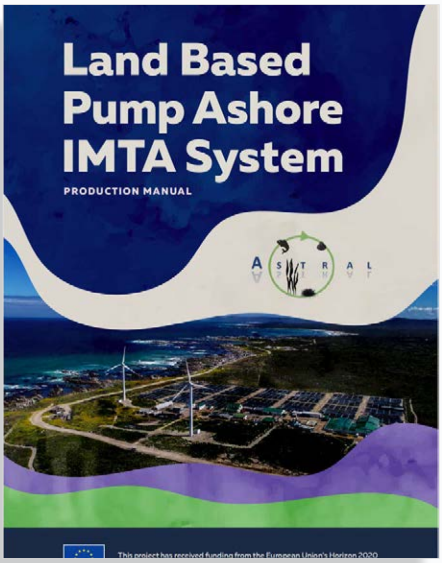


Open Water IMTA Production Manual

This manual contains detailed descriptions of the methods employed to produce the open water species trialled in ASTRAL. The species included fed and extractive species of fish, seaweeds, molluscs, and echinoderms.

IMTA Biofloc Production Manual

This manual contains detailed descriptions of the methods employed to produce the ASTRAL RAS (Recirculating Aquaculture Systems) with biofloc species trialled. The super-intensive production in a biofloc system serves as a sustainable and biosecure alternative to traditional intensive culture systems. Biofloc consists of uneaten feed, faeces, secretions, and their associated algal, bacterial, and microplankton communities.



Production Manual for Land Based Pump Ashore IMTA System

This manual contains detailed descriptions of the methods employed to produce IMTA species trialled in ASTRAL. It describes in detail the production techniques for land-based pump ashore IMTA system with partial recirculation. The ASTRAL species included fed and extractive species of seaweeds, molluscs, and echinoderms. Land-based IMTA carried out in the ASTRAL project refers to species production in either recirculating inshore biofloc systems or land-based pump ashore systems with partial water recirculation. Recirculation of water enables more control of certain physical and chemical parameters in production systems, including temperature, dissolved oxygen, pH, and nutrients, with the level of independence from the ambient environment dependent on the extent of the recirculation and geographic location.

Species for the future catalogue

This catalogue describes the ASTRAL IMTA species of the future. These species have been trialled at the ASTRAL IMTA labs in Scotland, Ireland, Brazil and South Africa and have been identified as the optimal species to be cultivated within each type of system, based on their cultivation performance, resilience, profitability and sustainability. The system types include open water IMTA (Scotland and Ireland); land-based pump ashore IMTA with partial recirculation (South Africa) and recirculating aquaculture system (RAS) using biofloc IMTA (Brazil). The potential for IMTA in Argentina and Nigeria is also described.


ASTRAL

All Atlantic Ocean Sustainable, ProfiTable and Resilient AquacuLture

GA no 863034

Research and Innovation Action (RIA)

Start date: 1st September 2020. End date: 30th September 2024

D2.7 Species for the future catalogue

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 863034

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2.2. IMTA Labs

The five lab environments provided an array of settings in which to test IMTA production. Through extensive trials, each lab developed a number of findings with regard to production:

Prospective IMTA Lab Argentina

- Assessment results of trophic interaction of the species and the growth performance but also develop specific technology, evaluate the circularity of the system, generate business models, promote specific regulations, and train specialized personnel.
- Promotion of IMTA as a production option.
- Relevant background information for any potential producer.
- Development of tools for decision-makers and policy-makers to promote IMTA.
- Generation of social license around aquaculture development in new environments.

IMTA Lab Ireland – Open Water IMTA

- Low Trophic Grid (LTG) development and design. The new low trophic grid is designed to create a pathway for current monoculture facilities to 'add' productivity. The grid model aims to maximize available space and minimize environmental impacts. The design allows the operator to adjust orientation, depths, and spacing of culture lines using multiple attachment points to facilitate a range of low trophic species. As the grid structure is submerged there is less visual impact, suspended culture limits interaction with the benthic environment and by utilising the main grid for fish culture, the co-location maximises uptake of nutrients released from fish rearing activities and reduces the number of anchor points by 50 % when compared to traditional longlines.
- Increased awareness for IMTA potential, transition from monoculture to IMTA.
- Development of best practice for open water systems.
- Communication, Dissemination, and Training.
- New knowledge and production methods generated.

IMTA Lab Brazil – RAS Biofloc IMTA

- New technologies for RAS biofloc species production developed. Biomass increased in this system. Reduction of waste achieved. Certification of system achieved.
- Increased awareness for IMTA potential, transition from monoculture to IMTA.
- Development of best practice for RAS Biofloc.
- Communication, Dissemination, and Training.
- New knowledge and production methods generated.

IMTA Lab South Africa – Land Based Pump Ashore IMTA

- New technologies and knowledge developed for commercial and new species in this system type. New species being produced at a commercial scale. Improved relationship with industry.
- Increased diversification — introduced new species, tropical sea urchin Tripneustes gratilla.
- Supplementary feed source (ca. 20% cost-saving).
- New innovative practices — machine vision application to measure urchins.
- Increased circularity —reduced energy cost (ca. 40% electricity saving) & protection from HABs.
- Microbiome modulation — improved growth, health & nutrient cycling.
- New innovative practice —faecal matter as dietary supplement to improve growth, survival & health of juvenile abalone.

IMTA Lab Scotland – Open Water IMTA

- Introduction of new species into this open water system. Improved production practices and recommendations for improved monitoring.
- Increased awareness for IMTA potential, transition from monoculture to co-culture.
- Development of best practice for open water systems.
- Local, national and international collaborations established to last beyond the project's lifespan.
- Communication, Dissemination, and Training.
- New knowledge & production methods generated.

3. Assessments

3.1. Environmental

Best Practices Zero Waste

Several experiments were conducted in open ocean, semi-closed, and closed IMTA systems. Waste reduction trials focused on closed and semi-closed IMTA systems to track nutrient flow. In Brazil, combining oysters and tilapias as organic matter filters in a shrimp biofloc system was explored, along with seaweeds to reduce nitrogen and phosphorus levels. Adaptive management approaches to developing the target of a zero waste IMTA system can be implemented by giving special attention to the selection of the species to be used, and considering biomass relations, water flow, feed amounts, water quality and the means for water recirculation (see Figure 4).

Experiments carried out in South Africa's commercial abalone farm have shown that the integration with algae provided a reduction in nutrient concentrations and allowed greater water recirculation. The results are encouraging and indicate the possibility of water reuse of around 75%. This is made possible by the integration of marine algae that consume dissolved nutrients to generate biomass. As a result, the system is less dependent on external power and considerably reduces the impact of effluents on the environment. Preliminary analysis indicates the possibility of increasing the farm's standard operational recirculation to 100% recirculation for short periods (3-4 days) of time. This is especially important when the farm is unable to pump seawater when toxic microalgae blooms occur.

Ireland developed integrated farming of fish, scallops, lobsters, urchins, oysters, and macroalgae in open sea, similar to Scotland with macroalgae and native oysters. Brazil's IMTA-lab showed that seaweed could control nutrient levels in shrimp culture. Oysters were less effective than tilapias in removing solids from biofloc systems. Microorganisms in bioflocs and probiotics improved water quality and feed conversion by transforming toxic nitrogen compounds and serving as food for shrimp and tilapia. South Africa's IMTA-lab found that seaweed integration reduced nutrients, external feed, and effluent emissions while enhancing water recirculation and providing abalone feed.

The case studies in Brazil and South Africa can be considered good examples of responsible aquaculture, where the management reduces the effluent production. The activities reported here are not intended to indicate one or another production system. Both systems, closed (Brazil) and semi-closed (South Africa), are options to be adopted. The integrated abalone and macroalgae production model may be interesting for investors from countries such as Argentina and Chile, in South America, which have adequate environmental conditions to produce this prized mollusc.

Likewise, European countries that already produce marine shrimp, such as Spain, Portugal, Italy and France, could produce shrimp using biofloc technology, integrated with fish and algae. This would increase production close to the European market, with reduced feed costs, in small areas, with no chemicals or antibiotics and basically with zero waste production.

Using the IMTA system, the farmer can diversify the production; reduce food costs, and add value to products obtained without effluent emissions (green certificate).

Figure 4: *Overview of Adaptive Managment Approach of Zero Waste IMTA System*

Conclusions From zero waste perspective

- 100% of fish meal in the shrimp diet formulation can be considered as a feasible alternative
- Reduction in crude protein levels is possible by using fish meal analogue (FMA) in shrimp diets for cultivation in biofloc systems
- Recirculation can be increased in abalone-Ulva, from 50% to 75%, as well as to 100% for short periods (3-4 days) as a mitigation strategy for harmful algal blooms
- In the 50% recirculation system, Ulva can remove ca. 60% TAN from abalone effluent
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- Development of a farm-scale urchin-Ulva IMTA model, as a valuable tool for environmental impact assessors, farmers, entrepreneurs, and investors to design farms, advise management practices and conduct economic, environmental, and social analyses

Circularity

The ASTRAL circularity assessment was initially conducted through the harmonisation of the concepts sourced from literature with respect to the definition of circular economy and its application to aquaculture. A framework, based on circularity-evidence metrics, was, then, developed to encourage IMTA and general aquaculture producers to measure and control the circularity performance of seafood farming.

In addition to bioremediation indicators, complementary metrics were applied to IMTA to quantify the level of implementation in terms of resource use efficiency strategies, which further ensured the alignment of these systems with circular economy.

Results confirmed that IMTA systems perform in line with circular attributes embedded in the definition of nutrient bioremediation. Metrics on bioremediation would promote standardisation of nutrient recycling rates, from which the effectiveness of the systems could be evaluated. In terms of resource use, the present assessment identified improvements in water recirculation and energy efficiency as being indicators of the economic benefits and higher resilience of IMTA systems. Moreover, the present assessment allowed the quantification of benefits in terms of feeding due to the reduction of linear ingredients in the feed formulation and improved FCR (feed conversion ratios).

Regarding infrastructure (capital goods), the present study addressed the lifespan as a fundamental parameter that should be considered in the circularity assessment. Generally, better maintenance or the substitution of infrastructure elements with increased durability would increase the functionality and thus the circularity. Infrastructure was studied in the circularity assessment through the MCI (material circularity indicator) analysed and compared between three scenarios (baseline, LTA and LTA improved). The integration of additional species into the monoculture system (LTA, low-trophic aquaculture scenario) showed a better circularity performance as the utility factor was increased by the increased biomass harvested with a few new structure elements required. Results confirmed that the MCI increased for the LTA improved scenario, in which the theoretical substitution of polysteel lines for seaweed cultivation with coconut fibre ropes, as bio-based material, decreased the unrecoverable waste and the virgin material.

In addition to this assessment, the collaborative work between work packages in ASTRAL evidenced that increasing the level of circularity in seafood value chains requires a multidisciplinary and holistic approach for implementation.

Policy recommendations

As part of the actions toward building synergies with other EU projects, the ASTRAL and iFishIENCI (among other EU projects) worked together on a policy recommendation document for a more circular aquaculture approach. While ASTRAL project was starting its implementation when the policy recommendations were elaborated, we worked together for the integration of the IMTA concept and perspectives within the recommendations. Particularly, this document provides suggestions regarding the following aspects (Figure 5):

- Definition of circular aquaculture,
- Methodologies for measuring circularity,
- Improving circularity, and
- Encouraging sectorial and cross-sectorial co-governance.

From the ASTRAL project, we collaborated for the integration of the muti-trophic aspects through the following recommendations, highlight in green in the next figure:

Figure 5: *Main ASTRAL contributions to the "Policy recommendations for a more circular aquaculture".*

On the other hand, and as it is reflected in Deliverable 7.7, the importance of enhancing cross-sectoral and co-governance approaches lies in the necessity of reviewing and updating legislation to avoid potential contradictions at national, regional, and local levels. In addition, further cooperation among diverse stakeholders must be pursued, not only to create a broader knowledge network, but also to introduce participatory approaches in decision-making procedures in which all stakeholders are able to actively participate. The document D7.7 also highlights the need of promoting the proper use of concepts in relation to IMTA practices. Consequently, the deliverable incorporates the concept of "co-product" to replace the term "waste" or "byproduct".

From a circularity perspective

The circularity performance of aquaculture systems can be evidenced through the study of resource use efficiency and nutrient management, which can be determined in accordance with the capacity to collect and use nutrients and uneaten feed fraction.

In the context of the ASTRAL project, we aimed to provide an evaluation of the circularity performance of IMTA production through the study of 4 different IMTA labs that were compared to monoculture conditions.

Figure 6 shows the main actions carried out by the ASTRAL IMTA labs that are highlighted through the different coloured boxes.

- Concepts were harmonized
- Policy recommendations regarding circularity (joint action with other EU projects and initiatives)
- IMTA labs were interpreted under a circular perspective and complementing with the LCA approach
- Metrics were applied to IMTA to quantify the circularity
- New indicators (Ireland, Brazil, South Africa IMTA Labs)
- Adaptation of MCI (material circularity indicator) to low trophic infrastructure (Scotland IMTA lab)
- Circularity of IMTA quantified and validated, not only in terms of nutrient recycling but also, regarding efficiency use of resources: water, energy, feed and materials

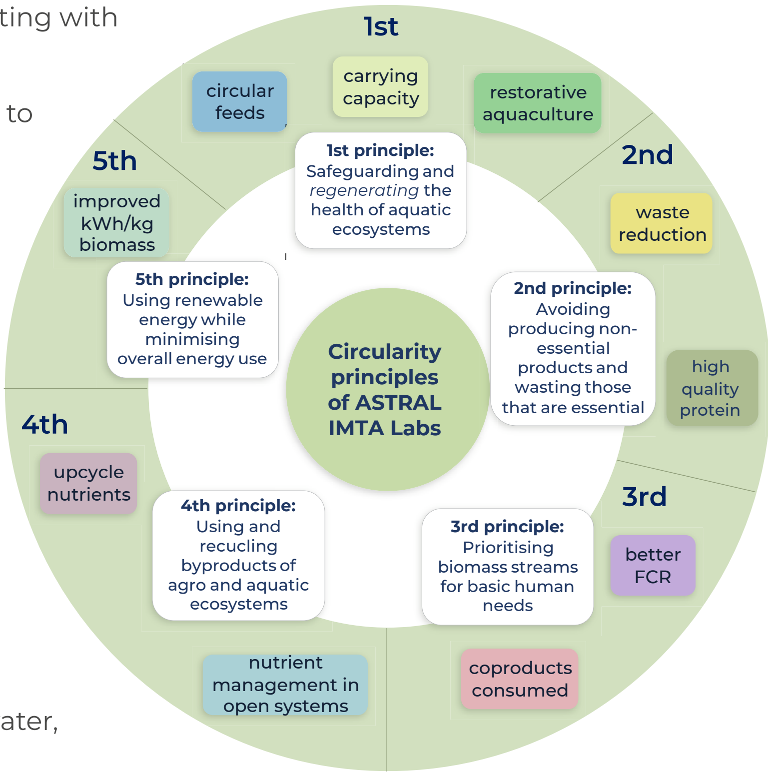


Figure 6: *Identification of circularity principles applied to ASTRAL IMTA labs (based on the study developed by Chary et al., 2023[1])*

1. This study refers to regenerative aquaculture as the farming approach that uses aquatic ecosystems conservation as the entry point to regenerate and contribute to provisioning, regulating, and supporting ecosystem services.

Life Cycle Assessments - LCA

Life cycle assessments (LCAs) have emerged as a key environmental accounting tool to quantify the impacts and provide useful information required to improve sustainability of various production systems and process value chains, including aquaculture. Many LCA studies on aquaculture have been performed assessing environmental impacts from fishing, fish feed, and aquaculture systems with different species and different designs (intensive and extensive). In aquaculture, LCA compares different techniques of production of one species and assesses the main contributing activities to the total impacts of producing that species. The overall aim of the LCA study in ASTRAL was to compare the environmental performance of monoculture (mostly aquaculture) and IMTA, to provide possible options for environmental improvement in IMTA, and thereby enable shifting monoculture aquaculture practice towards IMTA.

Sixteen impact categories were included, which are also the widely used categories for aquaculture systems:

- Climate change (kg CO2 equivalent)
- Ozone depletion
- Human toxicity, cancer
- Human toxicity, non-cancer
- Respiratory inorganics
- Ionising radiation, human health
- Photochemical ozone formation, human health
- Acidification
- Terrestrial eutrophication
- Freshwater eutrophication
- Marine eutrophication
- Land use
- Freshwater ecotoxicity
- Water use
- Resource depletion, fossils
- Resource depletion, mineral and metals

Details of the LCA studies can be found, including aims and scope for the studies comprising system boundaries, functional unit, results, and interpretation, in Deliverable 4.3. Overall, the results on the environmental performance of the IMTA systems compared to monoculture show the importance of moving towards the IMTA system to achieve sustainable aquaculture practices.

IMTA presents the potential to improve the recycling of organic matter and nutrients. This is due to the capacity of algae in an IMTA system to re-utilise waste products (nitrogen and phosphorus) from the cultured species. Moreover, the algal biomass can serve as a sustainable, nutrient-rich feed for other cultivated species. A key aspect of the bioremediation potential of IMTA is the balance between nutrient input and removal. Results indicate that seaweeds cultivated in open water IMTA take up nitrogen derived from fish feed, while phosphorus uptake by the seaweeds out-weighs the emissions. This contributes greatly to mitigating eutrophication while at the same time providing biomass for other sectors, such as aquafeed, that make it perform better in an aquatic environment. Infrastructure elements play a major role in the environmental performance in both monoculture and IMTA systems. Selection of materials can play a major role, such as using an alternative for stainless steel that can degrade faster. If the life expectancy can be improved it could result in fewer replacements, better maintenance, and lower impacts. Biomass yield is one of the most influential parameters to improve the environmental impacts in an IMTA system. By increasing the yield, we can reduce the overall impacts per kg of biomass produced in the system, although varying seasonal conditions, light regime, sea water temperature, flow rate, disease, storms, technical protocol variations can influence consistency in yield.

Environmental benefitis- LCA recommendations

- IMTA systems outperfom monoculture, under a life cycle perspective, considering FU as biomass harvested and craddle-to-gate perspective
- Eutrophication and climate change reduction by 40 and 48% of the total impacts in these categories in monoculture culture scenario
- Other Functional Units could be potentially evaluated for IMTA
- LCA allows the evaluation of IMTA systems although limitations are identified. European Product Environmental Footprint (PEF) initiative does not provide specific recommendations for IMTA systems

3.2. Economic

Since the first approaches to IMTA, systems have been improved in terms of technologies and methods. Nevertheless, barriers and risks exist, which is where ASTRAL has an important role to play in terms of better understanding the potential to design business solutions and new value chains. We have taken an in-depth look at the socioeconomic aspects of IMTA, and the inherent challenges currently faced. We have also conducted a preliminary cost-benefit assessment, defined through the lessons learned, best practices and the analysis of economic, environmental, social and regulatory aspects of IMTA. This analysis has enabled us to identify cost-effective solutions in support of IMTA processes, innovation potential and key area opportunities for business investment and growth.

Two approaches were used to conduct socio-economic assessments of IMTA ventures (Figure 7).

- A socio-economic analysis to identify trends in Atlantic aquaculture across the ten ASTRAL areas to assess the sector's characteristics, challenges, and practices. A subsequent cost-benefit assessment integrated economic data through meso- and micro-economic approaches, revealing external factors affecting systems (economic, environmental, social and regulatory aspects)
- A business models analysis comparing co-culture, monoculture, and IMTA systems using eight case studies, including 4 ASTRAL IMTA Lab. Data from interviews, reviews, and project deliverables informed a Business Model Canvas Analysis, followed by a cross-analysis using SWOT (internal factors) and PESTEL (external factors) frameworks.

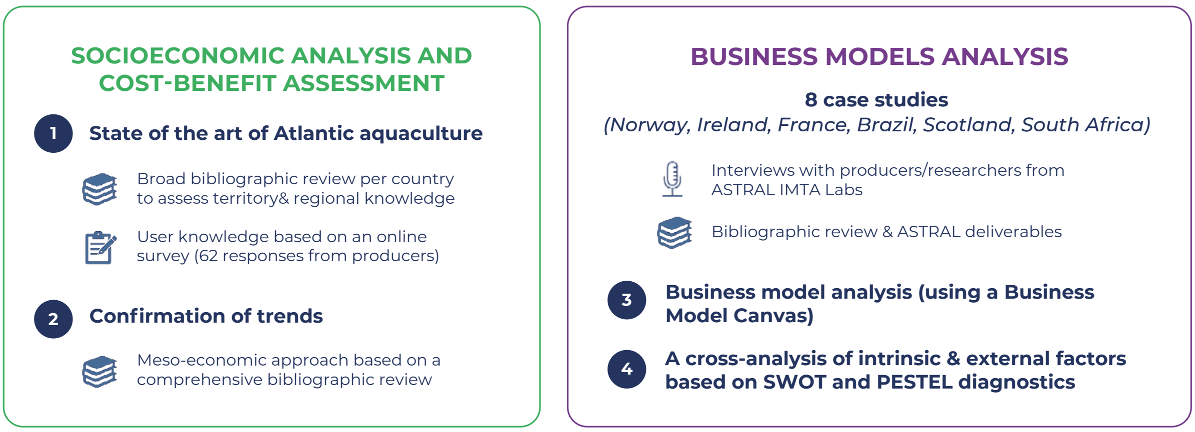


Figure 7: *Overview of Methodology for Cost Benefit Analysis and Business Model Analysis*

IMTA benefits and proven facts

The IMTA concept has not been demonstrated economically on a broad scale yet, with only a few studies having conducted a complete economic analysis, including external costs and benefits. However, the benefits gained through IMTA production have been proven in several scientific papers and studies, with the net present value (NPV) as well as profits and margins, growth rates and survival for IMTA systems rating higher than monocultures.

The size of the production site and the farm is also of importance as a smaller farm means greater flexibility, though investment costs and fixed prices are higher and more significant. Even if investment costs related to shifting to IMTA can be steep for a small farm (and in extension, for any farm), there is an expected rate of return on investment of approximately four years. However, IMTA can also improve the sustainability of seafood production, by reducing ecological impacts in proximity to intensive operations, and provide financial benefits via product diversification, faster production cycles and price premiums on IMTA products, which also has an effect on price volatility. Farmers should also consider which and how many species are incorporated into a system, as it has been shown, for example, that it could be more efficient to use three species, instead of four, in terms of return on investment.

One should also consider the demand for IMTA products. Social perception is key for this success as although consumers may be seeking out more sustainable food options, and may be willing to pay more for a premium product, there is a need to raise IMTA awareness with both the public as well as in the aquaculture community. It is important to note the inherent variation in environmental, infrastructural, capital, and scale factors in different potential sites. Developing an economic model that equitably assesses an array of IMTA sites is highly challenging as there are great differences in starting an IMTA farm in Europe compared to tropical regions, or between a small farm and a large farm.

Lesson Learned

Species' growth rate

- ❑ Growth rate is higher with IMTA systems because of the feeding process and the algal effects (mussel/scallop/seaweed or abalone/seaweed), depending on the value chain, but this is only true for certain species and combination of species (depending on the trophic links)

IMTA products as selling argument

- ❑ IMTA allows product diversification and could enable a price premium (+10%), but public awareness is very low, products are subject to price volatility and new markets/channels need to be created to be able to sell at price premium

Return on investment (ROI)

- IMTA NPV is always higher than that for monocultures and ROI is estimated to be 4 years for a small/family farm, but ROI can be much longer for a larger farm, which will have more investment costs to start an IMTA farm.

Production & HR costs

- IMTA systems tend to reduce the production and HR costs, but these effects can only be seen on small farms with specific characteristics

Environmental services

- IMTA allows to reduce the environmental impacts of such production, but no actual data are available to see the long-term effects of this production

Cost Benefit Analysis (CBA)

In ASTRAL, the Cost Benefit Analysis (CBA) aims to understand the impacts of IMTA regarding economic, environmental, social and regulatory aspects, in order to improve decision making and to favour the adoption of IMTA techniques. To design the CBA, we looked at models and steps that are followed by businesses when they are willing to restructure or start a new activity and are looking to estimate the related costs and benefits. Economic aspects cannot be considered alone. Developing and analysing IMTA models requires a comprehensive assessment of economic, social, regulatory and environmental issues. The CBA conducted in ASTRAL is based on producers' interviews from 2022 across Argentina, Brazil, France, Ireland, Nigeria, Norway, Portugal, Scotland, South Africa, and Spain.

Recommendations

The following section aims to summarise the main recommendations that arise from our analysis and the interviews conducted.

These recommendations have been drawn for producers, the aquaculture industry organisations and/or policy makers. For each entry, a sticker helps understand to whom the recommendation is addressed:

Economic

Economic Costs

- IMTA systems can initially require more resources and time for implementation, increasing production costs.
- Potential initial infrastructure costs as IMTA requires a different structure, anchoring systems for each species, potentially increasing infrastructure costs and a continued need for investment.
- Some producers stated that they need time to find a sustainable and profitable method, especially when starting from zero.
- As IMTA is quite new and still under development in most countries, there is a need for the producers to learn or get their employees to gain new competences to adopt this new technique, to better know species and their commercialisation.
- An essential need for knowledge of the right combination and trophic links between is under development, hence the importance of R&D effort.
- A need for commercial experience in IMTA and comprehension of markets.

Economic Benefits

- Less time required for water quality control and tank cleaning, resulting in lower labour and feed costs (and thus improved profitability). Potential for use of seasonal staff over longer periods, or existing staff being employed for more diverse tasks.
- Potential for reduced feed costs due to lower feed conversion ratio of species ratio compared to co-culture/monoculture systems.
- Potential for revenue diversification thanks to the novelty of the process (tourism through farm visits, new chain of products, etc.)
- As all products are being used for each production cycle, each element, even waste, is processed and used, improving farm efficiency.
- Potential for improved growth rate and size of product, which could lead to an increase in revenue.

Economic Perspectives

Access to finance

Access to finance is a key aspect for producers to develop IMTA projects. According to the IMTA farms interviewed, public funding is very important. It is all the more important since IMTA is mostly at the experimental stage for many producers. It is, therefore, the R&D phase that requires support to develop the best IMTA system (what type of crops, what volume and for what market). Many stakeholders report that businesses can find it difficult to secure investment, for instance, to buy and upgrade equipment, to invest in new technologies or for staff development and training.

Matching to market needs: quality, traceability and freshness

Market-based incentives are important drivers for producers participating in eco-certification schemes. Indeed, with a growing concern about food safety, more efforts have been undertaken to improve the food quality introduced in the market. Interviewed IMTA producers were convinced that the certification of their product is crucial for differentiation, traceability, easiest profit margins and profitability.

In general, consumers' perception of farmed fish is more negative than that of wild fish, due to concerns about the health freshness of the products, and the potential use of antibiotics or other chemical products. As such, food safety and in turn, traceability, are important elements of drawing consumer interest. As with other aquaculture producers, most of the IMTA producers interviewed already have internal traceability monitoring systems in place (though the parameters that are monitored vary tremendously depending on the farm size and country).

Production Costs

Owning an aquaculture facility can be expensive, mostly due to the infrastructure costs. The development of aquaculture businesses differ with regards to the aquaculture production types and species, as well as fixed and variable costs (fingerlings, juveniles, chemicals, etc.). The location of the farm also affects the capital intensity. Through the interviews conducted by the ASTRAL team, it is difficult to draw a general trend. For some producers, production costs have risen, while for others, the views are more mixed regarding the increase of costs. In general, human resources are the most significant elemant of production costs. Some IMTA farmers also mentioned the importance of feed in their budget. Aquafeed production is subject to common global market shocks and volatility. In addition, feed prices are further affected by fluctuating prices due to petroleum fuel and other transport costs. The varied species production in an IMTA system can impact the labour force: some are labour intensive (e.g. abalone) and some are seasonal (e.g. seaweeds). As aquaculture systems rely on energy for the production process, some farms are investigating renewable energy harvesters while others are looking for energy autonomy by installing independent infrastructure such as wind turbines.

Need for skilled staff

Aquaculture is an interdisciplinary practice by nature and requires skills in biological, technical, management, marketing and other related disciplines. Over the past decades, there has been a growing demand for technological skills related to digital technologies. Demand for such skills will increase in the coming years, however, are lacking in the current workforce. Aquaculture-specific engineering and technology training schemes to support technology adoption are key features to investigate for training programmes. Furthermore, the challenge of mastering the cultivation of several species at the same time appears to be a major obstacle to IMTA development, in addition to the complementary staff required. It is important to establish links between schools, training programme and jobs in aquaculture (e.g. through dedicated programs).

Adequate use and offer of technology
Aquaculture is a very unpredictable biological process, making it subject to more significant risks than most other activities. Thus, innovations must be introduced to improve the predictability and uniformity of the production methods. All of the interviewed farmers highlighted their link with research as a necessary condition to developing their business and to innovate. The development of new technologies – such as high-resolution satellite imagery, sensors, DNA technology, blockchain, the Internet of Things (IoT), big data, artificial intelligence (AI) and machine learning – is likely to affect the established data supply chain and disrupt the sector's management in the short-to-medium term. The producers have to know how to collect and analyse extensive data and need to be able to adapt their methods in response. Most of the interviewed IMTA producers use more traditional monitoring methods, which may have their own value, may affect a farm's ability to stabilise production and adapt to otherwise unanticipated fluctuations in the system. The challenge remains the access to these technologies for local farmers, due to prohibitive costs and lack of knowledge.

Environmental

Environmental Costs

- Production systems are subject to currents and weather conditions, causing damage and organic loading, leading to increased production and maintenance costs.
- With climate change, one can see an increase in disease occurrence in the system as well as an increase of HABs and discovery of invasive species, leading to increased production, feed and treatment costs.
- Environmental groups can be strong opponents and may object to IMTA implementation, which could lead to protests, demonstrations and damage to the farm, resulting in decreased revenue and increased maintenance costs.
- IMTA producers' interest in initiating/shifting to IMTA was partly due to the anticipated reduced environmental impact, however, they lack concrete data and results to this effect, hindering their ability to help raise awareness among the general public and consumers.

Environmental Benefits

- IMTA producers have observed an increase of oxygen level in their IMTA systems, due to the algal concentration, which can lead to bioremediation and increased ecosystem services, potentially resulting in reduced feeding and maintenance costs.
- IMTA producers stated that they also shifted to IMTA to reduce the negative externalities caused by their production systems, potentially resulting in reduced feeding, production and maintenance costs.

- IMTA producers noted that shifting to IMTA helped to reduce mortality rates of their species, highlighting that a relevant trophic combination between species can impact the growth rate (e.g. Ulva & abalone), potentially resulting in reduced feeding, production and maintenance costs.
- Some IMTA producers explained that a strong group dynamic helps farmers to produce more, get various sources of feeding and help with shipping processes, potentially resulting in decreased shipping and feeding costs.

Environmental Perspectives

Biosecurity

Biosecurity needs to be addressed in a multi-stakeholder's approach (producers, value chain actors and authorities): the need for long-term biosecurity management strategies, including implementation of international standards on aquatic animal health and welfare is crucial. Management of disease and biosecurity of fish stock remains a significant challenge for aquaculture production, and a constraint to growth. Some monoculture and co-culture producers fear an increased spread of pathogens between species with IMTA. As such, many IMTA farmers regularly monitor their production for pathogen management, and carry out research projects to develop knowledge on this aspect, especially regarding genetics and nutrition.

Climate change

Climate change highly impacts aquatic conditions. Interviewed IMTA farmers are convinced of this but do not really know yet how to assess this change and its effects. The direct effects include harmful algae blooms or influencing the physiology of finfish and shellfish stocks in production systems, while indirect effects may occur in the supply chain, such as prices, fishmeal, other goods and services needed by aquaculture producers that will not be available. Aquaculture producers must adapt their system to build resilience in the short term and in the long term, and IMTA systems could be a way to achieve this resilience. Further assessment of climate change impacts and the resilience capacity of farms is needed; in the meantime the priorities for most young farmers are economic viability and technical efficiency.

Aquaculture wastes as negative externalities

Aquaculture itself can generate pollution through release of organic wastes, chemicals and inorganic nutrients. Feed is a major source of waste in aquaculture systems, and this waste production depends on many factors, including its nutrient composition, method of production (extruded vs. pelleted), ratio of feed size to species size, quantity of feed per unit time, feeding method and storage time. Waste management is a key factor to sustain the production and to favour social acceptance. IMTA as an eco-friendly approach has a strong hand to play. This practice does not compromise the well-being of the natural ecosystem because of the synergistic functions of different extractive species, where both inorganic and organic waste are naturally regulated.

Water Quality
Optimal water quality varies by species and must be monitored in surface water and groundwater sources to ensure growth and survival. The quality of the water in production systems can significantly affect the organisms' health and the costs associated with getting a product to the market. Water quality parameters commonly monitored in the aquaculture industry include temperature, dissolved oxygen, pH, alkalinity, hardness, ammonia and nitrites.

Social

Social Costs

- Need to raise awareness on IMTA among employees and managers, and help them understand the benefits and value of such production methods, which has an associated HR and training cost.
- A lack of knowledge within the public and producer community regarding the IMTA model benefits, thus this is an obstacle for IMTA development.

Social Benefits

- The development of sustainable aquaculture contributes to the development and of coastal areas and communities through employment, environment preservation, etc.
- Producing and combining species that can absorb nutrients (e.g. seaweeds) and reduce pollution improve the perception of the aquaculture sector, which has experienced negative coverage in the media.
- South African producers explained that there is a strong group dynamic in their country, which helps farmers to All IMTA producers interviewed are involved in professional organisations (generally sectorised by species) and linked with research community: access to knowledge is important to implement pilot projects, networking, access to European and international projects, potential commercial contacts. Some also indicated that partnerships within the aquaculture community can enable farmers to produce more, access various sources of feed and simplify shipping processes.

Social Perspectives

IMTA production could enhance the social acceptability of aquaculture, once the concept is clearly explained. As of now, the general public is sceptical since they do not have extended knowledge on IMTA as well as difficulties to relate to a complicated acronym.

Perception of aquaculture and conflicts
Activities linked to our oceans, and widely to water, are significantly expanding within a highly competitive environment among countries and specific interest groups. Several types of areas exist:

- areas with existing regulated, restricted or prohibited access such as shipping routes, military exercise grounds, marine protected areas;
- areas used for productive purposes as fishing, agriculture, tourism, aquaculture;
- areas used for "non-productive" purposes such as inhabitants, occasional fisherman, sportsmen, tourists.

Users could have conflicting interests linked to the competition (spatial restrictions) or negative externalities (potential impact of aquaculture on water quality, wastes, etc.).

Regulatory

Regulatory Costs

- The bureaucratic red tape and the burden of complying with the licensing processes can lead to increased HR and license costs.
- As IMTA production is quite recent and no official regulation has been put into place, IMTA producers foresee issues regarding selling products coming from IMTA systems and its consumption by customers (biosecurity), potentially resulting in reduced profit and revenue.
- Since IMTA is not well developed throughout the Atlantic area, it can be complicated to get feedback and/or support from sector representatives and associations, as monoculture is the standard model and species are too segmented in their systems.
- As IMTA is quite new and not well developed, political changes or new/updated laws might slow processes and add new obstacles to growth, potentially resulting in increased HR and production costs.
- Regulation of species can be problematic, making IMTA development more complex and increasing administrative effort for team members as well as potentially increased license costs.

Regulatory Benefits

- Some national funding authorities have expressed their will to support aquaculture diversification and are planning to open calls for funding or direct funds to help producers in their development, support from policy makers thus signalling a potential increase of public co-funding.

Regulatory Perspectives

Spatial planning, a key driver for aquaculture development

Around the globe, increasing human activities in coastal and offshore waters have created complex conflicts between various sectors, competing for space and between the use or conservation of ocean resources. In addition, the profitability of an aquaculture farm and the potential environmental risks and impacts are important. Several tools, such as Marine Spatial Planning (MSP), have been promoted to achieve more ecosystem-based marine management, with a focus on balancing multiple management objectives. Both industry-specific and multiple-use planners rely heavily on spatially referenced data, Geographic Information System (GIS)-based analytical tools, and Decision Support Systems (DSS) to explore a range of options and assess their costs and benefits. Nevertheless, better tools are needed to evaluate and incorporate the economic and social considerations that will also be critical to identify potential sites and achieving successful marine plans for IMTA.

The importance of institutional support

Institutional support is crucial to developing sustainable and profitable aquaculture. Producers often highlight the complexity of procedures, which greatly hinders the development of this new approach. A simplification of procedures with greater coordination between public administration bodies is needed for producers. Stability in policy is also critically important, with frequent changes in government agencies preventing the achievement of continuous and sufficient investment and to adopting mid-term or long-term strategies. Governments can help industry players overcome obstacles by the provision of financial incentives, thereby providing recognition for the value of IMTA operations in addressing unpriced external costs. A system of incentives may be more effective than laws, rules and regulations to encourage a responsible and sustainable aquaculture. There is a real regulatory blockage of IMTA development - the regulatory framework seems to be fragmented, and often developed on a per-species basis. Developing IMTA on a broad scale will require regulatory adjustments.

CBA Recommendations:

The following section aims to summarise the main recommendations that arise from our analysis and the interviews conducted.

These recommendations have been drawn for producers, the aquaculture industry organisations and/or policy makers. For each entry in Figure 8, a sticker helps understand to whom the recommendation is addressed:

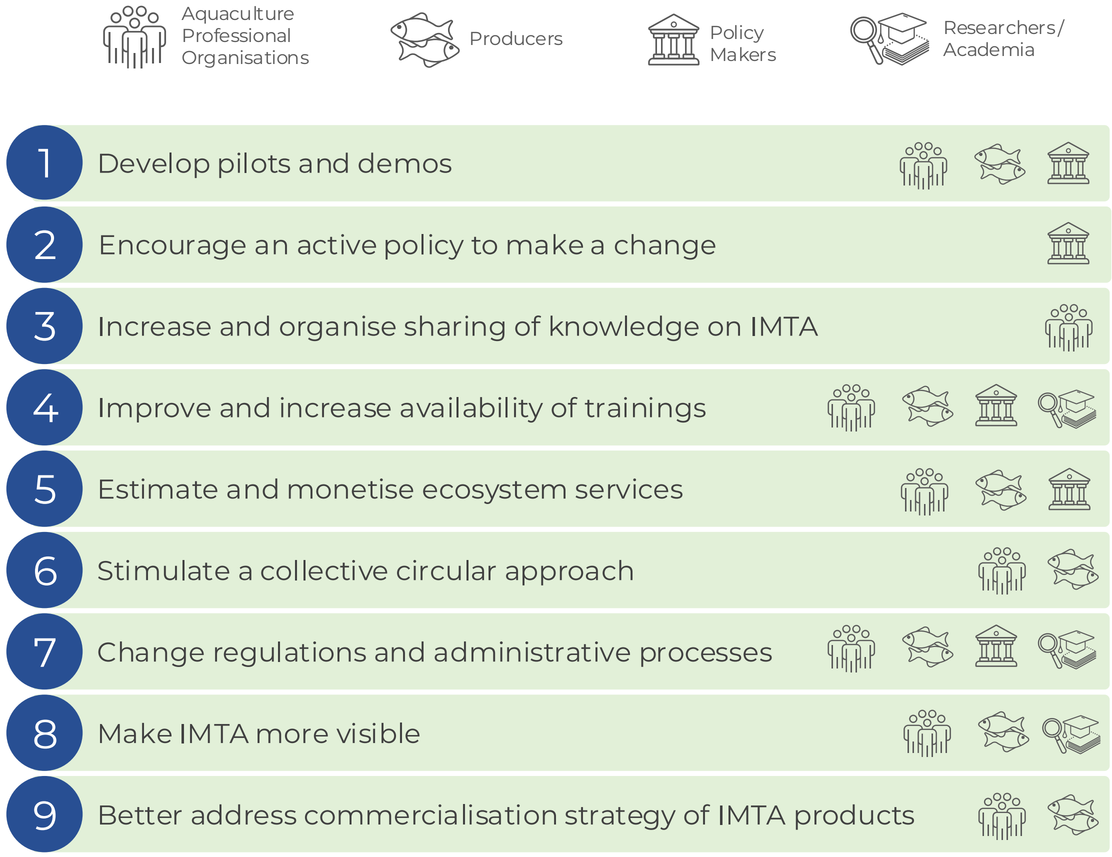


Figure 8: *CBA Recommendations*

Business Model Assessment

A business model assessment was conducted that clearly shows the plurality of aquaculture business models, both in traditional and IMTA systems. It allows a precise description of each economic operation, but also to project prospective scenarios for IMTA systems that are not at commercial scale.

The intention of this assessment is to support the development of the aquaculture sector in the Atlantic area by:

- highlighting the economic functioning of IMTA production and the economic advantages or disadvantages for each type of system, depending on the location and the species produced
- providing the various stakeholders an overview of different types of IMTA production, both for existing and experimental sites.
- providing producers and entrepreneurs de roadmaps, key steps and milestones that they need in order to get into the IMTA systems.

Figure 9 provides an overview of the key drivers identified.

Economic interest	◦ Additional economic dynamism to coastal areas with IMTA, enabling job creation & local economic growth ◦ Higher net present value (due to diversification of revenues from pooled production of multiple species.)
Change in consumer habits	◦ Increase in overall consumption of aquatic products & significant changes identified in consumer habits ◦ Growing interest for alternative protein sources, biobased products produced with sustainable methods & limited environmental impact ◦ Consumer awareness of origin of products & willingness to pay a higher value for a premium product ◦ Emergence of alternative sales channels: click & collect, baskets or home delivery: producers need to adapt to new channels
New markets	◦ Scientific evidence for multiple nutritional & health benefits from consumption of seaweeds ; ideal for functional foods & nutraceuticals ◦ Potential for using seaweed as an aquafeed ingredient ◦ High probability that Ulva will increasingly be grown in IMTA systems for aquafeed, & for human consumption in the future ◦ Wide range of applications for seaweeds but need for large amount of biomass with a higher market value ◦ The sector needs to open to new markets (biofuel, cosmetics, etc.) where the value of products remains high.
High-quality products	◦ IMTA products produced under controlled & sustainable systems ◦ Traceability increases quality & value (competitive advantage for producers) ◦ Labelling/certification of IMTA products, currently non-existent, may have disadvantages (quality criteria, label costs, etc.) but could be an opportunity for valorisation of IMTA products & criterion for increasing market value.
Branding	◦ Need to develop visibility of IMTA production with consumers & buyers to increase market value of products, ◦ Need for branding & marketing of sustainable IMTA production & products by producers to increase market value & highlight diversification of products compared to competition..
R&D and skilled human resourc-es	◦ R&D inherently a key element of IMTA systems' activity ◦ Need for expertise & skilled human resources ◦ Growing several species simultaneously with different trophic levels requires technical equipment & operating methods that can be complex & needing more expertise.
Political and financial support	◦ IMTA systems require considerable installation investments ◦ Operational expenses & R&D costs are important & mandatory ◦ Existence of these systems is highly dependent on existence & access to funding, as well as administrative support to follow through. ◦ Simplified policies that are adapted to IMTA & developed together with stakeholders are essential.
Market vision & commercial strategy	◦ Exploration of potential markets & understanding of the needs of various customers is limited. ◦ Producers must develop a marketing strategy that considers emerging markets & diversifies customer segments. ◦ Producers' marketing & commercial development skills must be developed to support sustainability & profitability of IMTA businesses.

***Figure 9**: Key Drivers in Business Model Assessment*

SWOT Analysis

ASTRAL conducted SWOT (Strengths – Weaknesses- Opportunities-Threats) analyses for the pool of technologies developed within the project. The aim of the project development is to improve, adapt, validate, and showcase application value for a pool of technologies (see section 4.2) to support aquaculture production and improve monitoring of associated environmental impacts. The pool (or toolbox) comprises a set of innovative components including emerging novel sensors, IoT kits for validation in IMTA sites and AI deep Learning to build IoT real-world models for sustainable aquaculture farming. The engineering work follows an agile approach where iterative cycles of development yield rapid prototyping, shortening the technical validation of system components. Various ASTRAL teams were involved in developing 6 different technologies and a detailed SWOT analysis is provided for each of them. Furthermore, common trends have been identified throughout the 6 technology strands to provide a global SWOT for the entire technological development effort. The array of different skills gathered within the ASTRAL project provides a strong team to meet the challenges presented and the capacity to implement a successful multidisciplinary approach to address them.

A major drive for the project is to develop low-cost solutions for IMTA aquaculture and the ASTRAL team worked closely with IMTA practioners to develop suitable tailored tools to assist them. However, it should be recognised that solutions developed here will have great relevance for many other applications beyond IMTA, such as water, agriculture and environmental protection domains. An individual SWOT analysis for each of the six technologies listed below is presented within Deliverable 6.6, together with an overall SWOT analaysis for the entire pool of technologies.

Finally, we provide an overall SWOT analysis for the entire pool of technologies, summarised in Figure 10.

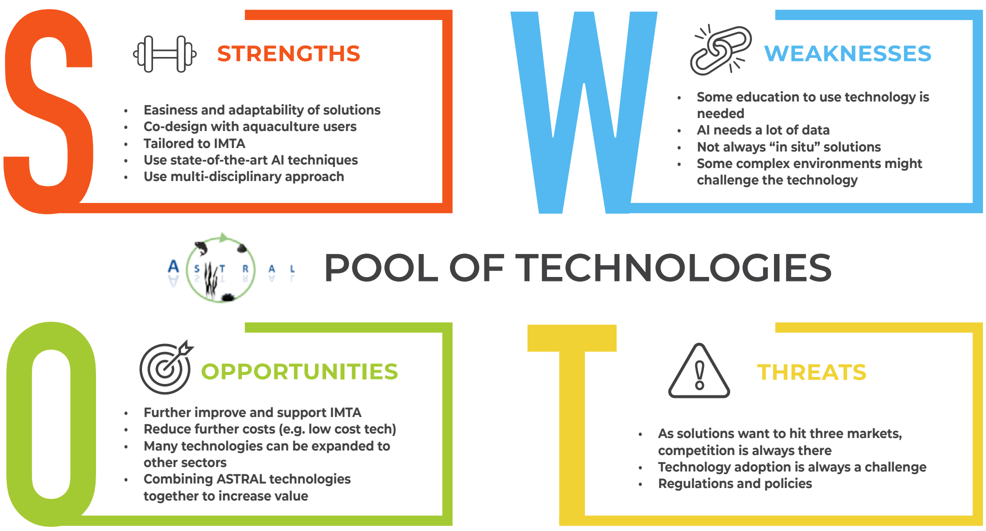


Figure 10: *Summary of SWOT Analysis for ASTRAL*

3.3. Social

The ASTRAL project held a series of IMTA and Society participatory workshops that were held online and in person between October 2021 and November 2022 at the following locations:

- Scotland, 22nd October 2021 (online)
- South Africa, 15th February 2022 (online)
- Brazil, 31st August 2022 (in person as an event at IV International Fish Congress & Fish Expo Brazil 2022, Foz do Iguaçu)
- Argentina, 8th November 2022 (in person at CADIC-CONICET, Ushuaia)

The main aim of the workshops was to consult the full range of identified stakeholders, gathering their views on perceptions of IMTA. The workshops were designed for interested parties to engage with the ASTRAL project, learn more about it and participate in a series of discussions that would contribute to ASTRAL project tasks and outputs on perceptions of IMTA, Social Licence to Operate (SLO), consumer preferences and policy.

Building Social License to Operate for Integrated Multitrophic Aquaculture

SLO Guidelines

Social Licence for IMTA can be defined as an ongoing relationship between a host community and IMTA producer, where community trust and support for the project are dependent on the producer meeting certain standards set by the community.

It is important that any development project is socially, as well as environmentally, sustainable. These guidelines were developed through the EU Horizon 2020 ASTRAL project in collaboration with IMTA stakeholders in Scotland, South Africa, Brazil and Argentina. They are aimed at people involved in or wishing to become involved in IMTA to help them gain and maintain a Social Licence to Operate and build a positive relationship between their operations and relevant communities. The SLO Guidelines provide an overview of approaches to building social license, some of which is summarised here.

Building Positive Relationships and Improving Inclusion has been shown to increase trust between communities and aquaculture operators. Steps to achieving are:

- Performing a stakeholder mapping exercise during the site selection process, mapping communities of place and communities of interest.
- Engaging with key environmental NGOs and communities at an early stage to discuss environmental benefits, listen to concerns, and consider and where possible, co-produce, mitigation plans.
- Developing community, where possible, empowerment options such as community shares in the company, or community-led benefits agreements.
- Being an active part of local society, which may facilitate genuine contribution to local communities and continual, easy access communication between key stakeholders, communities, and operators.

Engagement Process and Style is important in ensuring that ideas and information are successfully communicated. Where possible, engagement should be:

- A meaningful process, which listens to local views and takes those into account. • Open, honest, and transparent.
- Tailored appropriately for the target audience and distributed through an appropriate means, to ensure it is accessible.
- Consistent in providing information and evidence, answering questions and dispelling myths.
- Informing stakeholders of any risks and the actions to reduce them.
- Supportive of IMTA by showing the benefits and opportunities, highlighting its potential, and contextualising alternatives.

Creating Social Benefits has been shown to contribute to a positive relationship between project developers and communities. Steps to achieve this can include:

- Generating local employment opportunities where possible, through using local supply chains, collaborating with partners and/or directly providing training in IMTA-relevant skills and employing local people.
- Supplying local communities with accessible and competitively priced produce from local sites.
- Supporting the valorisation of local products and encouraging their entrance to market.

Environmental Stewardship has been found to be important to communities. Steps to minimise harm and to promote sustainability and environmental benefits can improve industry-community relationships. Steps to achieve this can include:

- Use the minimum area necessary for the system and try to avoid interference with local wildlife or existing human activities in the surrounding environment.
- Focus on sustainable, clean systems using renewable energy.
- Consider the advantages of traditional harvesting methods.
- Promote environmental benefits, e.g. carbon sequestration, helping mitigate climate change.
- Consider joining certification schemes. These can add to consumer confidence in the farm's practices.

Evaluating Effectiveness of Social License activities is necessary to ensure that engagement efforts are reaching communities in an accessible and appropriate way, as well as to identify how techniques can be improved to ensure best practice in the future. Steps to achieve this can include:

- Evaluating the health of the relationship between industry and communities by assessing how favourably the community is receiving information and materials.
- Identify pathways to improve engagement processes.
- Support research into the links between IMTA and society.

4. Technology

4.1. Technology User Guide

To achieve stability in an engineered ecosystem, a thorough understanding of its physico-chemical and biological dynamics and interactions is essential. Each IMTA system is unique in terms of siting, structure (flow-through, land-based, open-water), species cultivated, nutrient inputs and uptakes. Each system will have a different risk profile and different vulnerabilities to variable environmental conditions (including climate change), as well as to the introduction of biological hazards (biosecurity risks). Sites may be remote, or lack energy supply and communications infrastructure: each will have individual requirements and constraints for achieving the necessary insight into the operation of the system. Regardless of the size of the operation or its location, however, sensor device robustness and stable performance at the appropriate measurement sensitivity and frequency should always be a priority.

As interest in the industry grows and targeted technology becomes more readily available, physico-chemical and biological water measurement and monitoring solutions can be designed and built to meet the specific needs of each IMTA farm. The advantages of automated systems and the development of consistent datasets for identifying/predicting trends and change are clear – and the learning from these data to identify risk patterns and create early warning alerts can be invaluable.

While there are technology applications in many aspects of IMTA farming (feed automation and optimisation is another area of rapid technological development in mono-specie farming), ASTRAL developed a Technology User Guide that focuses on the use of technology for water quality, biomass measurements and monitoring. Bearing in mind the unique requirements of each site, farming system, and business model, this guide provides an overview of principal water quality parameters, biomass estimation methods, and sensor technologies commonly used to measure and monitor these variables. The guide provides information on a range of technologies suited to all levels of IMTA farming, from cost-effective solutions for small scale farms to more advanced and data-intensive systems appropriate for larger commercial and research operations wanting to increase efficiency in farm management and optimise production.

The guide provides a broad overview of the state of the technology landscape available for aquaculture, touching briefly on the relevant parameters, sensors, associated analytics, and considerations associated with their use and application. Examples are provided of relevant commercial solutions, in addition to pertinent ASTRAL-specific technological developments and research topics.

Although the ASTRAL project focuses primarily on integrated multi-trophic aquaculture (IMTA) production, the guide is approachable and informative guide, with a much broader scope, providing an orientation on several topics, including: the sensors and technology used for four different monitoring topics, namely physico-chemical water quality parameters and sensing methods, aquaculture stock and biomass estimation sensors, threat detection, and environmental variables; and the considerations in terms of instrument choice, operational environment, and system design.

4.2. Pool of Technology

The primary objective of the ASTRAL Pool of Technologies is to advance and enhance the practice of IMTA through the integration of cutting-edge technology assets (TA). The comprehensive objective is to create a cohesive and technologically advanced ecosystem that enhances the sustainability, efficiency, and productivity of integrated multi-trophic aquaculture. By achieving these objectives, the technology pool aspires to contribute to the broader goal of promoting responsible and environmentally friendly practices within the aquaculture industry.

The ASTRAL project has assessed water quality within IMTA sites through biosensors and MEMS-based UV-IS fluorometer-spectrometer technologies. A low-cost starting kit, integrating cost-effective IoT kits for real-time monitoring of water quality parameters allowed the ASTRAL IMTA labs to collect data on a continuous basis at an affordable budget. Off-the-shelf vision sensors coupled with AI deep learning models allowed macro-level biomass estimation and regional phytoplankton monitoring as proxy information for early detection of Harmful Algal Blooms. A low-cost imaging particle sensor for microplastic assessment and monitoring has been built and validated based on microplastics sampling within IMTA labs. The Artificial Intelligence Data Analytics Platform (AIDAP) provides an analytics cloud architecture for predictive modelling of physico-chemical parameters and biological water quality indicators. It also comprises an AI based infrastructure on which time-series data from multiple TAs installed at different IMTA lab locations can be linked together to generate readable outputs for aquaculture. Figure 11 illustrates ASTRAL Technology Assets overview.

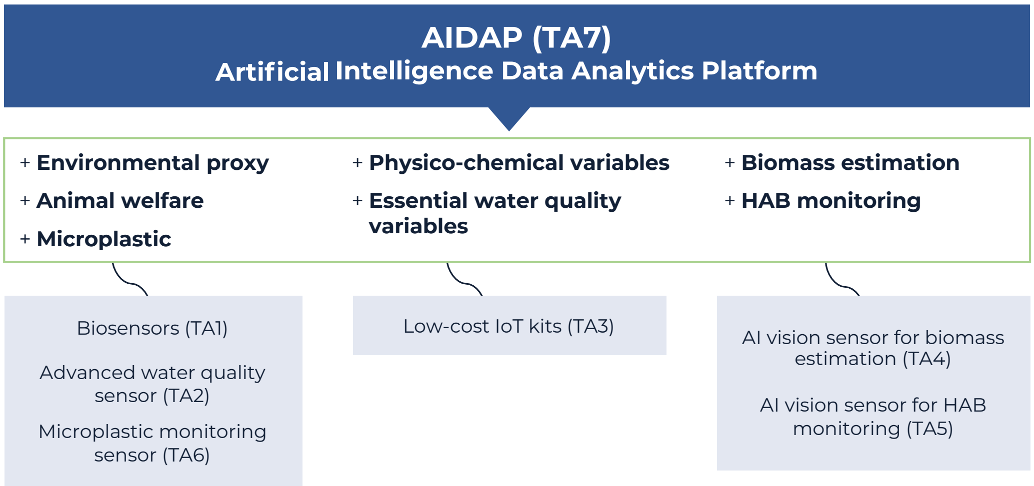


***Figure 11**: ASTRAL Pool of Technologies Overview.*

Biosensors

Bivalve molluscs are recognised for their characteristics as sentinel organisms in the context of environmental monitoring. Due to their sessile nature and high sensitivity to variations in aquatic conditions, they serve as valuable indicators of water quality. Bivalves possess the unique ability to close their valves, effectively isolating their soft tissues from the surrounding aquatic environment. Such biosensors also offer holistic insights into the overall water quality in aquaculture applications.

The ASTRAL biosensor technology introduces a groundbreaking approach to aquatic monitoring, featuring two distinct types: Vision-based and Micro-Electro-Mechanical Systems (MEMS) based biosensors (Figure 12). Both biosensors contribute to a comprehensive understanding of aquatic ecosystems by providing real-time proxy information for water quality assessment.

***Figure 12:** MEMs-based (left) and Vision-Based (right) Biosensor technologies*

Advanced Water Quality Sensor

The Advanced Water Quality Sensor is a cutting-edge autonomous spectrofluorometer technology designed for physico-chemical measurements in aquatic environments, such as chlorophyll level. It is positioned at the cutting-edge of aquatic measurements technology with its combination of affordability and advanced technology.

Low-Cost IoT Kit

The IoT (Internet of Things) kit stands at the forefront of real-time physico-chemical parameter monitoring in IMTA labs. Comprising a datalogger with support for various IoT communication protocols, this kit provides a cost-effective solution for monitoring water parameters such as temperature, dissolved oxygen, salinity, and turbidity. The kit's adaptability is underscored by its optimized self-powering capabilities, allowing it to operate efficiently in diverse environmental conditions. The deployment across multiple IMTA labs, each utilising different communication technologies, speaks to the IoT kit's versatility. With a focus on user accessibility through the AIDAP, the IoT kit represents a pivotal technology for real-time aquatic data acquisition and analysis.

AI Vision Sensor (Biomass Estimation)

This sensor comprises two innovative technologies, each tailored for macro-level biomass estimation of distinct aquatic organisms in accordance with IMTA lab needs (Figure 13). These AI vision sensors employ off-the-shelf camera systems to evaluate biomass of target species. The technology's strength lies in its adaptability and cost-effectiveness, providing a viable alternative for manual sampling and traditional biomass estimation practices in aquaculture.

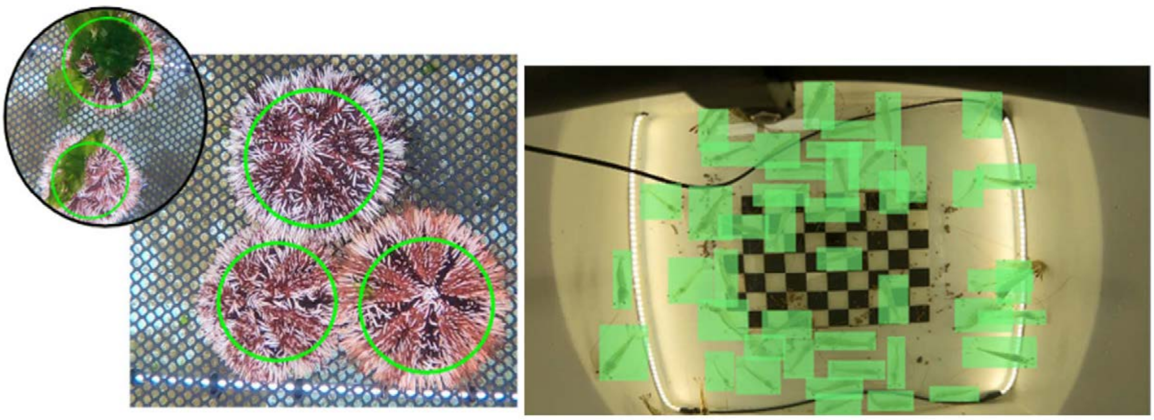


Figure 13: *Urchin (left) and shrimp (right) biomass estimation images.*

AI Vision Sensor (Phytoplankton Monitoring)

The AI Vision Sensor for phytoplankton monitoring provides an edge-based platform with low-cost high-resolution cameras coupled with AI deep learning models tailored for regional phytoplankton recognition. It aims at identifying phytoplankton groups or species in real-time as proxy information for Harmful Algal Bloom (HAB). The device has significant potential for precise phytoplankton analysis and HAB monitoring within IMTA environments.

Technology Asset 6: Microplastic Monitoring Sensor

The microplastic sensor is a standalone, benchtop, autonomously operating optical apparatus meticulously designed for the systematic examination of water samples in a continuous flow. Its principal function is the precise identification of microscopically sized polymer particles, colloquially known as microplastics, while concurrently differentiating them from other naturally occurring particles within the scrutinised water sample.

Technology Asset 7: AI Data Analytics Platform (AIDAP)

The AIDAP stands as a fully implemented and operational hub for AI applications within the ASTRAL project (Figure 14). Designed to offer user-friendly access to various AI innovations, the platform enables users to choose specific applications based on their needs. Notably, the Shrimp Detection application provides users with the ability to analyse shrimp sizes from uploaded videos, offering models for both murky and clear water scenarios. The platform efficiently manages job queues, allowing users to track and revisit previous submissions. Plans for online deployment and the incorporation of additional AI applications, including urchin detection algorithms, underline AIDAP's role as a comprehensive, real-time analytics platform for IMTA labs.

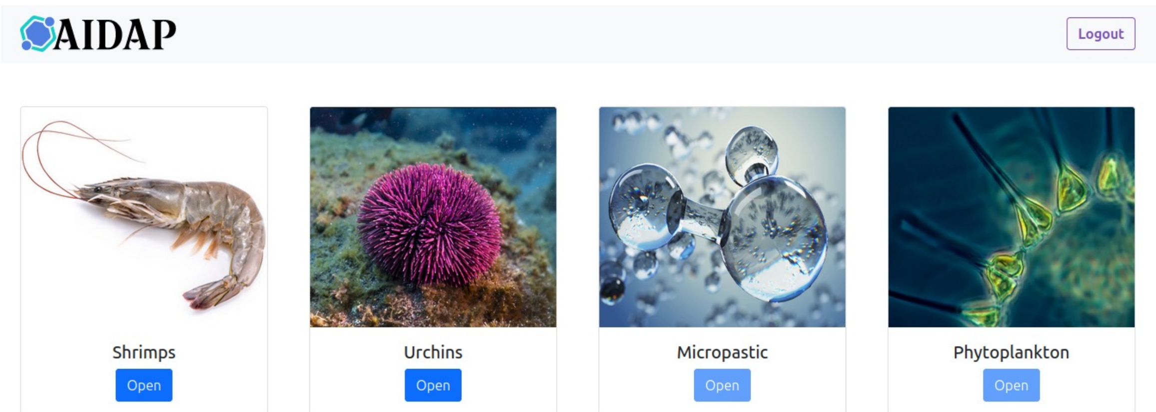


Figure 14: *AI data analytics platform interface.*

5. Monitoring Strategies for Environmental Threats

5.1. Overview of Emergent Threats and Current Monitoring Strategies

ASTRAL conducted an assessment of the regional and system-specific environmental threats regarding climate change, HABs, pathogens and emissions of microplastics. Based on these assessments and the technologies developed for monitoring purposes in the context of aquaculture and IMTA, monitoring recommendations were created. These monitoring strategies have the aim of providing recommendations on the best design, lists of relevant parameters and most appropriate sensors and observing platforms for IMTA-system-specific monitoring programmes (detailed overviews of monitoring considerations and recommendations can be found in ASTRAL Deliverable D5.5). It should be noted that ASTRAL's monitoring recommendations focus on the monitoring of the ambient or incoming water environment and not on monitoring of the production environment.

The report shows also some of the aquaculture stakeholder perceptions regarding the barriers to monitoring for relevant environmental threats, and has demonstrated where ASTRAL has addressed these issues through the development of innovative technologies in support of routine monitoring. Engagement with aquaculture stakeholders via two workshops indicated a general lack of availability of affordable technology for monitoring the four environmental threats discussed in this document (Figure 15), with the ability to monitor the emissions of microplastics ranking as the least accessible/affordable. While there was a good awareness about existing regional monitoring programs for HABs, pathogens and climate change variables, there appeared to be much more uncertainty around (or potentially lack of) monitoring programmes for microplastics emissions (Figure 16). Similarly, participants were also generally aware of national policies regarding monitoring for HABs and pathogens, however there was less knowledge and more uncertainty regarding policies for monitoring the variables related to climate change, and even less awareness of those relating to monitoring the emissions of microplastics (Figure 16). Thus, the recommendations and technology coming out of ASTRAL will be extremely valuable and important to drive this research space beyond the state of the art.

The stakeholder perspectives provide valuable insights into potential knowledge-gaps and barriers regarding regional monitoring programmes, available technologies to perform these actions, and where future efforts could be placed in terms of science communication and/or regulatory and policy development.

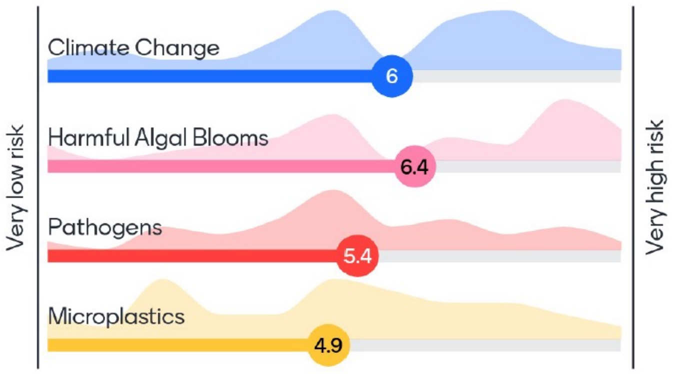
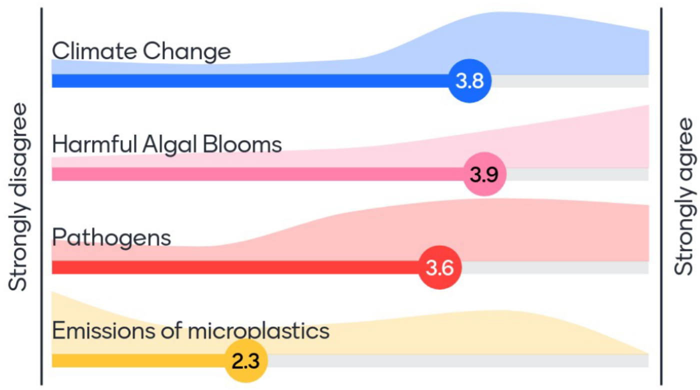


Figure 15: *Results of the questionnaire of one of ASTRAL's workshops. The level of threat/risk to aquaculture associated with the different variables (34 responses). [0 = very low risk; 10 = very high risk]*

Monitoring programmes for detecting:



National policies requiring monitoring for:

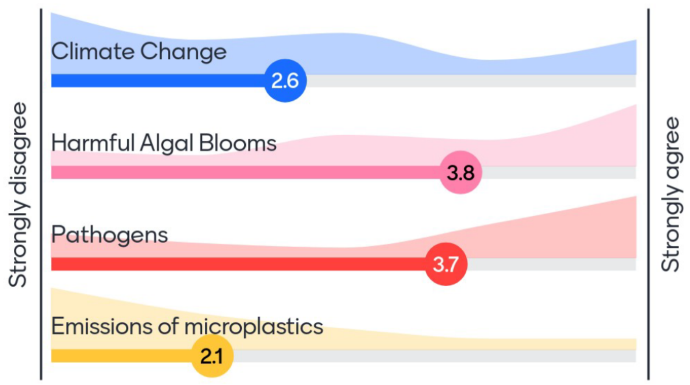
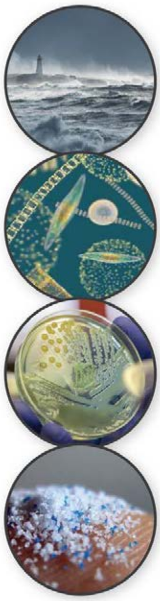


Figure 16: *Results of the questionnaire of one of ASTRAL's workshops. Question: There are [top] monitoring programs in my region and/or [bottom] national policies in my region that require aquaculture operations to monitor for each of the following variables (33 responses).*

[1 = strongly disagree; 5 = strongly agree]



Key messages for monitoring environmental threats

Aquaculture operations should be encouraged to maintain well quality-controlled environmental measurements in long term monitoring databases and to share these data with international data repositories to improve climate change related research

Harmful Algal Blooms are caused by complex interaction of biological, physical, and chemical factors – regional environmental knowledge is essential

Industry surveillance strategies should standardize the combination between molecular tools and biosensors, providing a more accurate, cost-effective, faster, and easier handling of data for pathogen detection and identification.

Stakeholder workshops indicated general uncertainty in the knowledge space (technology, policies) around monitoring Microplastics Emissions

5.2. Vulnerability to Climate Change

Different farmed organisms can tolerate different ranges in the chemical and physical properties of the water in an aquaculture facility (Figure 17). Maintaining water quality parameters within the optimal ranges for each organism helps to ensure their health and performance, while outside of these ranges the organisms may become stressed, resulting in poor growth, behavioural changes, diseases and mortalities. Climate change can affect both the variability and trends in several of the physico-chemical parameters relevant to marine aquaculture.

To identify climate related risks to IMTA and aquaculture, climate change induced trends were calculated along the Atlantic coast for the last 3-5 decades; an example is provided in Figure 18, while a comprehensive overview of this study is provided in ASTRAL Deliverable 5.1. The identification of trends was based on quality controlled observational data for sea surface temperature (SST), sea surface salinity (SSS), surface dissolved oxygen, surface pCO2 and surface nitrate, as well as observation-based calculations of surface pH. These results were used to identify environmental risk, seen as an acceleration of trends in the last decades. Regional consideration, monitoring considerations and recommendations were based on these results. It is noted that the results give an initial indication of the expected environmental changes, but do not evaluate the vulnerability of an IMTA farm's production to these environmental changes. To create more sustainable IMTA value-chains, the results must be considered in combination with the sensitivity of the IMTA species to these environmental changes.

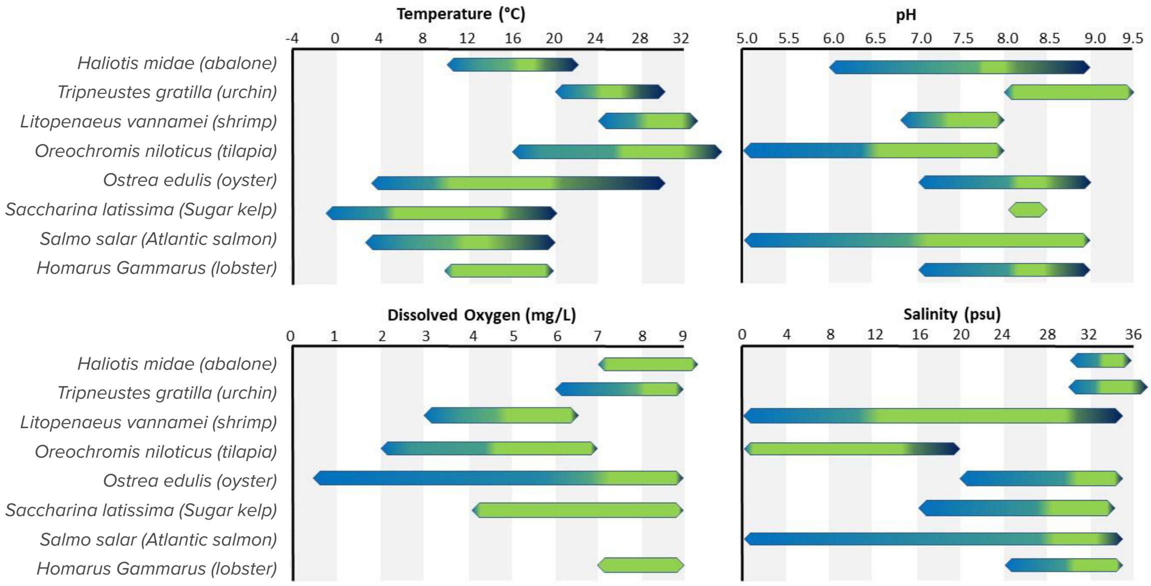


Figure 17: *Optimal (in green) and tolerance ranges (blue arrow ends) of some of the water quality parameters for key ASTRAL cultivated species. **Salmo salar dissolved oxygen tolerance range is 70-100% relative to temperature and pH*

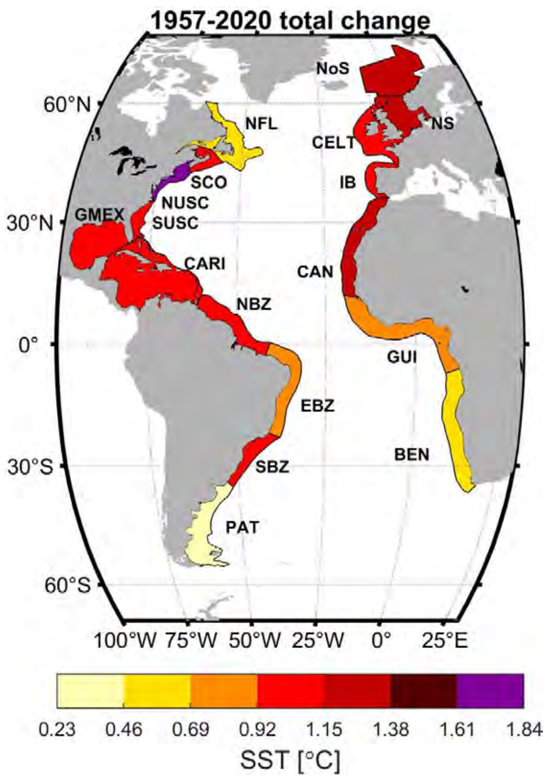


Figure 18: *Total mean SST change in the Atlantic LMEs from 1957 to 2020. From: Kessler, A., Goris, N., & Lauvset, S. K. (2022). Observation-based Sea surface temperature trends in Atlantic large marine ecosystems. Progress in Oceanography, 208, 102902.* [*https://doi.org/10.1016/j.pocean.2022.102902*](https://doi.org/10.1016/j.pocean.2022.102902)

Monitoring Recommendations for Climate-Related Variables:

Climate-related monitoring should always be considered in the regionally appropriate context according to the specific climatic risk factors. Some general recommendations on monitoring climate-related variables can be found in Tables 1, 2 and 3, while the monitoring recommendations for ASTRAL's IMTA sites are listed here.

Temperature: Should be monitored at the surface and depth at all sites to capture changes in stratification.

Salinity: Critical at the Beagle Channel site due to indications of decreasing sea surface salinity.

Dissolved Oxygen: Should be measured at all IMTA sites and upstream/downstream to capture broader changes.

Inorganic Nutrients: Regular nitrate measurements are recommended for monitoring and trend assessment, particularly for kelp growth.

Regionally Optimised Satellite Data: These products are beneficial for the Southern Benguela Upwelling System and could be developed for other IMTA regions.

Implementing comprehensive monitoring systems at IMTA sites, especially the prospective site in the Beagle Channel, is vital for developing accurate climate trend assessments and ensuring the sustainability of aquaculture practices.

5.3. Vulnerability to Harmful Algae Blooms

Harmful Algal Blooms (HABs) are algae that cause disruption to ecosystem function or aquaculture operations in a variety of ways, including: the production of toxins or harmful metabolites that affect animal health; the bioaccumulation of toxins in animals – affecting their safety for human consumption; mechanical damage (e.g. clogging animal gills); or by causing low oxygen events following the collapse and decay of high biomass blooms. While several of these impacts are related to algal density, even low algal concentrations can be dangerous depending on the degree of toxicity of the algae. HABs can include various types and species: while usually associated with dinoflagellates in the marine environment, they can also involve diatoms, raphidophytes and cyanobacteria. A comprehensive overview of the biotic and abiotic conditions favouring HAB development, the current impact on IMTA facilities, projected future impacts of climate change on HABs and recommendations of monitoring methods can be found in ASTRAL Deliverable 5.2, “Biotic and abiotic conditions favouring HAB development and associated future risks”.

No single factor is responsible for HABs, but rather a complex interaction of biological, physical, and chemical factors is synergistically required. HAB environments are highly dynamic, with changes in community composition involving viruses, grazers, and bacteria. These interactions are often species or strain- specific. Case studies indicate that HABs are highly spatially variable. This variability stresses the importance of monitoring in multiple locations using diverse methods. Seasonal and interannual variability as well as the local environment needs to be assessed in order to make monitoring recommendations. Nutrient enrichment of coastal water has been indicated as the leading cause in the increase in HAB incidence. However, nutrient loading alone is not sufficient to explain the increase in the number of HABs occurrences and a specific set of circumstances need to come together to provide the optimal conditions for bloom formation such as stable water column, optimum temperature, salinity, and light conditions. Temperature has a strong influence on phytoplankton community composition, with increasing annual temperatures broadening the window of seasonal HAB occurrence. Therefore, monitoring across the water column is recommended for nutrients, salinity, temperature, currents and stratification, as a basis for the causal environmental factors of HAB occurrence and proliferation.

Stakeholders indicated that a lack of personnel with experience, as well as the cost and a lack of appropriate technology are the biggest barriers to monitoring HABs (Figure 19). All ASTRAL IMTA facilities, regardless of their system type, have robust monitoring systems for detecting harmful algal species, focusing on nutrient, salinity, and temperature measurements, and biological parameters like Chl-a and algal cell counts. Remote sensing, satellite data, and predictive modelling are increasingly emphasized, particularly in Europe and North America. For the Beagle Channel, where no IMTA exists yet, monitoring provides a unique opportunity to study pre-IMTA conditions, enabling future comparisons once the IMTA is established.

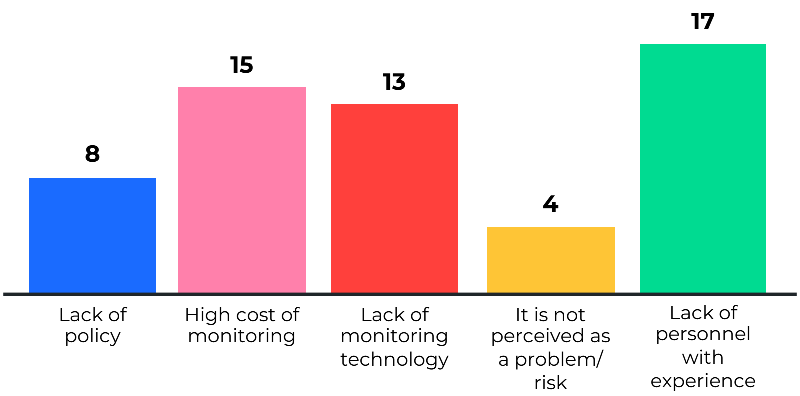


***Figure 19**: Results of the questionnaire of one of ASTRAL’s workshops.*
Question: What are the barriers to monitoring for HABs in your region? (27 responses).

Monitoring recommendations for HABs

While HAB monitoring should always be considered in the regionally appropriate context according to the specific geographic, seasonal and climatic risk factors, some general recommendations on monitoring HAB indicators and physico-chemical risk factors can be made for all sites see also Tables 3, 4 and 5):

- In many instances HABs are strongly associated with elevated biomass, and routine and frequent monitoring of Chlorophyll a (fluorescence) for non-species specific algal biomass estimates is fundamental. Monitoring could be done in situ (continuous), by field samples (daily) or using satellite data (daily).
- Species identification can be performed via microscopy or using a technological solution.
- In regions without specific national guidelines the monitoring could be done weekly over low risk periods and adjusted to a higher frequency according to season/risk (e.g. daily during bloom season, with frequency increasing after harmful cell counts are detected).
- Phytoplankton growth is very sensitive to nutrient ratios, and these should be monitored regularly with in situ field samples (monthly) of Nitrate, Phosphate, Ammonium, Silica, dissolved organic matter concentrations.
- Salinity should be measured either in situ or from field samples (weekly) and should be monitored across the depth range of the IMTA site to account for any stratification.
- Currents play a significant role in forecasting bloom movement and therefore risk of impact on IMTA sites: satellite data or models (daily), in situ (continuous) using a mooring.
- Upwelled nutrient rich water can prime a system for HAB growth. Temperature and upwelling should be monitored regularly using either satellite data or models (daily), field sampling (daily), and/or in situ (continuous) methods.
- Stratification, especially following an upwelling event, is a physical driver of HAB risk. To detect stratification in situ water temperature and salinity monitoring should be done both at the surface and at an appropriate depth (daily/continuous) covering at a minimum the depth range of the IMTA production site.

5.4. Vulnerability to Pathogens

All animal species are susceptible to disease, and these risks are elevated in constrained farming conditions and in the context of climate change. In aquaculture, the presence and proliferation of disease-causing pathogens is a primary consideration in the management of animal health and the mitigation of commercial losses. Pathogens are diverse regionally and the risk of proliferation and impact varies according to cultivated species as well as the environment. Pathogens are not generally well monitored until the appearance of diseased stock. The primary aim of a low-cost monitoring programme is to employ emerging technologies to identify the absence or presence of known pathogens in accordance with the identified site- and species- driven risk factors. Monitoring should be directed towards predicting and preventing disease outbreaks, and as such an understanding of pathogen-favourable environments is essential. An integrated monitoring system of environmental variables, animal response (via biosensors) in conjunction with pathogen identification (via molecular tools) supports a holistic understanding of risk and allows for targeted interventions as risk is elevated (for details see ASTRAL Deliverable D5.3). The costs of testing and a general lack of policy were noted amongst stakeholders as being the biggest obstacles to monitoring pathogens (Figure 20).

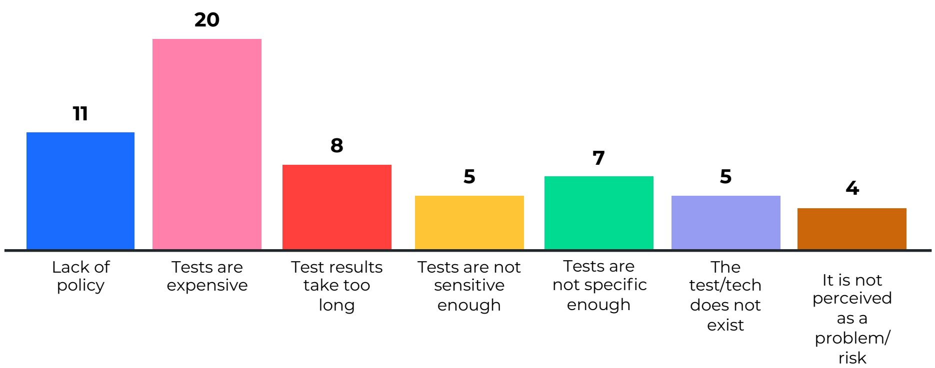


***Figure 20**: Results of the questionnaire of one of ASTRAL's workshops. Question: What are the barriers to monitoring for pathogens in your region? (27 responses)*

Monitoring recommendations for pathogens

Depending on the IMTA system different types of biosensors or molecular tools are recommended, based on the needs and characteristics of the labs, feasibility, and pathogens present in the systems. Some general recommendations on monitoring pathogens can be found in Tables 1, 2 and 3, while the monitoring recommendations for ASTRAL's IMTA sites are listed here.

- **The open-water coastal IMTA systems:** Firstly, the introduction of biosensors in tagged fish (e.g. AEFishBIT operculum), should be evaluated to obtain real-time data about fish stress/health within the system. Early pathogen identification should then be based on samples obtained from mucosal tissues using field-compatible methods such as portable qPCR machines or Lateral Flow Biosensors (LFB). Based on previous studies, qPCR techniques seem to be optimal for bacterial pathogens (e.g., A. Salmonicida, Tenacibacilum, Vibrio spp., M. vicosa), meanwhile LFB are more optimal for rapid detection of viruses (e.g., Novirhabdoviruses, Oyster Herpes Virus). As for sea lice (C. elongates/L. Salmonis), several traps based on Light-emitting diode biosensors have been used to reduce the sea lice infestation. Further technologies based on techniques described for other parasites (e.g., qPCR for their adult life stage) together with the improvement of eDNA methodologies and machine learning implementation should be considered to tackle this problematic pathogen before an outbreak occurs.
- **Partially recirculating land-based IMTA system:** New and more sophisticated technologies to improve early detection of specific pathogens are recommended, particularly for Vibrio species (e.g., V. anguillarum, V. parahaemolyticus, V. harveyi and V. splendis), Haliotid herpesvirus-1 and several parasites (e.g., Amoeba, Spionids and sabellids). Moreover, considering the type of system, eDNA samples from the incoming or effluent seawater can be used to anticipate the entry or presence of specific pathogens in the system. Thus, for this type of sampling, digital qPCR is proposed for virulence related genes (e.g., hemolysin production, gyrase subunit B or malate dehydrogenase) of Vibrio species, lateral flow biosensors for herpesvirus and multi-locus barcoding for the identification of different parasite species. Moreover, wireless sensors networks are recommended for monitoring water quality parameters and microbiome metabarcoding is proposed to generate continuous data to anticipate system dysbiosis and a possible disease outbreak occurrence.
- **The biofloc recirculating land-based IMTA system:** analysis of eDNA samples collected from the   are proposed to monitor the presence or change in abundance (increase) of potential pathogens described for

the system. For this, the combination of wireless biosensor, microbiome metabarcoding and digital qPCR are proposed for improving surveillance of this system.

- **The prospective IMTA system in Argentina** also presents several potential pathogens that will need to be considered previously to implementation. Although the SENASA (Servicio Nacional de Sanidad y Calidad Agroalimentaria) is improving the notification and communication of disease events, further work should be done to identify the most problematic pathogens impacting the aquaculture industry in the Patagonian area and technologies to monitor the systems. Regarding the pathogens identified, digital qPCR and biosensors (LFB and wireless sensor) are suggested to be implemented in these new IMTA laboratories.

5.5. Vulnerability to Plastics

Plastic pollution has been increasing globally and has become an issue of growing concern, leading to many local, regional, and international initiatives aimed at better understanding of the sources, processes of degradation and distribution, and the impacts on the marine environment. Plastic equipment used in the fisheries and aquaculture industries contribute to emissions of microplastics into the sea, which likely have negative consequences for the marine environment and living organisms.

One of the specific objectives of the ASTRAL project is to map the distribution of pollutants of emerging concern in the selected IMTA open water labs, with a specific focus on aquaculture related microplastic pollution fingerprint assessments. The ASTRAL Deliverable 5.4 describes the development of a robust and reliable sampling device, describes sample preparation and analysis methods, with recommendations for routine monitoring.

The recommendations given for monitoring can be found in Deliverable D5.5 (also in Table 4). They are general, and not regionally or IMTA system-specific. Rather, a monitoring plan aimed at understanding the short- and long-term fingerprint of plastic litter implicit in industrial production is recommended. Several types of monitoring approaches are listed, as there are a number of different methodologies and technologies available. It is important to recognise that monitoring activities can be led and implemented by a variety of players not limited to aquaculture and IMTA managers, by engaging with and building synergy with researchers, local authorities, and community groups active in this field of work.

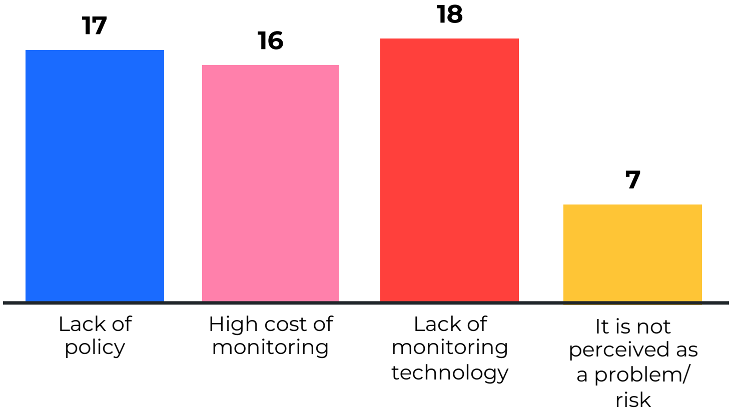


Figure 21*: Results of the questionnaire of one of ASTRAL's workshops Question: What are the barriers to monitoring for emissions of microplastics in your region? (27 responses).*

Stakeholder engagement indicated that there is a general lack of knowledge regarding regional policies and regional monitoring programmes (Figure 15) aimed at the emissions of microplastics, while the lack of policy, the high cost of monitoring, and the lack of technology all scored relatively equally high in terms of the potential barriers to monitoring for emissions of microplastics - again indicating general uncertainty in this knowledge space (Figure 21).

Regarding the barriers of the high costs and the lack of technology, the technology coming out of ASTRAL will be valuable and important to drive this research space beyond the state of the art. Within ASTRAL a microplastic monitoring sensor (TA6) was developed as a standalone, benchtop, autonomously operating optical apparatus capable of systematically examining water samples under continuous flow. Its principal function is the precise identification of microscopically sized polymer particles, colloquially known as microplastics, while concurrently differentiating them from other naturally occurring particles within the scrutinized water sample. The imaging component features a commercial infinity-corrected microscope objective in conjunction with a tuneable lens, facilitating the acquisition of sharply focused images across the entire size spectrum of microplastics (ranging from 0.5 to 5mm). Complementing this arrangement is a high-speed industrial digital camera, ensuring expeditious image capture capabilities.

Recommendations for mitigation

Plastic pollution is a significant concern in aquaculture due to its potential negative impacts on aquatic ecosystems and marine life. The following mitigating actions should be considered:

- **Reduce Plastic Usage**: Minimise the use of plastic materials wherever possible. Biodegradable or reusable materials for containers, nets, ropes, and other equipment should be encouraged
- **Proper Waste Management:** Proper waste management practices ensure that any plastic waste generated during aquaculture operations is collected and disposed of responsibly. Recycling and the prevention of plastic from entering waterways are important aspects of a waste management program.
- **Regular Cleanup:** Regular clean-up efforts in and around aquaculture facilities are required to remove any plastic debris that may have accumulated. This can help prevent plastics from entering water bodies and harming aquatic life.
- **Use of Eco-Friendly Alternatives:** Biodegradable fishing nets or compostable packaging materials with reduced environmental impact can help minimise plastic pollution in aquaculture.
- **Education and Awareness:** Aquaculture practitioners, employees, and stakeholders should be made aware of the potential impacts of plastic pollution on aquatic ecosystems and the importance of reducing plastic usage. Awareness campaigns and training programs should be promoted to encourage responsible practices.
- **Investment in Research and Innovation:** Research efforts to identify and develop innovative solutions for reducing plastic usage and pollution in aquaculture should be supported. This effort may involve developing new materials, technologies, or practices that are more sustainable and environmentally friendly.
- **Regulatory Measures:** Regulatory measures aimed at reducing plastic pollution in aquaculture should be complied with and advocated for. Policies and initiatives that promote the use of sustainable materials and practices within the industry should be developed and implemented
- **Collaboration and Partnerships:** Collaboration with other stakeholders, including government agencies, environmental organisations, and industry associations, is an essential component of building capability to address plastic pollution in aquaculture collectively. Pooling resources and expertise can lead to more effective solutions.

By implementing these recommendations, aquaculture operations can help mitigate their contribution to plastic pollution and promote environmental sustainability in the industry.

Plastic pollution: environmental issue of emerging concern

Recent reports have speculated that the aquaculture industry possibly contribute to the environmental distribution of macro-, micro- and nano-plastic in the aquatic environment.

Actions

Focus and application of standardized sampling strategy.
Apply reliable detection technologies and reporting methods.

Recommendations

Chemical use: The use of certain chemicals for disinfection and water treatment can contribute to the breakdown of plastic materials.

Cleaning practices: regular cleaning and maintenance activities that involve scrubbing or pressure washing can exacerbate this issue.

Temperature and UV: Elevated temperatures and UV exposure within IMTA in some area of the world can accelerate the degradation of plastic components. In these areas plastic equipment's should be replaced more frequently.

Plastics-Key messages

Plastic pollution is a significant concern in aquaculture due to its potential negative impacts on aquatic ecosystems and marine life. The following mitigating actions may be considered in the future:

Proper waste management:

Implement proper waste management practices to ensure that any plastic waste generated during aquaculture operations is collected and disposed of responsibly. This may involve recycling or proper disposal methods to prevent plastic from entering waterways.

Table 1: Open ocean systems monitoring recommendations per risk type

Indicators	Risk factors	General monitoring recommendations	Specific monitoring recommendations
CLIMATE CHANGE			
▫ Sea surface temperature (SST) ▫ Sea surface salinity (SSS) ▫ pH ▫ Partial pressure of Carbon Dioxide (pCO_2) ▫ Dissolved Oxygen (O_2)	▫ General sparsity of Nitrate data ▫ System is completely open to the ambient environment and most vulnerable to climate change	▫ Climate variable monitoring should preferably take place at the same location(s) and same time of day over long periods ▫ Aquaculture operations should store and quality control their own data, to assess environmental changes towards safeguarding their business ▫ Aquaculture operations should be encouraged to share their environmental monitoring data for research purposes ▫ Regionally optimized satellite data products (e.g. SST) are useful for assessing long term trends	▫ Temperature monitored twice daily at the surface and another sample depth to assess stratification ▫ Dissolved oxygen daily at facility and another position upstream/ downstream ▫ Total Nitrogen measured regularly (weekly to monthly)

HARMFUL ALGAL BLOOMS			
▫ Various dinoflagellates and some diatom species ▫ Different species bloom at different times between spring and late summer ▫ Different species have different nutrient, temperature and turbulence preferences	▫ System completely open to the ambient environment ▫ Monitoring of remote locations can be difficult	▫ Chlorophyll a (fluorescence) for non-species specific algal biomass estimates: in situ (continuous), field samples (daily) or satellite data (daily) ▫ Species identification via microscopy or technology solution, e.g. flow-cam, planktoscope: weekly, or adjusted according to season/risk ▫ Nutrients and ratios, e.g. Nitrate, Phosphate, Ammonium, Silica, dissolved organic matter: field samples (monthly) ▫ Salinity: in situ or field samples (weekly) ▫ Currents: satellite data or models (daily), in situ (continuous) ▫ Temperature and upwelling: satellite data or models (daily), field sampling (daily), or in situ (continuous) ▫ Stratification: In situ temperature and salinity at surface and appropriate depth (daily/ continuous)	▫ Decreased monitoring frequency in winter or when site not active ▫ Assess river run-off, precipitation, tidal cycles as required ▫ Make use of regional HAB bulletins/ predictions when possible

PATHOGENS			
▫ Bacteria: Aeromonas salmonicida, Tenacibaculum spp., Vibrio spp., Moritella viscosa ▫ Virus: Novirhabdovirus; Salmoid alphavirus (SAV); Oyster Herpes Virus (OsHV) ▫ Other: Sea lice, Protist, Oomycetes, fungi	▫ System is completely open to the ambient environment ▫ high susceptibility to several bacteria, viruses and parasites ▫ more prevalent in spring/summer when water temperatures increase ▫ Outbreaks more prone during overcrowding and increased stress	▫ Wireless sensor network for continuous monitoring of water quality parameters; specifically temperature increase and Oxygen decrease ▫ Monitoring animal behaviour as early warning sign ▫ Have specific sampling protocols in place for each type of analysis	▫ Lateral flow biosensors for rapid detection of viruses ▫ Biosensors in tagged fish to provide real-time data on fish stress/ health ▫ Light-emitting diode biosensors to reduce the sea lice infestation

Table 2: Land-based partial recirculation systems monitoring recommendations per risk type.

Indicators	Risk factors	General monitoring recommendations	Specific monitoring recommendations
CLIMATE CHANGE			
▫ Sea surface temperature (SST) ▫ Sea surface salinity (SSS) ▫ pH ▫ Partial pressure of Carbon Dioxide (pCO2) ▫ Dissolved Oxygen (O2)	▫ General sparsity of Nitrate data ▫ System is only partially open to the ambient environment through intake water pumped into system ▫ Not as vulnerable to climate change as the open systems	▫ Climate variable monitoring should preferably take place at the same location(s) and same time of day over long periods ▫ Aquaculture operations should store and quality control their own data, to assess environmental changes towards safeguarding their business ▫ Aquaculture operations should be encouraged to share their environmental monitoring data for research purposes ▫ Regionally optimized satellite data products (e.g. SST) are useful for assessing long term trends	▫ Temperature monitored twice daily at the surface and another sample depth to assess stratification ▫ Dissolved oxygen daily at facility and another position upstream/ downstream ▫ Total Nitrogen measured regularly (weekly to monthly)

HARMFUL ALGAL BLOOMS			
▫ Various dinoflagellates and some diatom species ▫ Different species bloom at different times between spring and late summer ▫ Different species have different nutrient, temperature and turbulence preferences	▫ Generally lower risk associated with HABs due to ability of system to go onto full recirculation for 12-48 hours in cases of severe blooms. ▫ Risks vary between cultured species and different HAB species ▫ Increased occurrence of HABs from spring to late summer ▫ General HAB risks include: clogging of gills, production of toxins - affecting animal health and consumption safety, decreased dissolved oxygen following high biomass bloom collapse	▫ Chlorophyll a (fluorescence) for non-species specific algal biomass estimates: in situ (continuous), field samples (daily) or satellite data (daily) ▫ Species identification via microscopy or technology solution, e.g. flow-cam, planktoscope: weekly, or adjusted according to season/risk ▫ Nutrients and ratios, e.g. Nitrate, Phosphate, Ammonium, Silica, dissolved organic matter: field samples (monthly) ▫ Salinity: in situ or field samples (weekly) ▫ Currents: satellite data or models (daily), in situ (continuous) ▫ Temperature and upwelling: satellite data or models (daily), field sampling (daily), or in situ (continuous) ▫ Stratification: In situ temperature and salinity at surface and appropriate depth (daily/ continuous)	▫ Decreased enumeration frequency in winter ▫ Increase enumeration frequency (sub-daily) when bloom is detected at water intake location ▫ Make use of remote sensing products of Chlorophyll a and phytoplankton type when-ever possible to assess potential bloom location and movement relative to intake pipe location ▫ Monitor tides (e.g. during bloom prioritize pumping water into system at high tide)

PATHOGENS			
▫ Bacteria: Vibrio spp., Rickettsial like – organisms, Cyanobacteria, Streptococcus ▫ Virus: Haliotid herpesvirus 1 (HahV-1) ▫ Other: Protozoa, Polychaetes, Oomycetes, Sabellid, Amoeba - Paramoeba invadiens	▫ low incidence of disease outbreaks ▫ Temperature rise ▫ Outbreaks more prone during overcrowding and increased stress	▫ Wireless sensor network for continuous monitoring of water quality parameters; specifically temperature increase and Oxygen decrease ▫ Monitoring animal behaviour as early warning sign ▫ Have specific sampling protocols in place for each type of analysis	▫ Analysis of eDNA samples collected from the system to monitor the presence or change in abundance (increase) of potential pathogens ▫ qPCR for virulence related genes of Vibrio species ▫ Lateral flow biosensors for herpesvirus ▫ Multi-locus barcoding for the identification of different parasite

Table 3: Land-based recirculation systems monitoring recommendations per risk type

Indicators	Risk factors	General monitoring recommendations	Specific monitoring recommendations
CLIMATE CHANGE			
▫ Sea surface temperature (SST) ▫ Sea surface salinity (SSS)	▫ General sparsity of Nitrate data ▫ System is only partially open to the ambient environment through intake water pumped into system ▫ Not as vulnerable to climate change as the open systems	▫ Climate variable monitoring should preferably take place at the same location(s) and same time of day over long periods ▫ Aquaculture operations should store and quality control their own data, to assess environmental changes towards safeguarding their business ▫ Aquaculture operations should be encouraged to share their environmental monitoring data for research purposes	▫ Temperature and salinity of water monitored at intake on a daily basis

HARMFUL ALGAL BLOOMS			
▫ Various dinoflagellates and some diatom species ▫ Cyanobacteria bloom in estuaries and lagoons ▫ Different species bloom at different times ▫ Risks vary between cultured species and different HAB species ▫ Different species have different nutrient, temperature and turbulence preferences	▫ Very low risk to IMTA due to recirculation of water in cultivation system ▫ Risks vary between cultured species and different HAB species ▫ General HAB risks include: clogging of gills, production of toxins - affecting animal health and consumption safety, decreased dissolved oxygen following high biomass bloom collapse	▫ Chlorophyll a (fluorescence) for non-species specific algal biomass estimates: in situ (continuous), field samples (daily) or satellite data (daily) ▫ Species identification via microscopy or technology solution, e.g. flow-cam, planktoscope: weekly, or adjusted according to season/risk ▫ Nutrients and ratios, e.g. Nitrate, Phosphate, Ammonium, Silica, dissolved organic matter: field samples (monthly) ▫ Salinity: in situ or field samples (weekly) ▫ Currents: satellite data or models (daily), in situ (continuous) ▫ Temperature and upwelling: satellite data or models (daily), field sampling (daily), or in situ (continuous) ▫ Stratification: In situ temperature and salinity at surface and appropriate depth (daily/ continuous)	▫ Water pumped from estuary is treated before use in cultivation systems

PATHOGENS			
▫ Bacteria: Vibrio spp., Rickettsial like – organisms, Cyanobacteria, Streptococcus ▫ Virus: Haliotid herpesvirus 1 (HahV-1) ▫ Other: Protozoa, Polychaetes, Oomycetes, Sabellid, Amoeba - Paramoeba invadiens	▫ low incidence of disease outbreaks ▫ Rainy season, low salinity ▫ High temperature and luminosity ▫ Outbreaks more prone during overcrowding and increased stress	▫ Wireless sensor network for continuous monitoring of water quality parameters; specifically temperature increase and Oxygen decrease ▫ Monitoring animal behaviour as early warning sign ▫ Have specific sampling protocols in place for each type of analysis	▫ analysis of eDNA samples collected from the biofloc to monitor the presence or change in abundance (increase) of potential pathogens ▫ biosensors (LFB and wireless sensor) ▫ digital qPCR

Table 4: Monitoring recommendations for Microplastics

General monitoring recommendations	Specific monitoring recommendations	Mitigation recommendations
MICROPLASTICS		
▫ Establish a benchmark at a regularly visited site ▫ Use consistent methodologies ▫ Standardize reporting as proposed by international coordinating bodies ▫ Sampling in rivers and estuarine ecosystems should be included for source monitoring to establish baseline levels of litter ▫ Oceanographic info (SST, current strength & direction, wind and wave strength & direction) can support an integrated characterisation of the dynamics of MP pollution ▫ Application of particle distribution models in aquatic environments is strongly recommended	▫ Sampling locations should be targeted to include litter and microplastics ▫ Water extracted using pumps, 1-7m below surface ▫ Sequential filtration using 1 mm, 300 µm and 10 µm mesh ▫ Filter sufficient volumes (100 – 1000 liters per sample) to obtain a stable measurement ▫ Avoid sampling during an algal bloom ▫ In the absence of concrete knowledge of sampling interval required, annual monitoring is recommended ▫ Monitor and report MPs according to size and category; number of particles (concentration), grain size, shape and mass also useful ▫ Do joint water and sediment sampling if possible	▫ Reduce plastic usage ▫ Proper waste management ▫ Regular cleanup ▫ Use of eco-friendly alternatives ▫ Education and awareness ▫ Investment in research and innovation ▫ Regulatory measures ▫ Collaboration and partnerships

6. Internationalisation and Cooperation

Building International Collaboration

ASTRAL created a collaborative ecosystem for aquaculture in the Atlantic developing the 'Atlantic Aquaculture Network', a distributed and non-centralised network aimed to foster international collaboration among the Atlantic area connecting science-business-industry-policy makers.

An important effort has been done developing blue skills in aquaculture, by specific technical training carried out in 8 different Atlantic countries, and promoting ocean literacy activities for young generations as a critical step towards a sustainable aquaculture.

It ensures a well-informed, responsible, and innovative future workforce capable of balancing economic development needs with the imperative of environmental conservation.

The creation of more than 50 ASTRAL school clubs and the incorporation of Nigeria to the All-Atlantic Blue Schools Network contributes to continuing these activities in the long term as a legacy of ASTRAL.

6.1. Atlantic Project Award in the category International Cooperation

ASTRAL was recognised with the Atlantic Project Award 2023 in the category of International Cooperation. The Atlantic Project Awards feature outstanding initiatives, successful collaborations and achievements relevant to the implementation of the Atlantic Action Plan 2.0. These projects have taken place within the European Union Atlantic Area over the past year and showcase success stories, best practices and partnership models that could be scaled up at the regional, national, European and international level, while promoting the key priorities of the Atlantic Strategy.

In particular, ASTRAL was selected for having achieved a number of results, including

- Creation of the Atlantic Aquaculture Network to engage stakeholders from research institutes, aquaculture SMEs/industry, public administration, policymakers, as well as end user organisations such as fish farms, seafood producers, using the Aquaculture Helix platform;

- Seven High-Level meetings have been organised or co-organised by ASTRAL, involving European counties, Brazil, South Africa and US to promote international cooperation across the Atlantic area; and
- Several activities on awareness, ocean literacy and training: schools' campaign, educational material, communities' awareness, summer/ winter schools, training courses, training videos, women empowerment and gender mainstreaming in aquaculture.

For more information, please visit the Atlantic Project Awards site.

ATLANTIC STRATEGY
Supporting the Atlantic Action Plan

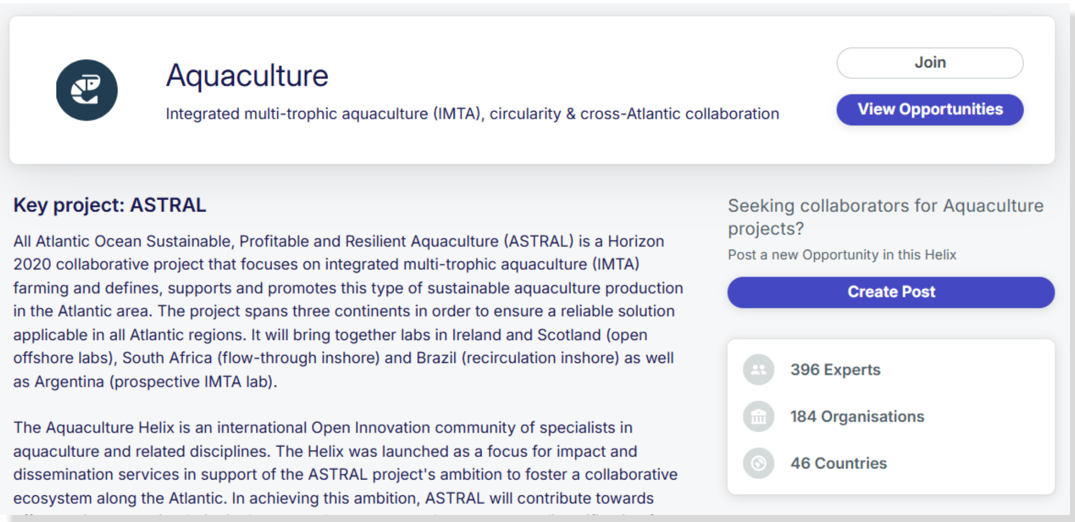
6.2. All-Atlantic Ocean Research and Innovation Alliance (AAORIA) Forum

ASTRAL is pleased to be a part of the All-Atlantic Ocean Research and Innovation Alliance (AAORIA), which is the result of science diplomacy efforts involving countries from both sides of the Atlantic Ocean and aims to enhance marine research and innovation cooperation along and across the Atlantic Ocean.

6.3. The Aquaculture Helix

The Aquaculture Helix, an online community hosted on the Crowdhelix platform, was established in December 2020 with the aim of gathering relevant aquaculture stakeholders and facilitating their collaboration. It currently features 396 experts from 184 organisations across 46 countries.

Within the Helix, users can post events, share opportunities, seek expertise, connect with experts, or engage with project results. The Helix was launched as a focus for impact and dissemination services in support of the ASTRAL project's ambition to foster a collaborative ecosystem along the Atlantic. A distinctive feature of the helix is its matchmaking algorithm (recommender engine), which connects posted opportunities with experts and institutions possessing the required expertise or infrastructure.



Sources: *D7.3 ; https://crowdhelix.com/helixes/aquaculture*

6.4. Atlantic Aquaculture Network

The Atlantic Aquaculture Network is an effort to gather stakeholders and expert networking influence towards "promoting institutional changes in aquaculture management", aiming at social acceptance, reputational capital and social license. The backbone of the Network is the Aquaculture Helix, a virtual community and marketplace around ASTRAL to support its long-term establishment.

Since 2021, ASTRAL has organised 10 High-Level meetings / sessions on aquaculture topics around the Atlantic area.

Some examples of events that have been key to this network include: Side-events at the All Atlantic Ocean Research Forums (2020, 2021), Side Event on Sustainable Aquaculture at the European Maritime Days (2023), High-Level event on Climate-Food-Ocean challenges at the UNODC in Barcelona (2024), High-Level event on Satellite Earth Observation for Sustainable Fisheries and Aquaculture in Nigeria (2024) and two Atlantic Aquaculture International Conferences in Brazil (2023) and South Africa (2024), among others.

7. Education and Capacity Development

Children's Day Fiesta (May 25th, 2023). Students with Word Search

7.1. Human Capital Development Plan

The Human Capital Development Plan (HUCAP) of ASTRAL aimed to improve professional skills and create a highly trained workforce in sustainable aquaculture in the Atlantic region. The plan promoted and disseminated the production technologies developed at the ASTRAL IMTA Labs in Brazil, Ireland, Scotland, South Africa, and the prospective one in Argentina to end users, contributing to the ASTRAL objectives of increasing circularity in aquaculture by 50 to 60%, boosting revenue diversification, and creating new job opportunities for major actors in the aquaculture value chains. The plan also expanded its scope by adding training topics for new value chains with economically viable aquaculture businesses, enhanced market access, zero waste, sensors and biosensors, emerging aquatic pollutants, climate change impacts and fish health.

The plan focused on the assessment of the current workforce, several human capital building activities, development of an IMTA and ocean literacy curricula as well as women empowerment and mainstreaming in the aquaculture sector. ASTRAL has developed a gender-sensitive Human Capital Development Plan to improve professional skills and competence among stakeholders in IMTA production and other thematic areas of the ASTRAL project.

Women play a significant role in the production and processing of aquaculture products, but still are a vulnerable part of the society in many areas. According to FAO (2022), the policy on advancing gender equality in aquaculture guided the adoption of major ways to promote and support the role of women as key agents of change to achieve Blue Transformation. However, most women are low-skilled in aquaculture production and generally have a lot of constraints that militate against their strong participation in aquaculture production. Building women's capacities and resilience in IMTA will enhance sustainability and increase aquaculture production in the Atlantic area.

The main goals of the 'Human Capital Development Plan' of ASTRAL have been to improve the skills and knowledge of the workforce in sustainable aquaculture with special focus on IMTA, to increase productivity, and to enhance safety and quality standards in the aquaculture sector of the Atlantic area.

ASTRAL aimed to create a highly trained workforce focused on sustainable aquaculture that is (i) prepared to address Atlantic multi-sectoral/disciplinary challenges but also (ii) acknowledges regional-specific scientific/societal challenges, opportunities and needs. ASTRAL aims to include these perspectives in academic and non-academic training sessions (including educational curricula for primary to tertiary levels of education and improve professional skills and competences in IMTA).

Training programs and human capacity development varied from country to country but hinged on two main methods: Formal and informal education channels. Methods for formal education included approved and structured primary, secondary and tertiary curricula, while informal education revolves around skills development and innovations among others. Informal education methods may include short training courses, vocational training, study tours, excursions, field trips, seminars, conferences, on-the-job training, coaching, mentoring, e-learning, workshops, Students' Industrial Work Experience Schemes (SIWES), industrial training (IT), internships/apprenticeships and summer/ winter schools.

Bilateral meetings and meetings with the leaders of the training activities were carried out during the first 12 months of the ASTRAL project to set the syllabus of the planned activities, scope, and audience. Additionally, internal discussions were held with partners from Argentina (CONICET), Brazil (FURG), Nigeria (NIOMR), Spain (LEITAT) and South Africa (UCT) to discuss specific aspects related to the expectations and differences of training gaps in each country (duration, scope, topics) to adapt them to the specific regional necessities and legal regulations. After the Mapping of Capacity Development Activities, a detailed map of training activities was developed, identifying specific content, assigning leaders for each activity and a time schedule for the expected activities.

This ASTRAL HUCAP has emerged as a pivotal framework for nurturing a skilled and adaptive workforce in aquaculture, with a special focus on promoting those practices in line with sustainable food production. The commitment to ongoing evaluation and feedback mechanisms has allowed us to refine and tailor the contents of each of the capacity-building activities, ensuring that they remain relevant and effective for the different geographic areas of the Atlantic involved in ASTRAL. As a result, our trainees

Figure 22: *Examples of educational materials developed in ASTRAL*

are better prepared to tackle the multifaceted challenges of monitoring, productivity, and sustainability in aquaculture. We recognise that investing in human capital is not just a one-time effort but an ongoing journey, therefore we will ensure as much as possible that the capacity-building activities of this HUCAP will be openly available to all those interested in the aquaculture sector. This plan serves as a blueprint for the future, guiding our ongoing efforts to develop a resilient and proficient workforce that is instrumental in achieving ASTRAL long-term strategic objectives.

ASTRAL Training Activities

ASTRAL has contributed to the development of a highly trained workforce focused on sustainable aquaculture whose professional skills and competences will be improved by means of:

- Two Summer/ Winter Schools
- 13 General Training Courses
- 13 Apprenticeships
- Workshops & Webinars

Additionally, three different curricula for general aquaculture, IMTA production and Ocean Literacy focusing on primary, secondary schools and higher education have been developed to fulfil the identified gaps in this teaching sector. All capacity development activities include the active support of women involvement aiming to promote their access to new and emerging markets in aquaculture in EU and non- EU Atlantic countries.

Summer / Winter Schools

A Winter School on Technologies and Circularity for a Sustainable Aquaculture in 2023 in Spain to explore innovative technologies and circular economy approaches to address the challenges of improving the environmental footprint of the aquaculture industry. This included a number of activities such as workshops, lab visits, panel discussions on sustainability, technology, and circularity.

A Summer School on Integrate Aquaculture in 2024 in South Africa to provide introduction to integrated aquaculture including several IMTA topics, such as an overview of IMTA, seaweeds in IMTA, sustainable strategies for improving health, modelling in aquaculture, nutrition and microbiome characterisation.

Training courses

A number of training courses were held including:

- Integrated farming of fish and shrimp in biofloc systems in Brazil to provide specific knowledge and develop practical skills on innovative production systems in aquaculture with a special focus on IMTA and BFT.
- Integrated Aquaculture in South Africa to explore marine aquaculture and the implementation of IMTA in selected African countries (Namibia, Mauritius and South Africa), and globally, to improve the sustainability of aquaculture.
- IMTA for Women in Aquaculture in Nigeria to provide skills in aquaculture; introduce integrated aquaculture; introduce basic concepts about sustainability and sustainable food production; job linkage and job creation through small business cases; improve networking among the participants; and build /boost self confidence in women.
- Bases and Concepts for the Development of Aquaculture in Argentina to transfer cutting-edge knowledge about the potential of aquaculture in Argentina, have awakened their interest in sustainable multitrophic aquaculture and have informed them about training and employment opportunities in a national and international setting.

Group picture of the ASTRAL Training Course on 'IMTA for Women in Aquaculture' (15 March 2023) in Lagos, Nigeria

Apprenticeships

ASTRAL Apprenticeships involved theoretical and practical training for students and professionals, aiming to help trainees to acquire relevant skills in their chosen field by learning from experienced professionals in the IMTA Labs, and use of technology developed in ASTRAL for monitoring of production. It allowed the apprentices to earn practical experience while they learned and gained relevant skills needed to improve competence and build a career. All the offered apprenticeships were attached to well-developed IMTA Labs for periods ranging from 3 to 6 months. At the end of the program, the trainees were evaluated to assess the knowledge acquired and will be awarded with a Certificate of Apprenticeship by the host lab in the framework of the ASTRAL project. Training for students as well as professionals

Example topics of the apprenticeships included:

- Pilot commercial sea urchin/Ulva integrated systems
- Integrated farming of fish and shrimp in biofloc systems at IMTA facilities in Brazil
- Operation and management of an IMTA lab (field and laboratory operations)
- Lobster cultivation as part of Integrated Multi-Trophic Aquaculture
- Monitoring of water quality in aquaculture at the Laboratory of Ecology, Physiology and Evolution of Aquatic Organisms (CADIC-CONICET) in Ushuaia, Argentina.

Curricula for General Aquaculture, IMTA production and Ocean Literacy

After an assessment of the current workforce, it was identified that in Nigeria, training and developmental programs in aquaculture, ocean literacy, climate change, mitigation and ocean influence are taught in many primary, secondary, and tertiary institutions. Other subject areas taught include marine pollution, ocean conservation, beach cleaning, and the importance of the consumption of safe and nutritious seafood. However, these topics do not follow a defined structure and are taught as part of more superior environmental topics.

Therefore, to align the courses through the blue economy, including Sustainable Food Production and Ocean Literacy as main aspects, ASTRAL, with the support of the Nigerian Institute for Oceanography and Marine Research (NIOMR), developed a teaching curriculum oriented towards primary, secondary, and tertiary institutions. These curricula provide a list of educational topics in aquaculture and ocean sciences for both formal and informal education that can be easily adapted to other Atlantic areas. The development of the contents for higher education, including a university course for 'Aquaculture production and Ocean Literacy' for the Nigerian University Commission – NUC, have been developed considering the discussions with academic specialists from NIOMR and the Director of Curriculum Development of the NUC in Abuja, Nigeria.

Additionally, ASTRAL developed an online platform derived from this HUCAP and linked to its website as a source of training content in sustainable aquaculture. Different ASTRAL resources such as Webinars, Workshops, and Training Courses are accessible to the public on ASTRAL YouTube Channel.

7.2. Focus on Women

Women have a key role in seafood sustainability as decision makers and managers, as a medium for technology transfer and communication, as advocates for resilient aquaculture production, as ocean literacy teachers, and in contributing to food security. However, gender mainstreaming in aquaculture is very nascent in Nigeria. Aquaculture is gender biased in terms of prominence in participation. The male counterparts dominate in ownership, control and access to aquaculture production systems. Participation of women is prominent in processing and marketing, hatchery and live food units, fisheries research, education and training as reflected by the numbers of female graduates employed (focal area of IMTA adoption).

The ASTRAL project has targetted women's participation in the seafood sector by focusing on:

- Empowerment and mainstreaming of women into aquaculture
- Provision of healthy seafood for the future
- Ocean and climate change literacy
- School campaign on sustainable seafood for the future
- Training and human capital development

ASTRAL has had the potential to introduce new aquaculture value chains to women in Nigeria in the form of IMTA as well as market access and network linkage among and within Atlantic countries.

ASTRAL's partner in Nigeria, NIOMR, has campaigned on the importance of safe and nutritious aquaculture seafood also addressing climate change resilience and ocean influence. To do so, NIOMR and ASTRAL have produced educational material and created the ASTRAL school club, a family game (seafood cooking competition and treasure hunt), and developed activities and materials focussed on ocean literacy.

ASTRAL participants are also pleased to be a part of the newly established NOWA (Network of Women in Aquaculture), which is a social entrepreneurship project that envisions gender equality and inclusivity in the aquaculture sector highlighting the frequently "invisible" work of women. The Network is active in connecting female academics as well as those working in or wanting to break into the sector, fostering knowledge exchange at both local and global levels.

7.3. Focus on Youth

The ASTRAL project contributed to the implementation of the 2030 Agenda for Sustainable Development Goals (SDGs) as well as of the EU-Brazil-South Africa Belém Statement on Atlantic Ocean Research & Innovation cooperation. ASTRAL's activities with younger generations are contributing to the Belém Statement's shared priority on "promoting of ocean literacy and broadening engagement in ocean sciences and ocean literacy" and to SDG 14 Life Below Water which aims to protect, conserve, and ensure the sustainable use of the oceans.

Since the start of ASTRAL project, the Nigerian Institute for Oceanography and Marine Research (NIOMR) has been working with several primary and secondary schools which were adopted as ASTRAL schools and within each one, ASTRAL School Clubs were created with smaller groups of students (24-plus clubs). The Clubs aimed to make learning a fun activity as an extracurricular program and part of the human capital development of ASTRAL. Some of the activities included Do-It-Yourself activities such as setting up small fish farms in the school and their homes (aquaria), creative drawing and video images, telling stories and essay writing on ocean related subjects. In addition, NIOMR partners collaborate with teachers in awareness activities on marine pollution, on recycling and upcycling and organizing clean-ups in schools, streets, parks, and beaches.

Additionally, ocean literacy activities were carried out with local communities. These activities mostly included talks and beach plastic clean-ups aimed at raising awareness for ocean protection, promoting the importance of safe and nutritious aquaculture seafood as well as addressing climate change resilience. With the purpose of adding a more interactive and educational aspect in events with a larger audience, being in schools or with locals, ASTRAL produced educational materials that could be easily translated to be used within the different countries collaborating in ASTRAL and beyond (Figure 22).

The main aim of our work with schools and local communities was for children and their families to develop social awareness about the ocean and seafood. More specifically, for children to grow into environmentally conscious adults and work towards the protection and conservation of the ocean but also to contribute to the development of their local economies through sustainable practices and jobs, in this case, focused on sustainable and resilient aquaculture.

Educational Materials

The launch of the ASTRAL educational materials to be used by teachers as well as in family games was organised by the Nigerian Institute for Oceanography and Marine Research (NIOMR) in collaboration with NMCN (Nursing and Midwifery Council of Nigeria, a category B parastatal of the Federal Ministry of Health), the All-Atlantic Blue Schools Network, and the Lekan Bakare Foundation. These activities reached more than 170 students, and the goal was not only to facilitate and strengthen the dissemination and impact of the project's outcomes but especially to promote social awareness on "seafood of the future".

Three types of educational materials were produced and used in awareness activities and game competitions, word search, crosswords, cross match and jigsaw puzzles (Figure 23). Word search and cross match exercises are easily printed on paper while jigsaw puzzles were printed on a durable material.

To fully cover the Atlantic dimension of ASTRAL, the materials were developed with the collaboration of ASTRAL IMTA Labs. Local species being produced in the four IMTA labs were included: Brazil, Ireland, Scotland and South African. Students and families were given a brief introduction on how to play including short presentations on sustainable aquaculture, with a focus on IMTA; they are also made aware that different regions in the Atlantic will produced different seafood. Jigsaw puzzles with IMTA culturable species were officially launched on May 2023, by NIOMR

Figure 23: *Examples of educational materials*

As part of the Researcher Days annual educational event across Norway, the NORCE Marine Research Center in Mekjarvik hosted an open day in September 2024. In addition to educational activities for youth, visitors could view an ongoing experiment assessing whether the interaction between different sea animals (salmon, mussels) and algae can be a factor in reducing the environmental impact of fish farming on the sea. Based on real conditions, an experiment with a longer duration was run to look at the interaction between these marine organisms.

Researchers Day 2024 in Norway at the NORCE Marine Research Centre in Mekjarvik

In addition to the materials developed within the project, ASTRAL collaborated with the All-Atlantic Ocean Youth Ambassador (AAOYA) program on a volume of the Bridging the Ocean booklet series, a collective of concepts and conversations focussed on the ocean in relation to bringing awareness to the challenges the ocean is facing. The volume title is Food Security, and aims to share information that may develop an understanding about food systems, so that readers can contribute to their sustainable practices and can meet food security demands in a way that respects our oceans. Among several topics, the volume includes a section on IMTA and an ASTRAL crossword puzzle (Figure 24).

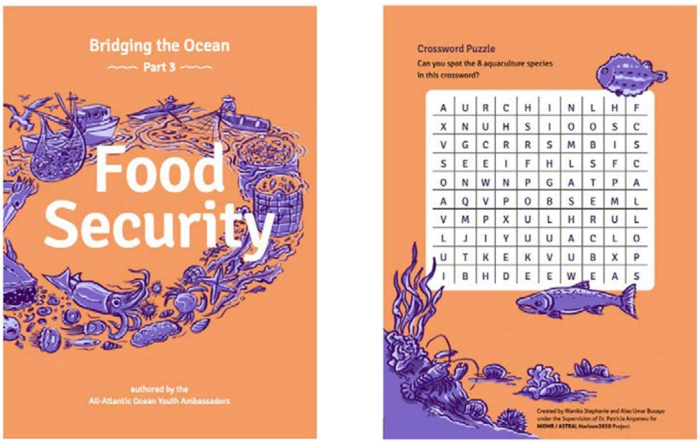


Figure 24: *Youth Ambassador Bridging the Ocean Booklet on Food Security cover page (left) and Crossword Puzzle page, material developed by NIOMR as part of ASTRAL project's WP7 activity (right)*

8. Legislation and Policy

8.1. Overview

A review of aquaculture legislation was carried out to provide a current overview of the regulatory framework, first focusing on Europe and then covering the national, regional, and local levels. This allowed for the identification of the status of aquaculture innovations such as IMTA systems in the current legislative frameworks of Europe and several Atlantic countries. In addition to an extensive literature review and workshops, several semi-structured interviews were conducted with different stakeholders such as producers, academics, scientists, policymakers, and experts covering a wide array of diverse actors on the subject to have a better and broader understanding of the aquaculture practices within the contexts that constitute ASTAL's project.

It is no secret that there have been various and serious efforts to regulate aquaculture practices around the world. This can be observed through the extensive regulatory documentation issued by several countries at different administrative levels, such as national laws, acts, conduct codes, codes of best practices and practice guidelines, among others. These can cover a wide range of related topics, from general concerns to more specific actions. Nevertheless, each regulation is indispensable for building a broader understanding of aquaculture matters.

One of the main concerns to successfully develop IMTA systems is the current legislative framework which in many cases constitutes a barrier to fully developing IMTA systems, being in-shore or offshore, smaller, or bigger productions, for local or international consumption.

8.2. Methodology

Desktop and empirical studies on governance, policy, food safety/consumer trust, and social acceptability were conducted. A review of existing regulatory frameworks, policies and legislation related to aquaculture systems in the EU, Argentina, Brazil, Ireland, Scotland, South Africa, and other countries was developed in order to comprehend the situation at different administrative levels and to detect opportunities and challenges when introducing more sustainable and innovative aquaculture practices. In addition, a total of 35 semi-structured interviews were carried out (including the contribution of key actors in the aquaculture industry within their respective countries) as well as four workshops across five countries, and a focussed policy recommendation workshop.
In addition, themes such as food safety, participatory approaches in decision-making procedures and social acceptability were addressed, as well as an overview of the legislation at the European and national levels. Lastly, a review of several projects at European level integrating policy recommendations regarding aquaculture practices was completed. Projects such as AQUAVITAE, GAIN, IMPAQT, IFISHIENCI, INTEGRATE and

others were taken into consideration. Four main themes were taken into consideration: 1) Policy domain, 2) Environmental dimension, 3) Social dimension, 4) Communication domain. Moreover, within these four topics, other main features were included in, such as: certification schemes, customs policies, administrative bureaucracy, dissemination strategies, circularity aspects, and environmental aspects (Figure 25 and Table 5).

Figure 25: *Methodology Legislation and Policy Review*

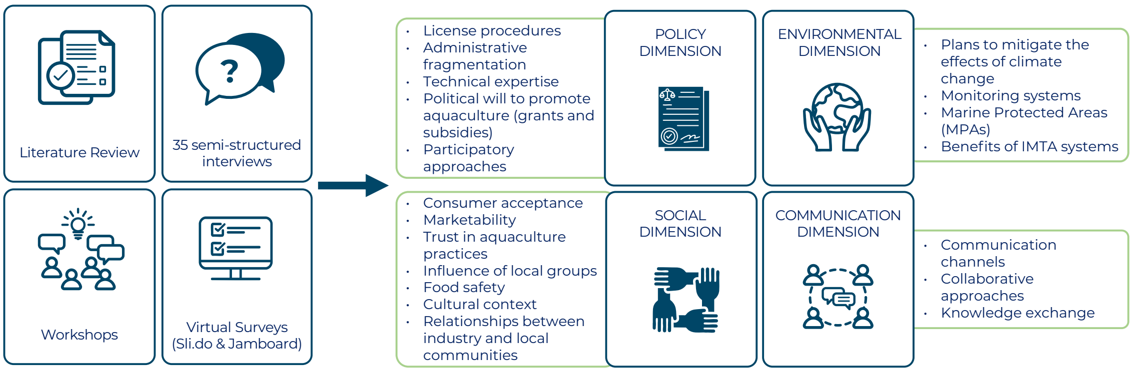


Table 5: *Policy Recommendations Methodology*

Variables	Dimensions	Categories	Indicators
Policies	Administrative bureaucracy	Certifications	Supported Certifications Standards
		Monitoring	Penalties
			Rewards
		Licences	Too lengthy/ expensive
		Legal lops	Regulatory ambiguity and week legislation
	Customs policies	Production transit	Import/export of species
	Political will	Regulatory agencies	Lack of technical assistance and control by the state
			One-stop shop approach
		Promotion of aquaculture or IMTA system activities	Grant and subsidies (pressures and/or incentives)
		Political stability	Long-term plan
			Consensus among political agents
	Transparency	Transparent decision-making procedures	Granting criteria
			Licensing/leasing criteria
			Participation of stakeholders
		Easy and open access to information	Updated and public information
		Institutional perception	Participatory approach
Social dimension	Social Licence to Operate (SLO)	Social culture	Groups of interest (Stakeholders)
	Consumer's acceptance	Educational efforts	Enhance trust in aquaculture practices
		Market	Labelling/ marketability
	Food safety	Legal framework	Certifications

8.3. Legal Framework

The Water Framework Directive (WFD) has been the primary legal basis for water protection in Europe since 2000. Subsequently, the EU Marine Strategy Framework Directive 2008/56/EC was adopted as a form to protect the marine environment across Europe. In this regard, this Directive indicates that Member States must develop marine strategies aimed at achieving or maintaining "good environmental status", which is defined as "different uses made of the marine resources are conducted at a sustainable level, ensuring their continuity for future generations". A number of regulations have also been established, such as EC Regulation No 1224/2009 focusing on control and monitoring matters, the CMO Regulation (EU) N° 1379/2013 allowing fish farmers to be recognised as producer organisations (with its inherent administrative challenges), and the Common Fisheries Policy Regulation (Regulation (EU) No 1380/2013) which aims to ensure that fishing and aquaculture practices are environmentally sustainable in the long-term, while also aligning with the objectives of accomplishing economic, social and employment benefits. The Maritime Spatial Planning Directive (Directive 2014/89/EU) sets up the framework for Marine Spatial Planning, which seeks to promote "the sustainable growth of maritime economies, the sustainable development of marine areas and the sustainable use of marine resources". The Integrated Maritime Policy of the European Union, lays out the application by Member States of maritime spatial planning with the purpose of contributing to the established goals of "sustainable development of energy sectors at sea, of maritime transport, and of the fisheries and aquaculture sectors, and to the preservation, protection and improvement of environment, including resilience to climate change impacts". Furthermore, the Commission proposal for a new Fisheries Control Regulation COM/2018/368 covers matters related to traceability in regard to all aquaculture products, extended also to products imported from non-EU countries. These regulatory documents represent a value path towards the regulation of aquaculture practices.

More in-depth measures have been developed through the European Green Deal. Among its diverse goals, this deal aims at contributing to achieving a circular economy considering actions such as "combating food fraud, including strengthening enforcement and investigate capacity at EU level, and to launch a process to identify new innovative food and feed products, such as seafood based on algae". In addition, aspects regarding consumers behaviour are introduced, meaning that, "The Commission will explore new ways to give consumers better information, including by digital means, on details such as where the food comes from, its nutritional value, and its environmental footprint". Furthermore, the creation of new jobs is addressed within this deal. It is stated that "the circular economy offers great potential for new activities and jobs". More specifically, the Farm to Fork Strategy includes innovative aspects within the aquaculture sector. It lays out the potential of this practice to mitigate climate change through, for example, carbon-sequestration (through cultivation of seaweed and molluscs). Furthermore, it aims at achieving at least 25% of EU's agricultural land under organic farming by 2030, but it also sets the goal of increasing organic aquaculture. The Action plan for organic production in the EU also with a goal of promoting organic aquaculture. In addition, “the Commission encourages EU Member States to include the increase of organic aquaculture among the objectives of their reviewed Multi-annual National Strategic Plans for aquaculture. Furthermore, the Commission staff working document on a sea basin perspective to guide the European Maritime and Fisheries Fund (EMFF) programming stipulates that the EMFF (future European Maritime, Fisheries and Aquaculture Fund, EMFAF) should be used to promote sustainable aquaculture practices such as organic production”.

On the other hand, the document adopted in 2021 “Strategic guidelines for a more sustainable and competitive EU aquaculture for the period 2021 to 2030 (COM (2021) 236 final)” sets a series of recommendations that emerged from close consultation with different bodies, administrations, and stakeholders such as, EU Member States, Aquaculture Advisory Council, public consultation, as well as the opinions of the European Parliament on the development of EU aquaculture. Moreover, this document refers to the current efforts to develop a specific initiative to encourage the “production, safe consumption and innovative use of algae”. According to the Farm to Fork strategy, algae “should become an important source of alternative protein for sustainable food system and global food security.”

8.4. IMTA EU Legal Framework

One of the primary regulations concerning these systems is Regulation No. 767/2009, especially Article 6º. In this regard, IMTA practices are potentially limited since it removes the “option of introducing filter-feeders or detritivores in the facility which feed directly on fish waste” This also represents a setback in the contribution of IMTA systems to the implementation of CE in aquaculture practices within the EU.

8.5. Aquaculture National Legal Framework

Several countries have developed aquaculture regulations to address practices within their territory. For instance, Scotland has elaborated an extensive legal framework addressing these practices, such as low-tropic systems. In this regard, the following table lists regulations regarding aquaculture practices, especially low-trophic aquaculture. Furthermore, after conducting a literature review it was found that Argentina, Canada, Cyprus, France, Italy, Norway, Portugal , and South Africa have made efforts to regulate aquaculture practices at national level. Nonetheless, each country features different regulations for this practice. In France, aquaculture is not regulated as a whole, inland fisheries legislation applies to inland aquaculture (pisciculture continentale), whereas mariculture (élevages marins, cultures marines) is regulated under marine fisheries legislation.

In addition, some countries have established other types of regulations such as codes of conducts, condes of best practices, practice guidelines that usually address issues as quality standards. For example, Canada has established a Code of Conduct for Responsible Aquaculture, the UK has a Quality Assurance Scheme, and Thailand has a Code of Conduct and Good Aquaculture Practice Guidelines.

8.6. IMTA's state within national legislative frameworks

There are no policies or regulations that specifically address the development of IMTA practices. Nevertheless, there are regulatory frameworks that seek to encourage more sustainable aquaculture. For instance, in Galicia (Spain) the Galician Aquaculture Strategy (ESGA) has been established to design and manage aquaculture activity in the territory. In this regard, the strategy aims at promoting the development of employment opportunities and wealth in a balanced manner, with environmental respect and integration through the reconfiguration of aquaculture. However, it is also stated that IMTA still requires a current legal framework to address aspects such as, legal security, economic feasibility, and environmental sustainability. Similarly, in South Africa this practice can be carried out under integrated permits, whereas in Portugal it can be implemented under a polyculture licence. Nevertheless, it is worth mentioning that "the absence of regulatory or economic benefits from offsetting nutrient discharges and of approaches which value ecosystem services is challenging for business models. Legal and regulatory uncertainty on biosecurity and food safety is problematic". (Aquavitae, 2023). For further details of the regulatory environment in each ASTRAL project country, please refer to D7.7.

8.7. Recommendations

Many jurisdictions have processes, regulations, policies and voluntary codes to guide the aquaculture industry, all of which have a focus on environmental and social acceptance as well as high quality and reliable food production, however, IMTA is not recognised as an established method to meet these parameters, this needs to be reviewed. Certification and the implementation of industry standards dedicated to IMTA are required if this method of food production is to gain traction in the market alongside existing monoculture products. Dedicated certification for IMTA products is needed to show potential customers that these products have been farmed in sustainable way, making use of the valuable aquaculture resource while creating beneficial ecosystem services increasing circularity and reducing waste. The following table provides an overview of the main recommendations developed based on the above methodology.

Table 6: *Policy Recommendations table*

Topics	Policy recommendation
Stakeholder interactions	Promote and harmonize the interaction between government institutions and the scientific sector.
	Promote and facilitate interdisciplinary and inter-institutional work.
	Promote investment in the aquaculture sector and support access to financial services to encourage IMTA and other sustainable technologies (e.g., low trophic aquaculture, green energy)
	Include IMTA in marine spatial planning regionally to create an enabling environment for these sustainable aquaculture technologies
	Further cooperation among producers, researchers, scientists, and regulators is key to promote more novel technologies within the aquaculture industry
Regulation and Administration	Implement specific IMTA regulations articulated between the ministries, secretariats, and national, provincial, and municipal government directorates.
	Streamline existing regulatory frameworks (e.g., policies, permits) by creating a dedicated legal framework for the management and sustainable development of the aquaculture sector.
	Enabling specific policies and simplification licenses to facilitate aquaculture of low trophic species critical for IMTA (above is a more general requirement for aquaculture, whereas this one is specific policy for important IMTA species)
	Development of food safety standards for seaweeds
	Recognition of IMTA as it has the potential to conform to organic standards thus adding to the goals of the Farm to Fork strategy and the organic food movement worldwide.
	Legislation and the resulting administrative processes to be reviewed to facilitate and support the emergence of new IMTA approaches.
	Review of legislation on food safety aspects to recognise IMTA products - Regulation (EC) No. 767/2009.
	Adoption of the policy recommendations developed in the context of EU projects regarding the harmonisation of the circular aquaculture definition and metrics to measure and control the circularity performance.
	Agreement on some terms related to circularity of IMTA, such as the term "coproduct" instead of "byproducts" and "nutrients" instead of "waste".
	Devel op regulations for species to enhance the development of IMTA systems.
	Future pathways need to be developed to enable carbon and other nutrient credits processes.
	If there are regulations on fish and a number of invertebrates, regulations on seaweeds are absent in many countries and should be developed.
	Incentives to encourage monoculture farmers to diversify to IMTA.

	Introduce One-stop-shop approach to address administrative fragmentation.
	Feasibility to implement IMTA systems at an experimental and small-scale level should be relatively easy.
	Investments regarding aquaculture agreed during previous legislation must be guaranteed.
	More technical assistance for licencing procedures.
	No current regulations for IMTA systems, however, it can be addressed within aquaculture legislation through environmental, sustainable, and technical innovation aspects.
	Review and update legislation to avoid potential contradictions at national, regional, and local levels.
	The feasibility to accommodate multiple species in one licence should be pursued.
	The incorporation of participatory approaches in decision-making processes involving a wide variety of stakeholders, must be reinforced.
	Updated and flexible legislation and regulatory framework are required to address IMTA.
	Well-informed decisions based on science by policymakers and regulators are essential.
Database	Facilitate access to data generated by different stakeholders, increasing it through dissemination and exploitation plans.
	Generation of data through KPIs, allowing comparability between aquaculture systems and a possible European circularity aquaculture database through a common circular aquaculture framework and methodology.
Certification	IMTA to be incorporated into existing permits and incentives granted to encourage IMTA (e.g., reduction in permitting fees, certification)
	Recognison of IMTA and its role within bio-economy through bioremediation and resource efficiency.
	The results confirmed that the IMTA systems performed in line with the circular attributes embedded in the definition of nutrient bioremediation. Metrics in bioremediation would promote standardisation of nutrient recycling rates.
	Standardisation of bioremediation calculation to promote the nutrient credits.
	Circularity metrics under the PEF initiative applicable to aquaculture and interpreted together with LCA
Research & capacity building	Create experimental aquaculture facilities designed to evaluate productive trials on a pilot scale, managed in coordination between academic and research institutions and the government.
	Promote coordination of aquaculture research and innovation activities
	Provision of appropriate support services (e.g., animal health, food safety testing, laboratory services, extension services)
	Improve the capacity and build the expertise of government staff.
	Increase awareness of the environmental benefits of IMTA practices.
	Increase understanding of IMTA systems and enhance the expertise of policy makers and regulators.
	Promote the proper use of concepts in relation to IMTA practices. For example, avoid the use of terms such as "fish wastes/faeces". "Co-products or by-products" can be used instead. Increasing the societal acceptability of IMTA will require the use of appropriate vocabulary to develop the appropriate image.

The numerous valuable insights gathered can be pulled into a number of key policy recommendations, from a need for updated and flexible legislation, simplified administrative approaches, increased awareness of the environmental benefits of IMTA, the use of participatory approaches and engaging local communities, to fostering closer cooperation among producers and intensifying educational efforts. Figure 26 summarises these policy recommendations

POLICY DIMENSION

- Updated and flexible legislation and regulatory framework required to address IMTA.
- Review and update legislation to avoid potential contradictions at national, regional, and local levels.
- Improve capacity and build expertise of government staff
- More technical assistance for licencing procedures.
- Well-informed decisions based on science by policymakers and regulators essential.
- Introduce one-stop-shop approach to address administrative fragmentation.

ENVIRONMENTAL DIMENSION

- Increase awareness of environmental benefits of IMTA practices.
- Future pathways need to be developed to enable carbon and other nutrient credit processes.
- The feasibility to accommodate multiple species in one licence should be pursued.

SOCIAL DIMENSION

- The incorporation of participatory approaches in decision-making processes involving a wide variety of stakeholders must be reinforced.
- Promote the proper use of concepts in relation to IMTA practices.
- Engaging in a dialogue with local communities about the benefits and negative impacts of resource development.
- Introduction of certification schemes vary from one country to another, but overall are not used.

COMMUNICATION DIMENSION

- Closer cooperation among producers, researchers, scientists, and regulators is key to promote more innovative systems.
- Educational efforts should be put in place not only to enhance trust in aquaculture but to communicate how this activity, but especially IMTA can be environmentally stable.

Figure 26: *Policy Recommendations Results*

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