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ASTRAL

***A**ll Atlantic Ocean **S**ustainable, Profi**T**able and **R**esilient **A**quacu**L**ture*

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Evidence of accomplishment

Report

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Acronyms

AI: Artificial Intelligence

BIM: Bord Iascaigh Mhara (Ireland's seafood development Agency)

CBA: Cost-Benefit Assessment

DAFF: Department Agriculture Forest and Fisheries (South Africa)

DNA technonology: Deoxyribonucleic Acid Technology

EC: European Commission

EPV: Earnings Power Value

EUMOFA: European Market Observatory for Fisheries and Aquaculture

FAO: Food and Aquaculture Organisation

FTE: Full Time Equivalent

GVA: Gross Added Value

HACCP: Hazard Analysis Critical Control Point

HR: Human Resources

IBGE: Instituto Brasileiro de Geografia e Estatistico

IMTA: Integrated Multi-Trophic Aquaculture

IoT: Internet of Things

IPCC: Intergovernmental Panel on Climate Change

MSFD: Marine Strategy Framework Directive

NACA: Network of Aquaculture Centres in Asia Pacific

NPV: Net Present Value

OECD: Organisation for Economic Co-operation and Development

RAS: Recirculating Aquaculture System

ROI: Return On Investment

STECF: Scientific, Technical and Economic Committee for Fisheries

SWOT: Strengths - Weaknesses - Opportunities - Threats

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Summary

The deliverable 6.2 aims to carry out a socio-economic assessment and a cost-benefit assessment (CBA) in order to provide a foundation to promote the adoption of Integrated Multi-Trophic Aquaculture (IMTA) techniques by the aquaculture industry.
However, approaching IMTA economics requires a progressive methodological process.

To meet the objectives of designing business models and addressing profitable value chains, the socio-economic assessment and the cost-benefit assessment has been organised in two stages:

1. First, this report D6.2, which describes a state of the art of the aquaculture in the ten ASTRAL partners' countries and a basis of the CBA in the Atlantic area, is based on producers' interviews conducted in 2022. This report draws the main Atlantic aquaculture trends (Chapter 3), an IMTA cost-benefit assessment (Chapter 4) and a conclusion, listing an IMTA SWOT analysis, the CBA synthesis and main recommendations for producers, sector organizations and policy makers (Chapter 5).
2. Second, this report and the IMTA CBA will be used as a baseline to draw IMTA business models and develop case studies, that will be integrated in a specific section in the Deliverable 6.3 Business models (due in Month 35).

1 Introduction

Consumption of seafood has grown twice as fast as the human population since the 1960s (OECD). This substantial growth has driven some consequences, such as the world's fishing capture reaching its maximal capacity. When facing with this rising demand, aquaculture stands-out as a response to the need to increase fish, invertebrates and seaweed productions. Nevertheless, the rapid growth of aquaculture strongly impacts the ecosystems in terms of pollution, consumption of resources, wastes, etc. It also raises questions on the quality of products and the threats that the sector faces from external factors such as climate change and diseases.

To continue to grow, aquaculture must develop innovative, responsible and profitable cultivation methods to optimize its efficiency and meet societal requirements. In this context, the Integrated Multi-Trophic Aquaculture (IMTA) farming is an important and promising concept to tackle some of these aquaculture challenges. Therefore, IMTA is a remarkable topic for the European Commission (EC) in the ambition of meeting the society needs in a sustainable way. The EC has developed some initiatives and goals related to the EC's Blue Growth strategy, the EU FOOD 2030, the Maritime Strategy Framework Directive and Climate-Resilient Ocean Economies, amongst others.

Since this topic needs to be better addressed, the EC has awarded funding to European projects to work on these issues. It is in this framework that ASTRAL, a Horizon 2020 collaborative project, is focusing on IMTA farming as a possible solution to tackle aquaculture challenges in the Atlantic Area. The project objectives include defining, supporting, and promoting this type of sustainable production across this area. Thanks to sixteen partners located in the Atlantic area, ASTRAL develops and promotes collaborations in agreement with the Belem Statement and beyond. The Belem Statement is a joint Declaration on Atlantic Ocean Research and Innovation Cooperation between the European Union, Brazil and South Africa, signed in 2017. It underlines the crucial role of oceans « in the development of national and regional economy in the achievement of the Sustainable Development Goals and combating climate change"[1].

Since the first approaches, IMTA systems have been improved in terms of technologies and methods. Nevertheless, there are still some barriers and risks that need to be removed. Notably, one of the main challenges are the economics issues. Hence the importance of project such as ASTRAL to better understand and consider IMTA and to design potential business solutions and new value chains.

[1] Belem statement

In this deliverable, the WP6 team and relevant ASTRAL partners proposes to develop an in-depth description of the socio-economic aspects of aquaculture and IMTA, along with the challenges it faces. It also includes a preliminary cost-benefit assessment, defined through the lessons learnt, best practices and the analysis of economic, environmental, social and regulatory aspects of IMTA. This first analysis will enable to identify cost-effective solutions in support of IMTA processes, innovation potential and key area opportunities for business investment and growth.

2 Methodology

In order to better understand the outcomes of our work and the main conclusions/trends that we drew, below is the described methodology for gathering data and information that led us to this analysis.

■ Atlantic aquaculture and trends

The socio-economic analysis aims to draw a state of the art of the aquaculture in the Atlantic area, especially in the ten ASTRAL involved countries: Norway, Spain, France, Portugal, Ireland, United Kingdom (Scotland), Brazil, Argentina, South Africa and Nigeria. This study aims to highlight the main characteristics of the aquaculture sector. It gives key elements to understand the aquaculture context and provides a framework to refine the analysis level.

This socio-economic analysis gathers a recent state of the art and the challenges of the aquaculture sector, including different axes, such as systems, practices, history, value chains, etc.

The methodology used was based on:

- the territory and regional knowledge (macro- and meso- economic approach) based on a broad bibliographic review per country,
- user's knowledge (meso- and micro- economic approach) based on an online survey.

Observation

The survey consists in a general questionnaire that includes 15 relevant closed questions. The survey was launched online to producers in each involved country at the beginning of May 2021. The producers had one month to answer. The questionnaire was translated in English, Spanish, Portuguese, and French to improve the chances of a high return rate by adapting the survey to the respondent's language. A list of 167 producers was preliminary established, 62 answered (return rate: 37,5%) with significant variations between countries. Only 59 responses were kept for the analysis, as 3 responses were from 2 countries outside the studied area: Belgium (1) and Netherlands (2). It has been decided to add the 4 replies from Namibia to those from South Africa, since both national aquacultures are quite similar in terms of geographical proximity, context and practices. We will use "Southern Africa" (covering South Africa and Namibia) instead of "South Africa".

Portugal	3	Brazil	5
Spain	1	Scotland	1
France	9	Norway	1
Ireland	14	Nigeria	7
Argentina	3	Southern Africa: South Africa - Namibia	12 + 4

Table 1: Responses to the questionnaire per country

Problems

The global response rate of this questionnaire (37,5%) is considered in the average (33% - Nigel Lindeman, 2018). However, the low return rate per country doesn't allow to analyse at the moment these results because of the lack of representativity. In the report, only the data from the 5 countries (France, Ireland, Southern Africa, Nigeria and Brazil) with more feedback have been used for the graphic representation (≥ 5 filled questionnaires).

Explanation

Various factors may explain the low feedback from some countries. Some assumptions considered could be addressed by the producers themselves:

- some producers are over-stretched; they are being asked for inputs in many surveys and interviews connected to COVID pandemic, *de-facto* experiencing stakeholder fatigue.
- this kind of collaboration is not usual in some countries; farmers are not used to share information about their production. It is necessary to convince them about the advantages of the project before asking them information, through concrete example of preliminary results. Culture is an important aspect to consider; producers can be very cautious and careful with the information.
- the level of implementation of IMTA is very low. Farmers are not willing to engage on questions not directly linked with their productions, systems, and infrastructures. It is important to consider the COVID pandemic; this event strongly affected the aquaculture companies and their priority at the present time is to survive the crisis in the sector.

Some of the assumptions could be addressed by the way we distribute the questionnaire. We plan to engage the producers on personal basis, one by one or in small groups. The personal connection is more rewarding and will allow the possibility to engage deeper with the industrial stakeholders, also showing preliminary results from the project obtained in the first year.

This online questionnaire sent by e-mail is one way to collect data. It was also another occasion to inform people about the ASTRAL project. This channel is easy to use and non- intrusive, ideal for a first level of understanding, but we know that response rate is not very high in general terms. In ASTRAL, we plan to use a multi-mode approach to enrich our analysis. This general survey has been deployed and made available on ASTRAL website. It is disseminated to new producers integrated in the ASTRAL network, during the 3 remaining years of the project, creating a more solid basis for the analysis.

■ Cost-Benefit Assessment (addition to the previous submission)

The present deliverable has been revised during the second semester of 2022 to integrate more economic data for trends recognition and actual conclusions for helping the development of IMTA.

The methodology used followed the approach used for all the analysis performed in the deliverable:

- A meso-economic approach based on a comprehensive bibliographic review,
- A micro-economic approach based on stakeholder's knowledge acquired with face to face interviews.

These face-to-face interviews with stakeholders conducted per country from the end of 2021 to August 2022 enables us to ask the same general questions as the first questionnaire and to collect in depth qualitative, and sometimes quantitative, additional data.

Collecting data faced two main obstacles:

- Most of the interviewees were not keen on providing economic data (confidentiality, lack of trust, no data available, etc.)
- IMTA development is quite recent in the countries involved in the ASTRAL project. Most of IMTA projects are at experimental stage and don't have economic data to share.

However, we were able to collect valuable ones through these interviews and in our bibliographic review, which confirmed the major trends we were able to draw with the online survey and our desk-studies.

An interview guide was designed and validated by WP6 members in late 2021. This action was carried out in coordination with WP7 partners (for the social analysis) and gathered the main issues to address the cost-benefit assessment.

Each ASTRAL country was represented by one ASTRAL partner as "National contact point" (the same ones who were appointed for the online survey), who were in charge of conducting interviews in their own country. The different ASTRAL interviewers had a guideline for performing the interviews, which was translated into four languages, for practical purposes (Spanish, English, French and Portuguese). The National contact points identified between 2 to 5 interviews to conduct. The IMTA labs have been interviewed too and their development will be well defined in order to evaluate the pertinence in comparison with the interviews of external farmers.

A total of 39 interviews were conducted from the ten ASTRAL countries from January to August 2022, with a test run in France, Norway and South Africa in January, to validate the interview grid.
The WP6 partners decided to broaden the interviews to co-culture and monoculture producers, for the following reasons:

- There is not a huge pool of IMTA producers and/or IMTA running projects in the Atlantic Area
- We would have interesting data from monoculture and coculture, to compare with IMTA data
- We could identify potential producers that would be interested in getting involved in the IMTA approach

15 IMTA producers were interviewed. Below is the distribution per country and production type (IMTA, co-culture or monoculture):

Country	Nb of interviews	IMTA	Co-culture	Monoculture
Argentina	**2**	1	0	1
Brazil	**4**	1	1	2
France	**4**	4	0	0
Ireland	**5**	2	1	2
Nigeria	**5**	0	1	4
Norway	**4**	2	0	2
Portugal	**5**	2	2	1
South Africa	**4**	2	1	1
Spain	**2**	0	0	2
Scotland	**4**	1	0	3
		35,90%	17,95%	46,15%

Table 2: Interview distribution per country and production type

3 Atlantic aquaculture and trends

Aquaculture[2] is the fastest growing feed production sector in recent years. According to the FAO, world aquaculture production reached an all-time high of 114.5 million tonnes with a total farmgate sale value of USD 263.6 billion in 2018: the world aquaculture production represented 82.1 million tonnes (USD 250.1 billion), 32.4 million tonnes of seaweeds (USD 13.3 billion) and 26 000 tonnes of ornamental seashells and pearls (USD 179 000) (FAO, 2020).

In 2018, world aquaculture contributed up to 46% to global fish production, up from 25.7 % in 2000. At the regional level, aquaculture production is dominated by China (89% of world total volume). Fish production through aquaculture accounted for 17.9% of total production in Africa, 17 % in Europe, 15.7% in the Americas, and 12.7% in Oceania (FAO, 2020).

In average, aquaculture production of farmed aquatic animals grew at 5.3% per year in the period 2001–2018. This slow progress finds its origin in the slowing down of activities in China, the world's largest producer, where growth was only 2.2% in 2017 and 1.6% in 2018.

World production of cultivated aquatic algae, mainly seaweed, has experienced a relatively modest growth in recent years, even down 0.7% in 2018. This change is mainly linked to the moderate growth in volumes of production of tropical seaweed and decline observed in Southeast Asia, while the cultivation of temperate zone and cold-water species continued to develop.

In 2020, a globally low growth rate caused by the slowdown in China and the Covid-19 crisis was observed. The pandemic caused widespread disruption in fisheries and aquaculture as production and supply chains have been impacted and consumer spending has been restricted by various lockdowns. The FAO estimates that the aquaculture production drop in overall output by 1.3% in 2020, the first falling-off recorded by this sector for several years (FAO, 2020).

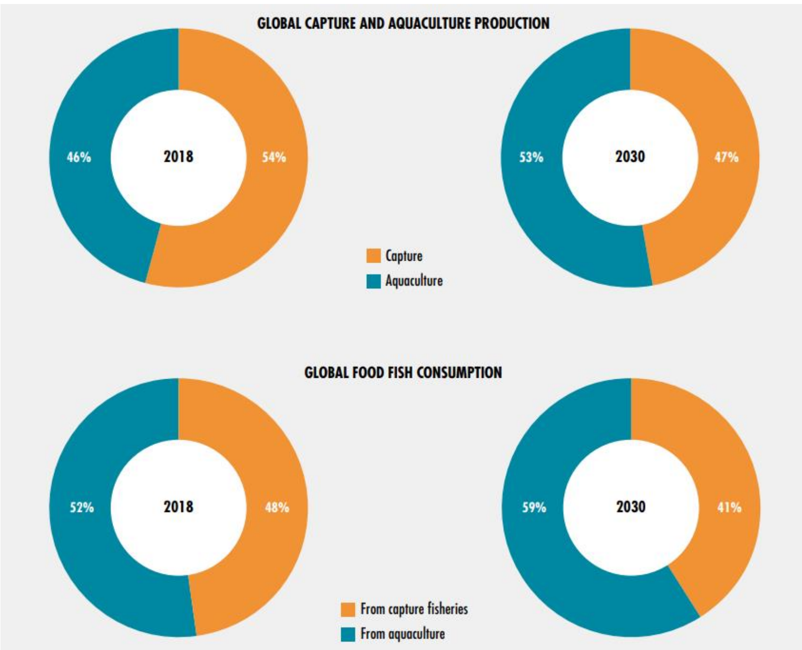
Aquaculture will continue to be the driving force behind the growth in global seafood production. The FAO projects that it will reach «*109 million tonnes in 2030, an increase of 32% (26 million tonnes) over 2018. Yet, the average annual growth rate of aquaculture should slow from 4.6% in 2007–2018 to 2.3% in 2019–2030*» (FAO, 2020, p. 181). This slowdown can be explained by the enforcement of environmental regulations, the reduced availability of water and suitable production locations, the

[2] Aquaculture is the farming of aquatic animals, including finfish, crustaceans, molluscs, etc. and aquatic plants and seaweeds, mostly algae, using or within freshwater, sea water, brackish water and inland saline water (FAO).

increasing of aquatic diseases, or a loss of productivity gains. «*The sector is expected to expand most in Africa (up 48%) and in Latin America (up 33%)* » (FAO, 2020, p. 184).

In 2018, an estimated 20,5 million people were involved (on a full-time, part-time or occasional basis) in aquaculture. Women accounted for 7,7% of the total.

Fish consumption is growing; it has been driven not only by production, but also by a mix of many other factors (rising incomes worldwide, technological developments, increased awareness of the health benefits of fish among consumers). “*About 88% of world fish production was utilized for direct human consumption. The remaining 12% was used for non-food purposes as fishmeal and fish oil»* (FAO, 2020, p. 8*)*. Major improvements in processing, as well as in refrigeration, ice-making and transportation favour a greater variety of product forms. «*Between 1961–2017, the average annual growth rate of total food fish consumption was 3.1%, outpacing annual population growth rate (1.6%). In the same period, it also outpaced that of all other animal proteins (meat, eggs, milk, etc.); in per capita terms, food fish consumption rose from 9 kg (live weight equivalent) in 1961 to 20.3 kg in 2017»* (FAO, 2020, p. 70).



Aquaculture occupies a growing share of our plates. In 2030, the FAO forecasted that 59% of fish for human consumption would have to be provided by aquaculture against 52% in 2018.

Figure 1: Increasing role of aquaculture (FAO)

Up to 2030, the FAO estimates that prices in the fishery and aquaculture sector are expected to rise in the long term. «*The average price of farmed fish could increase by 24%»* (FAO, 2020, p. 185). This is due to:

- On the demand side: improved livelihood income, population growth and higher meat prices.
- On the supply side: stable capture fisheries production, slowing growth in aquaculture production, and increasing structure costs (feed, energy and oil).

Fish and fish products will continue to be highly traded. The FAO forecasts that about «*36% of total fish production will be exported in 2030 in the form of various products for human consumption or non-edible goods»* (FAO, 2020, p. 187).

Some uncertainties exist caused notably by the Covid-19 crisis and several other factors: climate change, resource availability, macroeconomic conditions, international trade rules and prices, market characteristics and social conduct. That is why innovation will play a key role to gain competitiveness, boost productivity, and even to adapt or mitigate some effects.

Integrated Multi-Trophic Aquaculture: a promising practice to better respond to the problems faced by aquaculture

While aquaculture is growing all over the world, the industry is being facing numerous critics in the media. The sector, particularly the intensive production, causes a significant set of problems (anoxic zones, reduction in water quality, destruction of habitat, use of antibiotics, etc.). Aquaculture methods could always be improved, and IMTA can offer new alternatives and innovative solutions.

IMTA Lab Brazil

According to Chopin, Thierry (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; this practice was used dating back 4 000 years in 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). «*The actual expression "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. That is why IMTA experimental systems have been developed within the framework of research projects. The number of sites with a commercial purpose remains very limited. The approach is mostly under development. 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.).

While a real interest in these practices is observed, their adoption remains limited at the present time in the Atlantic area. Within the five ASTRAL IMTA labs (Scotland, Ireland, Brazil, South Africa and Argentina), the ASTRAL project continues to build the IMTA development.

3.1 Characteristics of the aquaculture industry in selected countries

3.1.1 Structure & resources

PORTUGAL

Aquaculture production in Portugal is very fragmented, producing small amount of many species. The sector is dominated by small companies with 96% of the Portuguese companies having less than 5 employees (STECF EU[3], 2020).

At the end of 2018, the country counted 1 515 licensed unit farms, related to 846 companies, with practices in freshwater, brackish and marine water; the number decreased by 17 units relative to 2017. The total area production was still practically the same, with an average size of 3.26 hectares per aquaculture operation. More precisely, in 2018, there were 729 companies for clams on bottom, 7 for marine fish production, 71 companies for oysters (mostly small family units) and 11 companies for seabass and sea-bream (mainly characterized by traditional production) (STECF EU, 2020).

Employees in the Portuguese aquaculture industry amounted to 1 652 persons, of which approximately 81% were employed in the shellfish sector in 2018. On average, between 2008-2017, workers increased by over 3% in the marine fish sector segment and decreased by about 32% in the shellfish sector. Season worker contracts are now more common in big companies than before (STECF EU, 2020).

SPAIN

Spain is a country of age-old marine tradition, with a coastline bathed by both the Atlantic and Mediterranean seas. It is one of the largest aquaculture producers of fish in the European Union.

[3] Scientific, Technical and Economic Committee for Fisheries (STECF)

According to STECF EU, the aquaculture industry represented 2 900 enterprises, representing a slight decline over the last decade: -2% compared to 2017, -5% between 2008-2018. In 2018, the sector accounted for 18 586 employees (+15% compared to 2017, but 16% decrease when considering the last 10 years).

The mussels' sector is the largest employer in Spanish aquaculture with 3 099 FTEs in 2018, which was 18% higher than in 2016. Traditionally, there are a lot of people working during high season; most of them are self-employed workers; so, the small familial units are the base of this segment.

According to EU newscasts for 2019-2020 (STECF EU, 2020), a 20% reduction is emerging in the number of people employed in marine aquaculture because of Covid 19 crisis, mainly in Galicia, where mussel production is concentrated.

FRANCE

Aquaculture is a traditional activity in France, the sector employed 15 249 persons, equating to 9 782 FTEs in 2018. From 2010 to 2018, the number of enterprises decreased from 3 171 to 2 782.
The shellfish sector, one of the main aquaculture segments, accounted for 2 455 companies (88% of the national total), mainly small scale and family businesses (69%). Employment reached 8 633 FTEs and seasonal jobs are quite frequent (STECF EU, 2020). Regarding the mussels' segment, in 2018, it accounted for 351 firms and 1 322 FTEs (STECF EU, 2020).

Oyster bottom culture accounted for 1 667 enterprises and 6 061 FTEs. Since 2008, the French oyster industry has faced mortalities of spat (shellfish less than one year) in pacific cupped oysters. To cope with this important mortality, «*some companies have increased the number of spat collectors and consequently the number of seasonal employees. As a result, the average number of jobs per company has risen from 3.1 in 2010 to 3.64 in 2018*» (STECF EU, 2020, p153).
Freshwater fish farming consisted of 327 companies in 2018, 75% being small scale or family businesses employing 1 150 FTEs (STECF EU, 2020).

NORWAY

Norway is one of the world's leading nations in terms of production from marine fisheries and aquaculture. The sector is concentrated, with the ten largest salmon aquaculture companies being responsible for around 65% of the total production (EY, 2019).
The aquaculture industry employed more than 8 800 employees in 2019, of which 90% worked in the salmon and rainbow trout segment. The employment rose for trout and salmon (+4.3% compared to 2018) while it was stable for molluscs and other fish species (Direktorate of Fisheries Norway, 2019).

The sector represented 424 production companies (a reduction of -14 relative to 2018): 281 in salmon and rainbow trout, 16 in seaweeds, 43 in molluscs, crustaceans and echinoderms and 84 in other fish species (cod-char-halibut) holding 1903 licences. 60% of the companies in salmon are small and the ten largest companies had a market share of about 55% (Direktorate of Fisheries Norway, 2019).

ARGENTINA

Argentina is the second largest country in South America. The seafood sector (fisheries and aquaculture including processing) employed around 35 000 people in 2018 (0ECD, 2021).

Aquaculture in Argentina is an emerging activity with an annual maximal production fluctuating between 3,000 and 4,000 t/y, mainly focusing on freshwater fish (MAGyP, 2020). Marine aquaculture has been historically a marginal activity, focused on mussels' farms in longline systems at a small artisanal-pilot scale, while no productive marine fish farming has been successfully deployed despite several attempts.

BRAZIL

Aquaculture is one of the fastest-growing industrial activities in Brazil.
Employment was estimated to be at 44 000 people in 2018 (an increase of 40% during the last 8 years) (OECD, 2021). Even though, aquaculture started in the 17th century, industrial aquaculture is still an underdeveloped activity with about 50 years of existence. The production comes from small farms, more than 80% having less than 2 ha. The sector accounted for around 233 000 farms in 2019 (200 000 freshwater fish farms) (Instituto Brasileiro de Geografia e Estatistica IBGE, 2020). Aquaculture is often

a secondary activity and small farms produce volatile incomes, where short term and unregulated work is common.

NIGERIA

Nigeria is one of the top aquaculture producers in Africa. Aquaculture contributes to around 25% of the fish production (Nigerian National Bureau of statistics, 2017). It is mainly practiced at a subsistence level. Production is generated by artisanal small-scale players characterised by limited production facilities. In 2012, the FAO estimated that employment in the aquaculture sector represented 13 627 people (FAO stats).

As per a survey carried out in 2019 by Mississippi State University (Feed the future innovation lab for fish) some 75% of surveyed farmers considered that aquaculture contributed to more than 50% of their household's income. Generally, farmers are engaged in other business such as agriculture and trade. 25% of the respondents focused on aquaculture as the only income generating activity (Oliver Kaleem *et al.* 2020).

SCOTLAND

The aquaculture sector supported 11 700 jobs in the Scottish economy in 2O18. It directly employed 6 260 persons. Aquaculture processing, as a labour-intensive segment, was the largest employer (63%), followed by salmon production (29%). The workforce is skilled with relatively high wages in comparison to other rural employers (BIGGAR economics, 2020).

In 2019, the shellfish production reflected 129 businesses with farming on 326 active sites, mainly located on the west coast. 56% of the sites producing shellfish were in the Shetland. From 2009, the number of companies decreased by 21%, especially due to amalgamation (Marine Scotland Science, 2019). In 2018, there were 22 trout farms on 52 active sites, 34 salmon farms (ova & smolts + salmon production) on 302 active sites, and 13 businesses of other species (halibut, brown trout, etc.). Vertical integration has been observed in the finfish sector that provides a more direct control of value chain to secure several key services such as hatchery and veterinary departments (Marine Scotland Science, 2019).

SOUTH AFRICA

The Department of Agriculture Forestry and Fisheries (DAFF) estimated that the marine aquaculture sector employed 3826 people in 2015. That is a 17.5% average annual employment increase in the sector, compared to the previous year. Most jobs were created by the abalone sub-sector followed by tilapia and mussels.

There were 229 registered aquaculture companies (39 marine and 190 freshwater) in 2013 (Britz, 2016).

The foundation for an enabling environment to support growth of the aquaculture sector is in place, with the South African government prioritizing aquaculture in its National Development Plan to 2030, as a sector with high growth potential and a route to alleviating poverty, unemployment and inequality through enhanced food security.

Within the framework of the programme for the improvement of aquaculture development, the government supports investments in the development of aquaculture with aid. The aim is to stimulate the growth of the "blue economy". The objectives for the aquaculture sector are to more than triple production to 20,000 tonnes by 2019 and increase the value of current production from USD 48.2 million to USD 208 million and create 2500 new jobs (Britz, 2016).

IRELAND

There are 278 aquaculture production units in Ireland; this number being stable. There has been a long-term trend of amalgamation of businesses within mussels, salmon and minor fish segments, and in the oyster sector. The companies operate largely independently of each other in terms of depuration, distribution and marketing, with some cases of cooperation. (Bord Iascaigh Mhara -BIM-, 2020)

There are currently almost 2 000 people directly employed in Irish aquaculture according to Bord Iascaigh Mhara and the employment is stable, as of 2018. The mussel sector continues to decrease while the other aquaculture segments increased modestly. The shellfish sector was the biggest employer with a high proportion of part-time jobs. In contrast, there are mainly full-time employment with a higher average salary in the finfish sector (STECF EU, 2020).

Results of ASTRAL questionnaire
Structure and resources

Within the ASTRAL questionnaire, the results below provide additional detailed insights in 5 of the 10 involved countries with which we received sufficient feedback for a graphic representation and statistic representation.

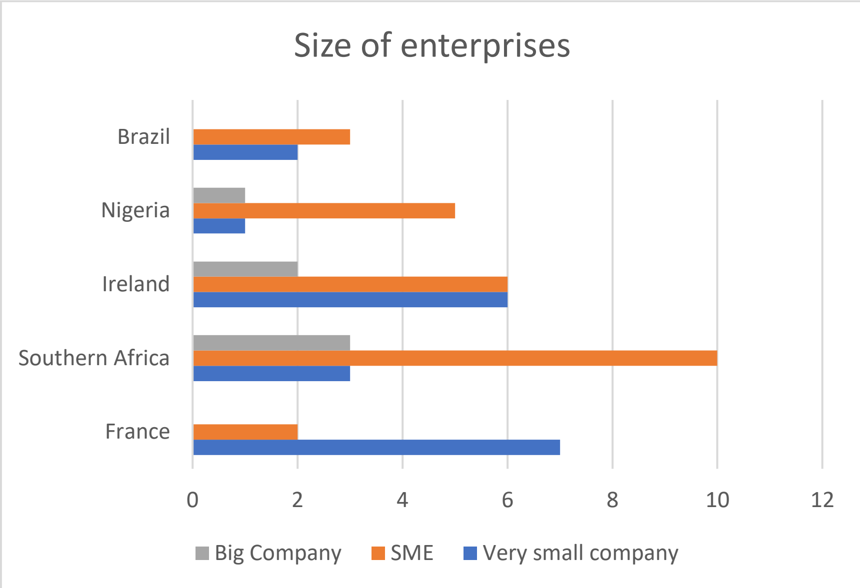


Figure 2: Size of surveyed enterprises

• A variety of enterprise sizes among the respondents

• A majority of SMEs with some big companies in Ireland and Southern Africa. MOWI as the world's largest producer of farmed Atlantic salmon is recorded in Ireland. It's otherwise 50/50 joint venture based in Bergen, Norway. Several MOWI establishments have replied to the questionnaire in Ireland. In Southern Africa, the big and experienced companies were driven by abalone producers (Group Viking, Abagold and Wild Coast Abalone). In Nigeria, Petex solution is an establishment of Petroleum Experts developing the integrating modelling software on oil and gas system.

• In France, a significant proportion of microenterprises in comparison with the other sizes.

• The diversity of enterprise sizes reflects a significant range of the number of full-time employees.

• Most of surveyed farmers (63%) has less than 15 employees.

• The responses confirm that the aquaculture sector mobilizes part-time and especially seasonal employees: 89% of French respondents, 78% of Southern African respondents, 50% of Irish respondents, 57% of Nigerian respondents and 80% of Brazilian respondents.

• The surveyed farmers employ mainly between 1 and 5 part-time and seasonal jobs, but rarely more than 50 (1 farm in Southern Africa).

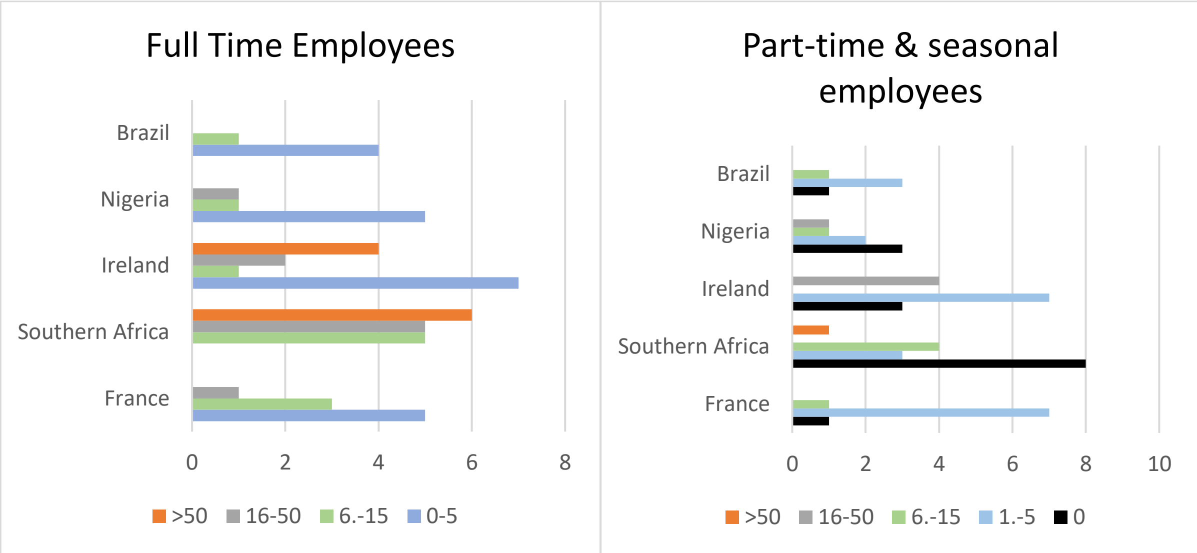


Figure 3: Full time and part time employees in the surveyed entreprises

3.1.2 Cultured species and practices and systems of production

PORTUGAL

The Portuguese aquaculture sector is largely confined to open sea, estuary zones and coastal lagoons. Almost 90% of aquaculture facilities are located in public domain areas, based on 10-to-25-year license, to be renewed only once (STECF EU, 2020).

«In Portugal, the aquaculture production based on bottom culture (grooved carpet shell) is mainly in estuaries areas and coastal lagoons. For marine fish, as turbot and sole, it is mainly located in the central region of Portugal. Off bottom oyster culture, also appears in estuaries, coastal lagoons and in the sea. Mussel in long line appears in south region of the mainland in open sea. The marine productions of sea bass and sea bream in ponds and cages are located both near the coast and in open sea in the Portuguese mainland coast and in the Autonomous Region of Madeira» (STECF EU, 2020, p246). We can divide the Portuguese aquaculture in four activity segments:

1. Clam on bottom farms producing grooved carpet shell:
   It is the most important segment in terms of production weight and sales value. Producers are in small areas of land in the intertidal zone. The farms have to face some constraints: seed availability, mortality peaks and unfavourable environmental conditions. As for positives, this

culture has a very low level of investments and operational costs are mostly wages and salaries. It is often necessary to resort to temporary labour (STECF EU, 2020).

2. Marine production of marine fish (turbot and sole) is the second most important segment. The production techniques used are tanks and recirculating aquaculture systems (RAS). The feed costs and the wages represent 44% of the total operational costs (STECF EU, 2020).
3. Oyster off bottom culture in intertidal zones:
   This culture usually uses bags and tables and, in the sea, Chinese lanterns on long lines. This segment requires significant manpower to maintain the farm activity, operational costs are mostly wages (33%) but also livestock costs (22%). The use of long lines in open sea entails high investments. This culture mixes extensive and semi-intensive systems (STECF EU, 2020).
4. Sea bass and sea bream in ponds and cages:
   The production techniques are semi-intensive and intensive in open systems. The production uses ponds with a high maintenance costs and low production densities. This culture is characterized by the weight of feed costs (39% of the total "operational costs plus depreciation of capital" in 2018), livestock (19%) and wages (19%) (STECF EU, 2020).

Portugal has invested significantly in aquaculture production. Many projects supported by the European Maritime Affairs and Fisheries Fund were conducted to foster improved production of new species, sustainable technologies, especially on spatial planning, seeking to develop synergies between different activities and multi-use of space. Finding new areas of aquaculture production, developing the innovation and investing in IMTA, will increase the Portuguese aquaculture sector.

SPAIN

Spain has a diversity of water resources and climates providing very favourable conditions to aquaculture development both in marine and inland (freshwater) areas: 8 000 km of coastline, large and minor river courses, lakes and dammed water capacity.
Around 90% of Spanish production takes place in marine waters, 5% in freshwater and 1% in brackish waters (EUMOFA- Eurostat & FAO- 2017).

The Spanish aquaculture industry is dominated by four main species in terms of value: European seabass, Atlantic bluefin tuna, Mediterranean mussel, and Gilthead seabream.

Seabass and seabream, the most important finfish species, are cultivated in the Mediterranean Sea, but also in the Spanish Atlantic coast and Canary Islands. Despite Spanish hatcheries, there are not enough juveniles for domestic production and imports are made from other countries. Most of the domestic seabass and seabream production is grown in cages. Livestock and feed constitute a high share of operational costs i.e. 64% of total (STECF EU 2020).

As a based-capture activity, the economic performance of tuna aquaculture is strongly dependent on the availability of livestock from the wild fishery and on change in the quotas for bluefin tuna catches in the Mediterranean. A reduction of quotas, implemented in 2010, decreased the supply of juveniles, causing the subsequent increase in the prices of the final product.
Feed based on fresh small pelagic impact the cost structure. The cost of juveniles accounts for 16% of total costs (STECF EU, 2020).

Mussel rafts are mainly located in Galician estuaries. The floating structures comprise of platforms; alternatively, long lines are used for cultivation of bivalve molluscs. It suffers big fluctuations in production output due to changes environmental conditions. Labour cost is the most important costs component. The activity has a low investment capital (STECF EU, 2020).

Trout production is the driver for inland aquaculture due to existing quality aquatic resources. Mainly located inland around all the regions of the country, the facilities are built on the banks of rivers, or their sources, that take advantage of the circulation by gravity of the water. Feed is the main cost within the raw materials, with 46% of the total cost structure when adding the cost of livestock (STECF EU, 2020).

FRANCE

Pacific cupped oyster, blue and Mediterranean mussel and rainbow trout constitute the main species of the French aquaculture. Saltwater fish farming (sea bream, bass) is a small concentrated sector (4 500 tonnes): 8 companies achieved 80% of sales. Pond fish farming is a traditional extensive activity with production reaching around 8 000 tonnes. Most of the production is valued on the restocking market followed by that of direct consumption (STECF EU, 2020).

• Oyster bottom

«The spat is supplied either by wild spat (produced by the farmers themselves thanks to collectors, or purchased to these farmers by others), or spat produced in hatcheries, or both. Faced with high mortalities of spat, hatcheries select and produce more resistant diploid or triploid spats that are dominant. If the cost of the seed is higher than the wild seed one, the growth of these oysters is faster (shorter production cycle) and rotation of stock is higher». «Livestock is the main cost (29% of the total operating costs and depreciation of capital)» except in 2018 where the wages and value of unpaid labour represented 34% of the total costs. «*Because of recurring recruitment difficulties, oyster farmers are increasingly having to resort to occasional staff, particularly temporary or foreign personnel*» (STECF EU, 2020, p. 153 & 157).

Mussels farmers

• Mussel bottom

The most important operational cost are wages. The activity also requires high investments and resulting depreciation. The purchases of mussels have risen significantly to compensate for mortalities (+45% from 2018 to 2015) (STECF EU, 2020).

•Trout tanks and raceways

Feed costs are dominating the cost structure (43% of the total operational costs including depreciation in 2018). Labour is the second largest structure cost item while livestock costs have been relatively stable over time (12%) (STECF EU, 2020).

NORWAY

With around 85 000 km of coastline corresponding to approximatively one third of the total land area, Norway has developed a major aquaculture industry in coastal areas.

The industry is dominated by its finfish sector, with Atlantic salmon and rainbow trout accounting for around 99% of the total volume produced. It produces also cod, halibut, char and some shellfish especially blue mussel (Statistics Norway, 2020). Of total aquaculture production value, finfish constitute 99% of value creation, molluscs and crustaceans 0,15% and algae less than 0,1%.

Most of Norwegian aquaculture is based on anadromous fish, where there needs to be both in freshwater and seawater at different stages of the production cycle. Open sea production is almost exclusively based on intensive cage culture for all finfish species. Activities across the various stages of salmon production cycle are summarized below:

- Egg and spawn production

It takes about 6-12 month. The top 5 largest companies had a market share of about 86% in 2019. Many of the companies are also crossing over into smolt production and even sea farming on a smaller scale. (EY, 2019)

- Smolt production - the process from fertilization of eggs to putting fish in seawater

All the top five companies by revenue are fully or partially owned by sea farming companies. Most of the companies involved in land based smolt facilities base their production on RAS technology, a way of controlling production and recirculating water in the fish tanks for a lower water consumption (EY, 2019).

- Sea farming

The process takes about 14-24 month. Compared to previous years, the price of feed and costs related to health because of sea lice / parasites (mitigation and treatment) have impacted the cost per kg fish. Norway is one of the countries that have invested the most in technology, and research and development (R&D) in the field of aquaculture. Important R&D investments have been made for alternative farming solutions and to increase sustainable aquaculture (offshore farming, larger post smolt, automation technologies, etc.) the last couple of years (EY, 2019).

ARGENTINA

In Argentina, most of aquaculture takes place in the Patagonian and Mesopotamian Regions. In 2021, the production was dominated by inland aquaculture, reaching 97% of the country's total production. The marine protective areas declined from 1.7% to 0.5% in the 2000-2017 period (FAO, 2020).
Rainbow trout, whose commercial activity began in 1970s, is now the first largest production with 2 177 tonnes. The second largest species is pacu (*Piaractus mesopotamicus*) with an annual production of 1 246 tonnes in 2021. Together, pacu and rainbow trout constituted 93% of the Argentine aquaculture volume and value in 2021 (FAO, 2021).

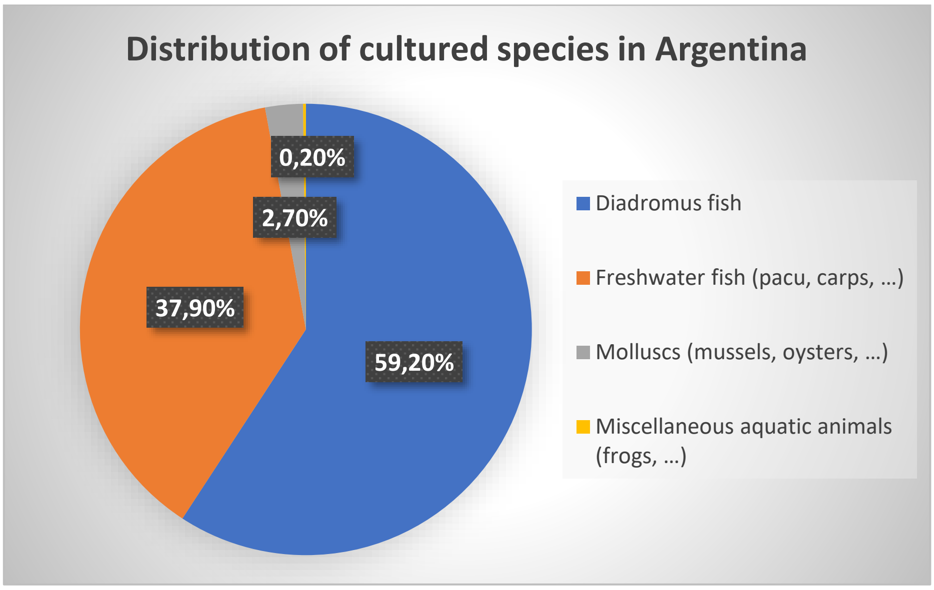


Figure 4: Distribution of cultured species in Argentina (Source: FAO, 2021)

BRAZIL

Brazil is a country rich in natural resources, suitable for the production of aquatic organisms. It is one of the largest hydrographic basins in the world (12% of all the surface of freshwater on the planet in addition to more than 4 million hectares of water reservoirs) combined with an 8 700 km coastline. 50% of the production is located in the Southern and the South-Eastern regions (Wagner *et al.* 2021).

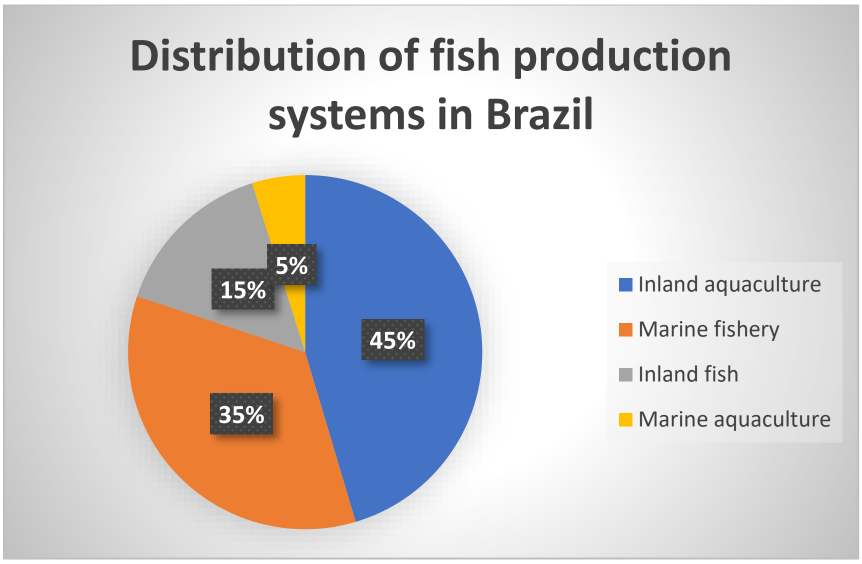


Figure 5: Distribution of fish production systems in Brazil (Source : Wagner C. Valenti. 2021)

Marine aquaculture growth is less rapid than in the freshwater area due to high investments requirements and insufficient infrastructure.

The cultivated species are numerous even though the sector is dominated by freshwater fishes (mainly Nile tilapia, but also tambaqui, tambacu, carps, etc.) followed by marine shrimps. Frogs' production is a traditional activity that has decreased due to sanitary issues. Molluscs (oysters, mussels, scallops, etc.) are also cultivated (Valenti *et al.* 2021).

The many production systems rely on a solid scientific community and strong capacities:

- Production in indoor flow through tanks are limited to the hatchery production of freshwater fish and ornamentals;
- Fish culture uses net cages in reservoirs;
- RAS is mainly used for crustaceans, other invertebrates, and recently for marine fish;
- Biofloc technology systems are developing for intensive production of tilapia and marine shrimps (Valenti *et al.* 2021).

NIGERIA

Nigeria has around 850 coastal km combined with 14 million ha of inland water. It mainly focuses on freshwater fish with catfish accounting for almost 55% of total production, tilapia (7.4%), cyprinids nei (7.9%) and torpedo-shaped catfishes nei (9.6%) in 2018 (FAO).
Aquaculture is dominated by an extensive land-based system. However, there exists semi-intensive system in fresh and brackish water ponds and intensive systems like raceways, silos, and tanks. Thus, farmers use multiple production systems: earthen ponds (58%), concrete tanks (38%), tarpaulin tanks (15%) but also RAS and flow-through (Adewumi A., 2015). According to a cost-benefit assessment made by Feed the future innovation lab for fish (Mississippi State University), earthen ponds has the most favourable cost-benefit ratio for catfish especially due to low operation costs: farmers achieve an USD 0.75 gross margin compared with concrete tanks (0.62) and other systems (0.56).

The West and Central African Council for Agriculture Research and Development and the University of Ibadan have recently promoted integrated multi-trophic aquaculture to help small farmers improve their production food security and income. It allows for increasing the supply of feed for the livestock farming system. The combination of fish, poultry/piggery and rice farming have flourished. Integrated multi-trophic aquaculture was estimated at around 14% in 2006 (Ozigbo E. *et al.* 2014).

SCOTLAND

Scotland is particularly well suited for aquaculture development with cold and low polluted waters and many fjords.

The production is dominated by Atlantic salmon. Within the global salmon market, the Scottish Atlantic salmon is considered as a premium product because of good environmental conditions and higher fish welfare standard (BIGGAR Economics, 2020). Scotland also produces rainbow trout, third main production of the country after mussel's production.
Regarding the shellfish sector, five main species are cultivated: Mussels, Pacific oysters, Native oysters, Queen scallops and King scallops (Marine Scotland Science, 2019).

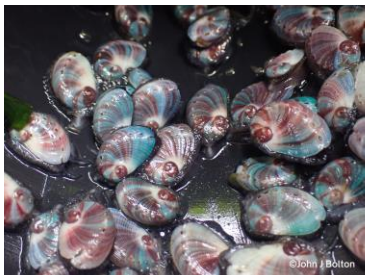
For the rainbow trout, seawater production accounted for 55.1% and freshwater production for 44,9% (Marine Scotland Science). Farmers used freshwater cages, freshwater tanks and hatcheries and seawater cages while production from freshwater ponds and raceways decreased in 2019.
For smolt, the types of facility used for the production in freshwater are cages or tanks and raceways. For fish put to sea, the majority (98%) were produced in seawater cages. (Marine Scotland Science, 2019).

Of the 52 sites recorded as being active in rainbow trout production in 2019, none were certified as organic. Of the 224 active Atlantic salmon seawater cage sites in 2019, four were certified as organic. (Marine Scotland Science, 2019).

Scotland also produces seaweeds although there is currently no fully commercial aquaculture production. Small to medium scale harvesting takes place in several locations, notably the Western Isles and Orkney.
The Scottish aquaculture sector is technologically advanced as a driver of productivity. Numerous innovations were deployed in recent decades such as automatic feeding, smart management and sea lice control.

IMTA with a focus on combining finfish, shellfish and seaweed in a production system is being researched and trialled but none are seen as commercially viable at present.

SOUTH AFRICA



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Abalone

Marine aquaculture in South Africa is dominated by molluscs (abalone, Pacific oysters and mussels). Dusky kob is currently the only finfish being grown commercially. Seaweeds (*Ulva*) are mostly farmed to bioremediate the abalone effluent to enable partial recirculation to save pumping costs and also for abalone feed. As a powerhouse of South African aquaculture, abalone are produced primarily for export to Asia and outshines all other aquaculture products with a 76% share of the overall value generated by the sector, as well as leading in product value (USD 30-50/kg), employment, and production volume. Based on a total of 20 operational abalone aquaculture farms in 2017, 12 are land-based with independent hatcheries, while 4 operate grow-out facilities only. There is 1 sea-cage farm and 2 ranching operations (DAFF, 2017). Recently a new approach to undertaking abalone farming has been developed in fishery areas depleted by poaching and in the kelp beds of the west coast, where abalone do not occur naturally. The South African Department of Forestry, Fisheries and the Environment (DFFE) has promulgated guidelines for the ranching of abalone and has issued experimental permits to companies to stock hatchery-grown abalone.

IRELAND

Salmon farming accounts for 64% of Ireland's aquaculture production and is valued at EUR 95 million. Shellfish farming is valued at EUR 51 million, including oysters and mussels farming valued at EUR 38 million and EUR 13 million, respectively. More than 90% of Irish oysters are exported, the majority going to France (STECF EU, 2020).
Salmon is grown in circular cages with a capacity of 20 000 m^3, located off the coast. The production cycle is 9 to 18 months, depending on the market size. The smolts are transferred in spring to grow-out sites and then to finishing sites for harvesting. The sector is capital intensive. (STECF EU, 2020).

For oysters in the intertidal zone, mainly trestle bags are used, but also floating/suspended baskets and shelf baskets are increasingly used. Smaller seeds of 6-8 mm are mainly imported from French and British hatcheries. Larger, mid-stage stocks are purchased from state-owned sites specialising in the early stages of the production cycle, and some 2-3 mm stocks are supplied by local hatcheries. The full production cycle is 3-5 years. (STECF EU, 2020).

Results of ASTRAL questionnaire
Cultured species, practices and systems of production

Cultivated species

• Among surveyed farmers, there is a majority of monoculture activity. In this context, “polyculture” was used to define co-culture producers.

• Brazil, Nigeria and France stand out with a significant proportion of polyculture activity. In Brazil and Nigeria, aquaculture constitutes an important subsistence activity, farmers are engaged in other production and businesses. Polyculture is also developed by the French respondents to seek the appropriate business model with this diversification.

• In polyculture, combinations of species are varied.

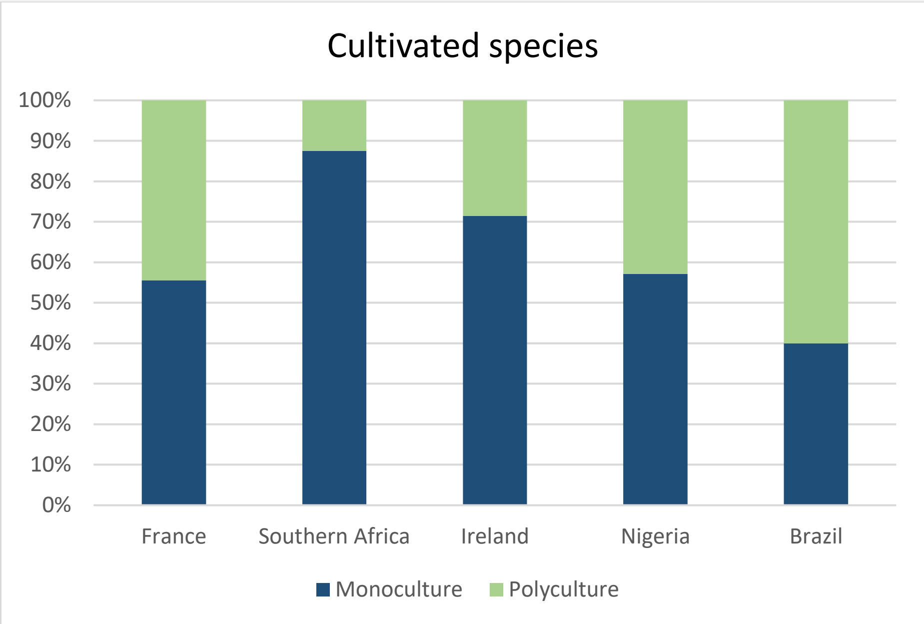


Figure 6: Share of monoculture and polyculture practices among the surveyed producers

France

Seaweeds	1
Bivalves	3
Fish	1
Abalones+seaweeds	1
Bivalves+Abalones	1
Fish+Seaweeds	1
Fish+vegetables	1

Southern Africa

Abalones	2
Bivalves	3
Fish	2
Molluscs	2
Fish+Bivalves +seaweeds	1
Seaweeds+Molluscs	1

Ireland

Seaweeds	1
Bivalves	1
Fish	7
Duckweed	1
Echinoderms+fish +seaweeds	1
Seaweeds+Echinoderms +Abalones	1
Echinoderms+Seaweeds +Bivalbes+Fish	1
Echinoderms+crustaceans +seaweeds+bivalbes+fish	1

Nigeria

Fish	4
Fish+vegetal	1
Fish+crustaceans +microalgae	1

Brazil

Crustaceans	2
Crustaceans + fish	3

Table 3: Cultivated species by the surveyed producers

Location of production area

• A diversity of location of production areas according to the countries, the species, and the respondents.

• Land-based production are particularly prevailing in Nigeria, Southern Africa and Brazil.

• Some producers develop their production on different sites, for instance in France and Ireland (mostly due to the biology of the cultivated species).

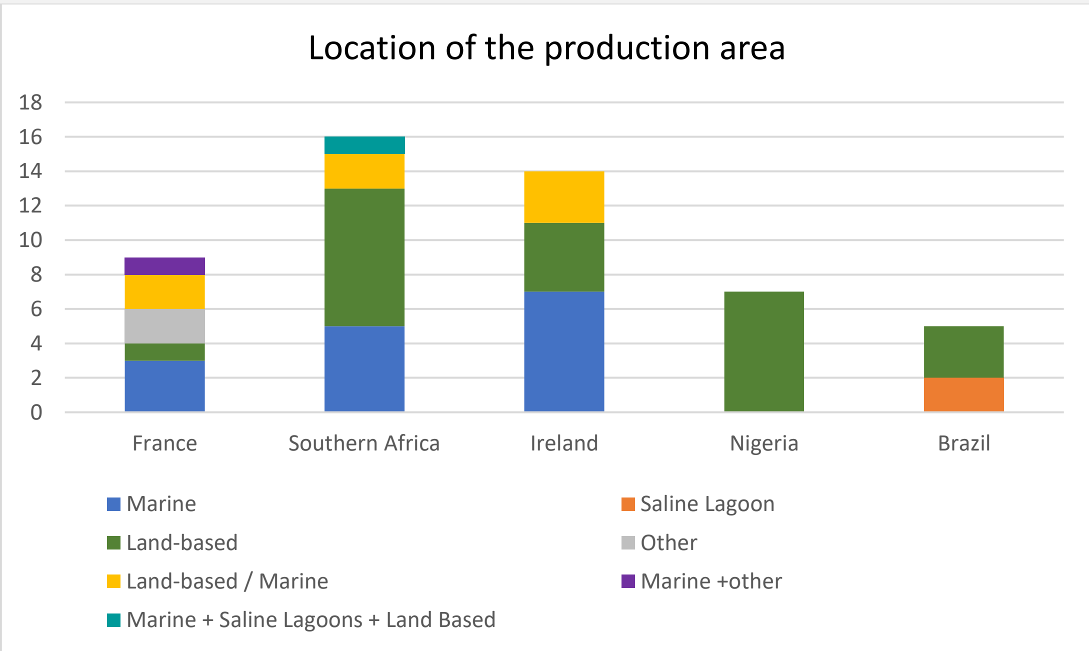


Figure 7: Location of the production area of surveyed producers

• In France, Southern Africa and Ireland, the surveyed farmers produce in marine waters.

• In Nigeria, respondents develop mainly their aquaculture in freshwater.

• According to the location of the production area and the biology of the cultivated species, some respondents develop their activity in different type of waters: marine and freshwater (anadromous species in Ireland) or marine and brackish water (aquaponics farm in France, crustaceans in Brazil).

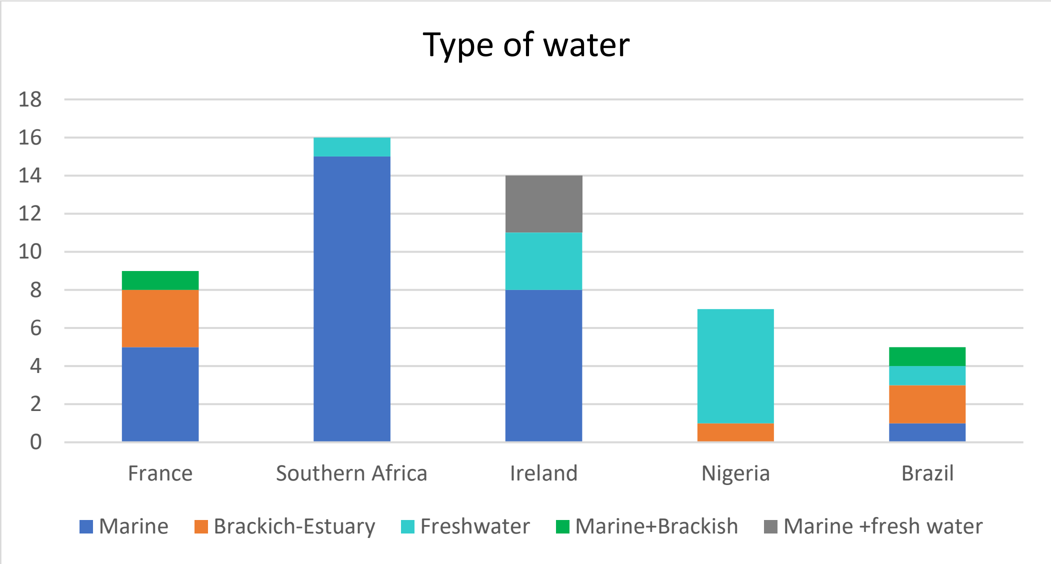


Figure 8: Type of water where the surveyed producers operate

Type of systems

• The majority of aquaculture systems used are mono-systems for 78% of respondents.

• The most represented system is the open water system, especially in France and Southern Africa.

• Biofloc system is only used by Brazilian respondents.

• Flow through system is mainly practiced in Southern Africa, Nigeria and Ireland among surveyed farmers

• Some producers mix systems, especially among Irish respondents linked with the cultivated anadromous species (salmon and trout).

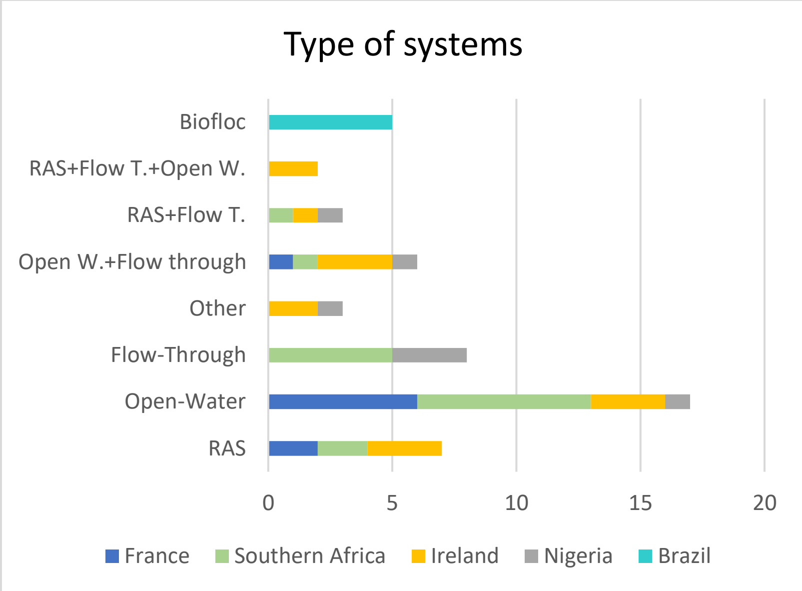


Figure 9: Type of systems used by the surveyed producers

Operational costs

• In France, most of surveyed farmers reports that salaries are the most important costs component including at microenterprises (in aquaponics) where such costs represent more than 80%.

• In Southern Africa, salary, energy-water costs and raw material (mostly feed) seem to be the main operational costs with some variation among respondents.

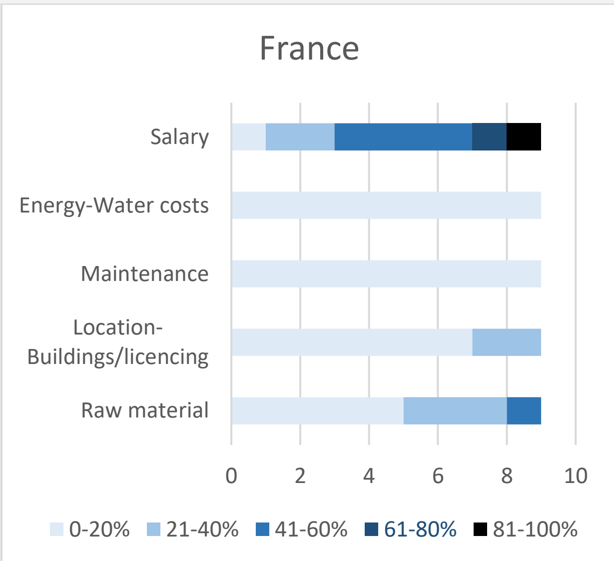


Figure 10: Distribution of operational costs for the surveyed producers in France

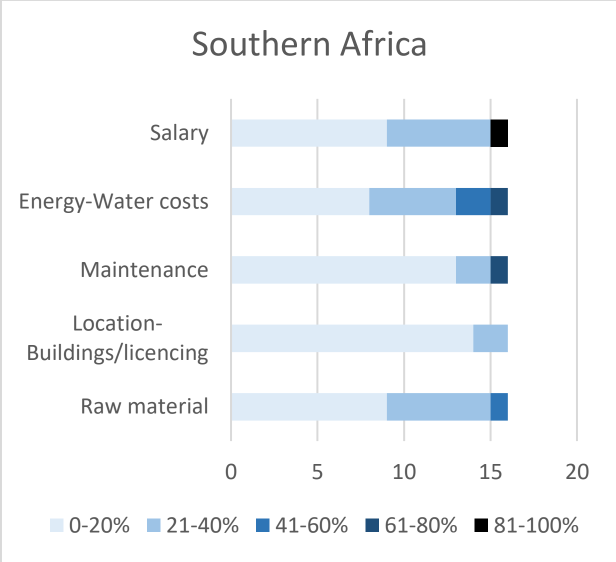


Figure 11: Distribution of operational costs for the surveyed producers in Southern Africa

• In Nigeria, raw materials are the highest operational costs: for 57% of respondents, these represent more than 40% of their expenses. These are followed by energy and water costs.

• In Ireland, salary and the water & energy costs are the most important structure costs especially for microenterprises. For 83% of respondents, salary costs reach more than 20 % of the total, for 25% of these it represents more than 40%.

• A big Irish company of salmon estimates that raw material are the most significant operational costs.

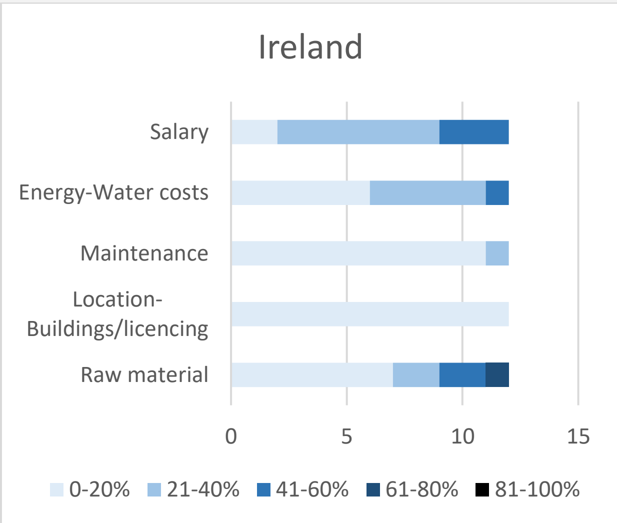


Figure 12: Distribution of operational costs for the surveyed producers in Ireland

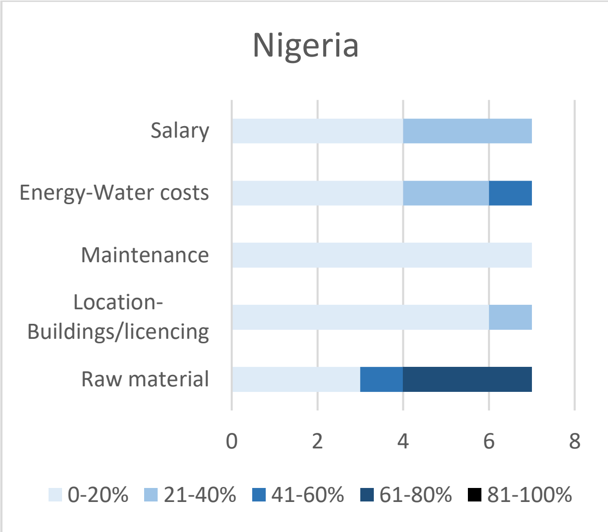


Figure 13: Distribution of operational costs for the surveyed producers in Nigeria

• In Brazil, the most important cost component is the raw material. For all the surveyed farmers, they represent more than 40% of their expenses, for one microenterprise, these reached more than 80%.

• The other operational costs of respondents are variably distributed.

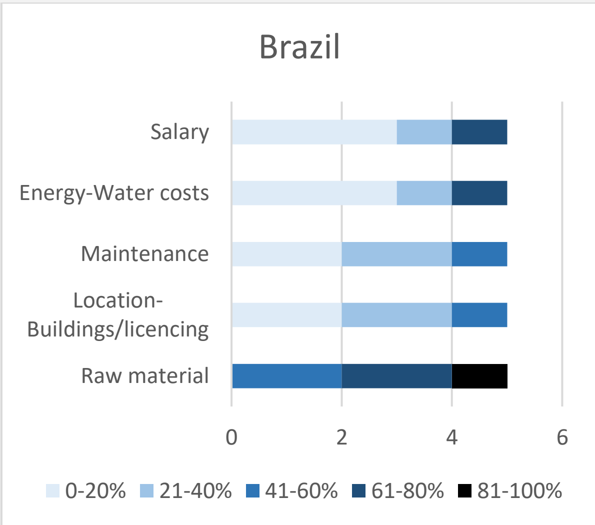


Figure 14: Distribution of operational costs for the surveyed producers in Brazil

3.2 Economic performance features in selected countries

3.2.1 The production

PORTUGAL

According to STECF EU, the Portuguese aquaculture sector produced and sold around of 11.8 thousand tonnes in 2018, which corresponded to an increase of 8% from 2017 to 2018. The total value of the production was €96.8 million, 18,5% higher than the previous year. It corresponded to a major production of clams, the most valued species. «*Production in brackish and marine waters continued to be the most important, corresponding to about 97% of total production by 2018*» (STECF EU, 2020, p244).

SPAIN

According to STECF EU, the Spanish aquaculture sector produced 329.7 thousand tonnes in 2018 generating a turnover of €719 million. Spain is the main aquaculture producer in Europe ahead of France, the second country (237.9 thousand tonnes). The production has increased by 18% compared to the previous three years.
Mediterranean mussel is by far the main harvested species in Spain, with a production in 2018 of 244 019 tonnes (74% of the production weight).

For EU nowcast (STECF EU, 2020), aquaculture production in Spain in 2019 decreased by 3% to 308 033 tonnes. «*The production suffered in late 2019 and early 2020 serious losses of fish caused by climatic and epidemiological episodes*» (STECF EU, 2020, p293); it also suffered economic effects of the Covid-19 pandemic. All of this took place together with a continuous reduction in household's seafood consumption in Spain during the last 8 years.

FRANCE

France is the second largest European aquaculture producer after Spain. According to STECF EU, the French aquaculture sector reached 237.9 thousand tonnes and €1 024 million in 2018. France is the European leader in oyster production with nearly 85% of total

Oyster farm

production. For mussels, it ranks second in terms of turnover thanks to a high unit price (€2.10 / kg) but third in volume, far behind Spain (284 000 tonnes at €0.50/kg).

France is fifth in the European Union for fish farming, in terms of production (6.4% of total production) and sixth in terms of turnover. It ranks second to produce salmonids and caviar (STECF EU, 2020).

In 2018, France produced 377 tonnes of algae and cyanobacteria in live weight equivalent (EPV) (Agreste, 2020). Two-thirds of this production is Spirulina (decrease of 21% in 2019 due to climatic conditions). France is the leading producer of algae and cyanobacteria in the European Union, providing 68% of production and 79% of turnover. Almost all the world production is carried out by Asian countries. European Union production is close to zero. In 2019, thanks to better technical mastery by the companies, seaweed production increased by 26% (STECF EU, 2020).

In 2019, a decrease of shellfish production was observed (estimated at 10% in weight) mainly due to predation for mussels and summer mortalities for oysters. Climate change and a loss of biodiversity seems to be the main causes of such a situation. This trend was confirmed for 2020, reinforced by the Covid-19 crisis. Summer spat oyster mortality has stabilized at a median level of 50% and are frequently included in the business plan of oyster farmers (STECF EU, 2020).

NORWAY

Norway´s total aquaculture production was 1.450 million tonnes in 2019 with a value of around €6.7 million (FAO 2020). Salmon, trout, and rainbow trout represented 99.6% of the total production. The aquaculture production grew by 7% from 2017-2018 and 42% from 2010-2019. During the previous couple of years, the production of crustaceans (-70%) and aquatic plants (-33.1%) decreased, while the production of molluscs (+27%), marine fish (+4.9%), anadromous fish (+7%) increased (FAO stats).

ARGENTINA

In 2017, aquaculture production reached 3 568 tonnes (EUMOFA, 2020). The sector is growing, and the production volume doubled from 2000-2017 but is still at a low level. Around 1 to 2% of the seafood production value came from aquaculture whereas more than 98% came from fisheries (OECD, 2021). Regarding the potential for development (long coastline, wealth of continental water resources, etc.), Argentina approved a new aquaculture act to boost the industry in 2015.

The share of diadromous fishes decreased from 53.4 % to 38.3 % in the 2000-2017 period. In 2017, rainbow trout reached 1 367 tonnes in volume, around €9.4 million in value; pacu, respectively 1 885 tonnes and €14.1 million. Between 2010-2017, pacu production, as the fastest growing species, increased by 200% (EUMOFA, 2020).

BRAZIL

Brazilian aquaculture has registered a continued growth in recent years. Currently, Brazil is the second largest aquaculture producer in the Latin American and Caribbean region. In 2019, the production reached 800 000 tonnes (IBGE 2020). It has doubled in less than 10 years. Around 50% of fish production comes from aquaculture (Wagner C. *et al.,* 2021). The FAO projected that the production would increase by more than 30% in the 2018-2020 period.

According to Peixe and ABCC (National fish and shrimp producers' association, respectively), the country produced 760 000 tonnes of freshwater fishes (around 530 000 tonnes according IBGE 2020) and 90.000 tonnes of shrimp in 2019. In the past 5 years, it has jumped 25%. This segment represented around 90% of the country's aquaculture and 95% of the number of farms. Brazil is also the fourth largest producer of tilapia in the world (530 000 tonnes in 2021) (Peixe 2022).

NIGERIA

Nigeria is the largest aquaculture producer in the Sub-Saharan region. In 2018, the production was valued at 291 323 tonnes (FAO), around 30% of the total fish production. Between 2000 to 2015, it grew 12% per year reaching 307 000 tonnes. Over the 3 last years, it has decreased slightly. Catfish, a popular fish, is the main harvested species (160 114 tonnes); its production remained stagnant in 2015-2018 period (O. Kaleem *et al*., 2020).

Nigerian aquaculture is faced with numerous constraints to develop: a lack of processing capacities, training, expertise in disease identification and management, inadequate technology and know-how, poor credit facilities, unfavourable transportation and supply, and weak storage facilities. The country has put measures in place to deal with these barriers to boosting a sustainable and profitable aquaculture sector (Adewumi, 2015).

SCOTLAND

On the shellfish sector, the production reached 11 456 tonnes directly sold for the human consumption and 6350 tonnes sold to other businesses for on-growing segment in 2019: 57% for mussels, 40% for Pacific oysters, and the remaining 3% for native oysters, Queen scallops and scallops. Except for Pacific oyster, the production decreased compared with 2018 due to several factors: poor growth, algal toxins, bad weather conditions and other factors (Marine Scotland Science, 2019).

Atlantic salmon production dominates the Scottish aquaculture sector by volume and value, accounting for 95% of finfish production by volume (Imani Development ad, 2017). In 2019, it reached the highest ever level recorded in Scotland: 203 881 tonnes (+30.7% from 2018) (Marine Scotland Science, 2019).

In 2019, the rainbow trout increased by 992 tonnes for a total of 7 405 tonnes (Marine Scotland Science, 2019).

SOUTH AFRICA

Total aquaculture production in 2015 was 5 418 tonnes, an increase of 4% compared to 2014. However, this amount does not include the ca. 2000t per annum of *Ulva* (most of it produced in IMTA systems), as it is not sold but used on-farm for feed.

Aquaculture production has increased by 2 775 tonnes (+105%) since 2006 (DAFF, 2017). According to Britz (2016), marine aquaculture production has increased by 32% for abalones, 30% for mussels and 15% for oysters. The overall growth rate of the sector was 8.7% between 2005-2013.

IRELAND

The greatest volume of Irish aquaculture production in 2018 is of blue mussels 38%, followed by Atlantic salmon 33% and farmed oysters 27%. There is a very small production of rainbow trout (1%) and flat oyster (1%). The greatest value is generated by salmon production (66%) followed by farmed oyster at 25% (STECF EU, 2020).

Results of ASTRAL questionnaire

Annual production

• The most significant proportion of surveyed farmers that produce more than 100 tonnes per year are in Ireland (salmon) and in Southern Africa (abalone) linked to the concentration of big companies (that have replied to the questionnaire).

• There is a significant diversity of profiles and sizes of respondents in France that have various annual production.

• In Nigeria and Southern Africa, we find many micro-producers (≤ 10 tonnes): the majority of respondents are microenterprises.

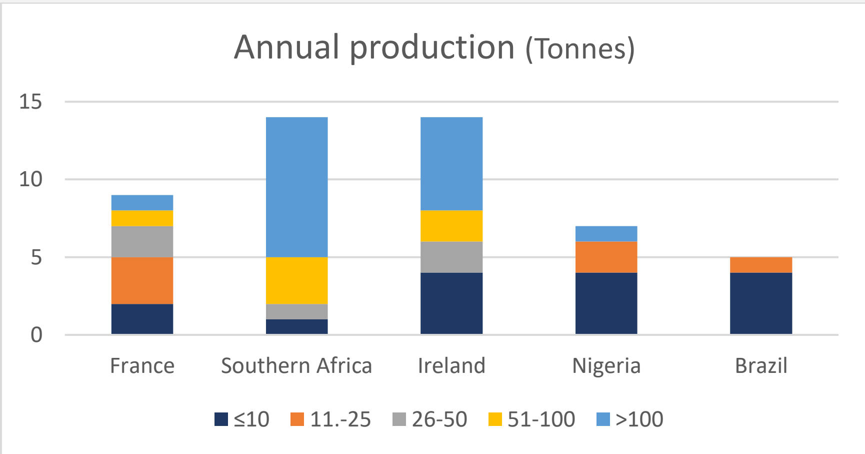


Figure 15: Annual production of surveyed producers

3.2.2 The market

PORTUGAL

In 2019, Portugal was the third biggest per capita fish consumer in the world with 57.19kg fish/person/year, with Maldives being the second (84.58kg fish/person/year) and Iceland the first (91.19kg fish/person/year).

Portuguese seafood demand is also remarkably diversified, with request for a high number of different species available in the marketplace. From 2017 to 2018, total income raised by 21%, and the operational cost also increased by 48%, this situation led to an increase of 23% of the Gross Added Value (GVA). The shellfish farming sector represented 67% of the total turnover. (STECF EU, 2020)

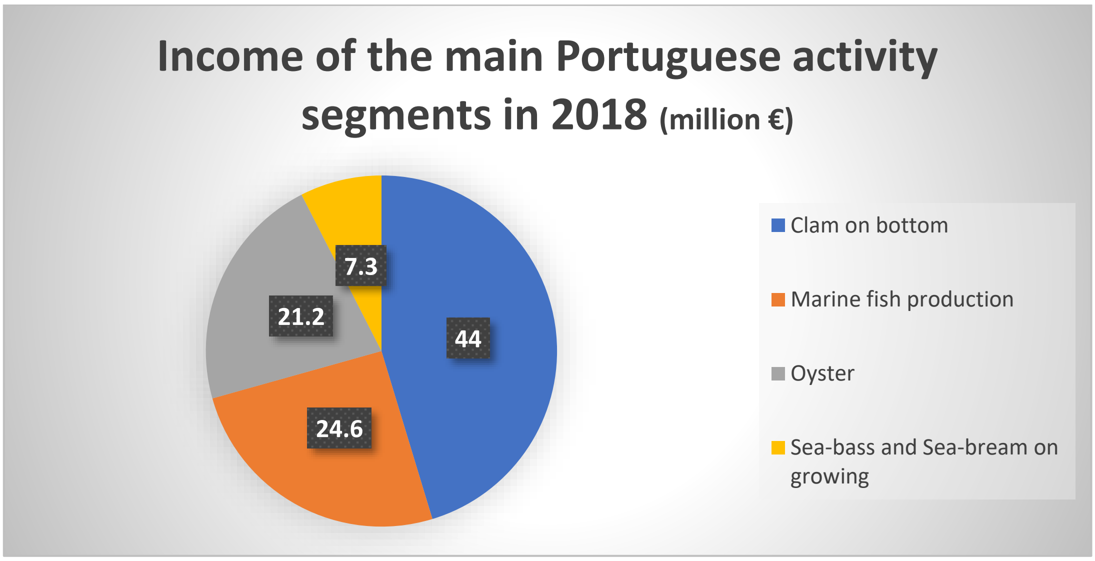


Figure 16: Income of the main Portuguese activity segments in 2018 (Source : STECF EU, 2020)

Most aquaculture products are for national consumption; however, the export sales are growing, with an increase of 6% to 33% from 2012 to 2018 in the total of sales. Exports represent 25% of total sales production and consist mainly of turbot (89%) and mussels and oysters (5%) (STECF EU, 2020).

Portugal lacks domestic suppliers to meet the consumption needs of fish, particularly of sea bream and sea bass. Thus, the country is importing most of the fish consumption by the Portuguese population causing a deficit of €1 022.9 million in 2017 (STECF EU, 2020).

On the other hand, *«freshwater production, sales and number of unit farms remain stable. This sector has little representativeness in Portugal, combined with a low acceptance of this kind of product in the national market and competitiveness difficulties with other countries in external markets» (STECF EU, 2020, p245).*

SPAIN

In terms of value, Spain is the second largest contributor in EU with 18 % of the total turnover in 2018. Since 2012, the value of the Spanish aquaculture industry has grown continuously to reach a turnover of €719 million in 2018 (37% higher than the average during the 2008-2017 period). EU noted that *« even though Spain has the largest aquaculture production volume (24%) it is only second in value (18%). This is due to the relative low market value of mussels, which represented three quarters of the Spanish aquaculture production volume, but only one quarter of the sales value »* (STECF EU, 2020, p25).

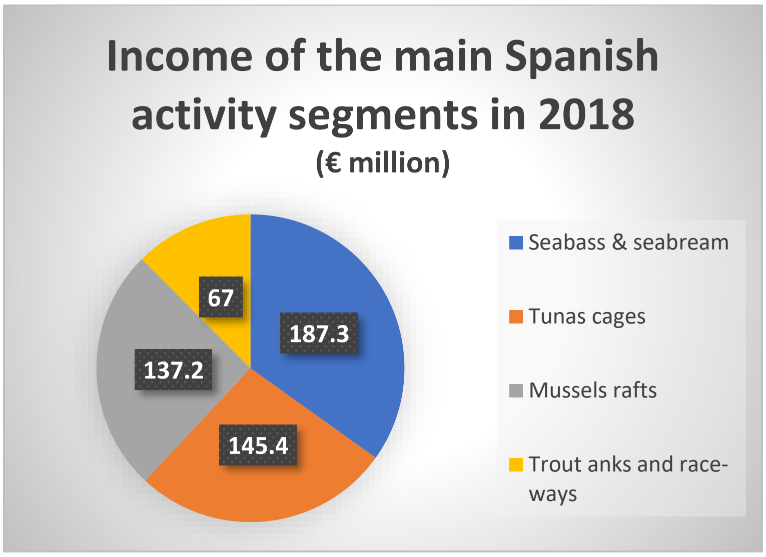


Figure 17: Income of the main Spanish activity segments in 2018 (Source : STECF EU, 2020)

In 2019, the purchase of fish represented an expenditure of €195 per capita and an average consumption of 22.53 kg/person/year. The most consumed product is fresh fish in 2019 (43.3% in volume – 39,9% in value) followed by canned fish and molluscs (19.6% in volume and 23.2% in value). Greatest evolution both in volume and value has been for cooked shellfish / molluscs with notable increases, 10.7% and 9.5% respectively. (STECF EU, 2020)

The Spanish trade balance for fish and fish products is in deficit, amounting to negative - €3,072 million in 2019. Between 2008 and 2018, exports increased by a total of 29%, while imports increased by 6%. (OECD, 2021). The main destination for exportation is the European Union (Italy, France and Portugal) and United States.

FRANCE

Total income was relatively stable from 2010 to 2018, reaching €909.8 million. The aquaculture sector made a net profit in 2018 of €118.5 million (STECF EU, 2020).

«Globally, France is a net importer of fish and fish products. Specifically, French mussels' production is not sufficient to meet the national demand. The imports of mussels (57 227 tonnes in 2019) mainly, from Netherlands or Spain in fresh mussels (respectively 13 275 tonnes and 19 216 tonnes), Chile (cooked or prepared mussels, 9 108 tonnes). French finfish products are in competition with foreign domestic productions where natural conditions, social and environmental standards are more

advantageous». However, France posted a €59.6 million credit balance for oyster in 2018. It exported in China (1/3) and Italy (1/3) (STECF EU, 2020, p161).
Two thirds of macroalgae are intended for human and animal food. Unlike microalgae, three quarters are intended for cosmetics and pharmaceuticals. Spirulina is used almost exclusively for human consumption (STECF EU, 2020).

NORWAY

The Norwegian aquaculture industry is, to a significant extent, export oriented. According to the Norwegian Seafood Council, aquaculture represented almost 70% of all Norwegian seafood exports by value, 44% by volume in 2020. The country is the world's second largest exporter of fish and fish products by value. It exported 1,2MT of fish from aquaculture which was worth NOK 74,2 billion in 2020 (Norwegian Seafood Council, 2021).
EU market represented 65% of total export volume. The demand has continued to increase continuously. After several years of substantial growth in the USA and Japanese markets, the export of salmon was reduced by 2-3%. Import is needed for fishmeal, fish oil and fish feed for its growing aquaculture industry, reaching €1 billion. These imports came mainly from EU and South America (EUMOFA Eurosfish 2018).
In the 2013-2018 period, the production cost per kg fish grew by more than 50% due to higher sea lice related costs (EY, 2019).

In 2015, consumption of fish and seafood products was 43.5 kg per capita. Fresh fish represented over half of all fish products for home consumption, and frozen fish about one third. (EUMOFA 2017)

ARGENTINA

Annual fish consumption reached around 7.9 kg per capita in 2018, a decrease of 5.9% compared to 2017 (8.4kg) (IES consultores). Within the new aquaculture act approved in 2015, the government expected an increase to 12 kg per capita in 2020 driven by fish from aquaculture. In 2018, it made a campaign to encourage domestic consumption.

Argentina exported USD 1 979 billion of fish and fish products in 2017, +5.4% annual growth rate during 2000–2017. Export was mainly composed of captured species: 61.8 % of crustaceans, 13% of molluscs, 23% of marine fishes, 1.4% of freshwater fishes (non-existent in the balance in 2000) (FAO, 2020).

BRAZIL

The aquaculture production represented a gross revenue of USD 1 billion in 2019. In average, the price of aquaculture products is estimated at USD 1.25/kg (IBGE, 2020).
Brazil has a large domestic consumer market focused on fish products for human consumption. Farmers sell to cooperatives, processing industry, wholesalers, retailers and directly to consumers but the distribution may be deficient (cold chain problems and other logistics challenges, high tax, etc.). Recently, other niche markets appear such as ornamental, baitfish, production of juveniles (Wagner *et al.,* 2021).

Brazilians consume around 9 kg of fish per capita yearly, of which 3 kg are estimated to come from aquaculture (Peixe, 2020) The annual per capita consumption has been substantially increasing in recent years through massive promotion campaigns. Domestic fish production is not sufficient to meet the national demand. The country can absorb all the production and needed to import 20% of all fish consumed (Atlantic salmon, hake, etc.) in 2019 for a value of USD 1.2 billion (IBGE, 2020). Exports of Brazilian aquaculture products are slowly increasing, with a total of 8000 tonnes of tilapia, 300 tonnes of tambaqui and 340 tonnes of curimbatã during the 9 first month of 2020. This volume has increased by 20% compared to the previous year (IBGE, 2020). However, exports are subject to many constraints such as internal demand, logistics, bureaucracy, international and national regulations that have made domestic market more attractive at the present time.

NIGERIA

The fish consumption is estimated at 13.3 kg per capita per year (FAO). This national average likely masks a much lower average among vulnerable population groups as well as a notable supply-demand gap. Increased fish production and consumption may contribute to alleviating food and nutrition insecurity. 80% of the production is for human consumption and 20% is for manufacturing of products such as fish oil, feed, etc. (Ozigbo *et al.,* 2014).

According to the Nigeria Fisheries statistics report, the Nigerian annual fish demand was estimated to 3.32 million tonnes in 2016 but domestic production is only about 1.12 million tonnes (capture and aquaculture). The deficit is largely supplied by imported products (mackerel, Alaska pollock, etc.). The country is one of the largest fish importers in the world. In 2018, imports were considered at USD 170 million mainly from Iceland, Russia and Norway (Nigerian National Bureau of statistics 2017). In 2014, the Federal Government announced the introduction of import quotas and a cut in fish import by 25%

per year to promote domestic production including aquaculture development. Based on a fast-growing population projected to reach over 250 million inhabitants in 2030, there is a huge opportunity to develop local fish production.

SCOTLAND

Aquaculture industry constitutes an important contribution to the Scottish economy. The sector generated £885 million Gross Value Added (GVA) in 2018. The direct GVA is estimated at £468 million. 54% was contributed by salmon production (BIGGAR Economics, 2020).

Salmon is an increasingly large part of the UK fish processing industry, and the majority is processed in Scotland. Often, exports are whole fish, for secondary processing in the destination country or bought for cooking at home or in hotels and restaurants. Secondary processing may be by smokeries, or seafood processors preparing with value-added sauces or as full meals (Imani Development *et al.*, 2017).

On the salmon market, several means to differentiate exist by specifications (e.g. Label Rouge 45, Organic 46, etc.), and by regions and species. From 2012 to 2019, salmon prices have more than doubled, €2.50/kg to €6/kg. The main competitors are Norway and Chile (BIGGAR Economics, 2020).
The largest market for Scottish salmon is the United Kingdom, where Scottish salmon products tend to achieve a premium price. Export sales of salmon from the UK are difficult to interpret from available statistics but appear currently to have a value around £400-500 million, excluding re-exports and processing of imported salmon, to the USA, France and China, the principal overseas markets. There is an increased demand in Asia and North America for niche quality products like Scottish salmon (BIGGAR Economics, 2020).

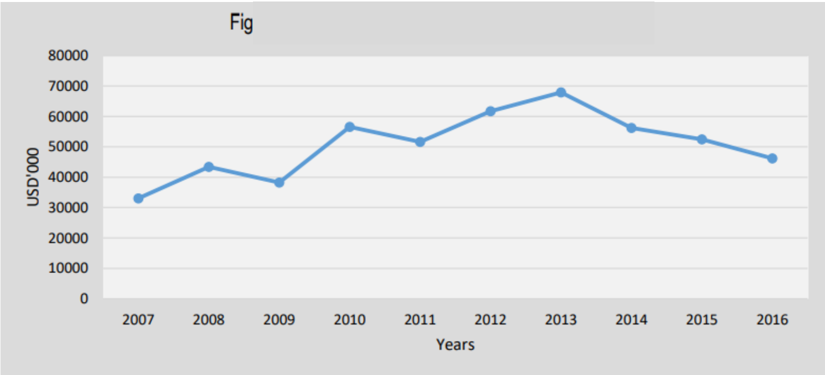
Regarding trout, the sale growth increasingly relates to trout fillets being produced by processors who package them for easy home preparation (in a similar manner to salmon fillets) (Imani Development *et al*, 2017).

Regarding shellfish, the mussels' and oysters' sales are growing. Their provenance is valued overseas, although most output (up to 95% for some producers) is supplied to the UK market (Imani Development *et al.*, 2017).

Even if the production of seaweeds is growing slowly, the market potential is wide: there has been rapid development in seaweed snacks, condiments and skin-care products in recent years and there is also growing demand for basic seaweed "meals". While wild harvest is likely to remain the most cost-effective form of supply, there will undoubtedly be demand for aquaculture production of higher value species as markets develop, requiring also further Research and Development (Imani Development *et al.*, 2017).

SOUTH AFRICA

According to a report by DAFF in 2017, aquaculture products from South Africa are marketed both locally and internationally, depending on the specific species. The trout industry markets the bulk of their products locally. The abalone industry markets the bulk of their stock in Asia. Therefore, the demand and supply conditions in the international market influence domestic prices directly. The figure below shows the price movement of aquaculture products from 2007 to 2016 (DAFF, 2017):



Source: FAO

Figure 18: Gross value of aquaculture production in South Africa

the gross value of aquaculture production has been moving on an upward trend from 2007 to 2013. Starting from 2013 to 2016, however the value experienced a decrease of 32%. The value of aquaculture production experienced a peak of USD 67 908 in 2013. Generally, there was a rise of 40% during 2016 compared to 2006 (DAFF, 2017).

IRELAND

The Irish aquaculture industry is primarily export oriented, with most of its output volume going to UK and EU markets. According to BIM's report in 2019, Irish aquaculture output volumes increased by

2.78% to 38 238 tonnes from 37 202 and decreased by 3.33% in overall value to €173 from €179 million. The shellfish sector's production, 25 897 tonnes, worth €61.4 million in 2019, increased in overall value by 5.5% compared to 2018. This increase was mainly driven by the rope mussel segment.

According to the EU Aquaculture Economic report in 2020, organically farmed salmon and farmed oyster continue to have the highest unit value per kg at €9.55 and €4.32, but both lost values slightly in 2019, by -1.2 and -1.4%, respectively, while both fresh mussel segments gained in unit value. The latter reflects the scarcity of this product in Europe (STECF EU, 2020).

Regarding on-grown salmon, the consumer-ready product, is exported to diverse markets: the EU, North America and the Near and Far East. The less severe drop in overall value for 2018 is due to an increase in salmon unit value to an average €9.55, whole-round. The sector has managed to remain profitable throughout most of the 10-year period (STECF EU, 2020).

Regarding farmed oyster, the market for Irish grown oysters was mainly the EU, emphasizing France taking 74% of total export volume (8 945 tonnes). Farmed oyster was produced by 144 businesses. Production capacity is growing steadily in pace with site licencing as more bay appropriate assessments are completed (STECF EU, 2020).

Regarding rope mussels, unit value for the fresh market varied, from €490 per tonne to €764 per tonne depending on market timing and stock condition at time of harvesting window. The margins in this sector have been relatively tight over the 2008 to 2018 period, with high labour costs and poor unit value of product determining profitability, year to year (STECF EU, 2020).

Results of ASTRAL questionnaire

Annual sales volume

• More sales volume in Ireland and in South Africa where most important surveyed farms are concentrated

• Sales volume based on production volume except in France: a differential for 2 respondents, which could be due to a mistake in filling the questionnaire or reflecting production losses, were observed.

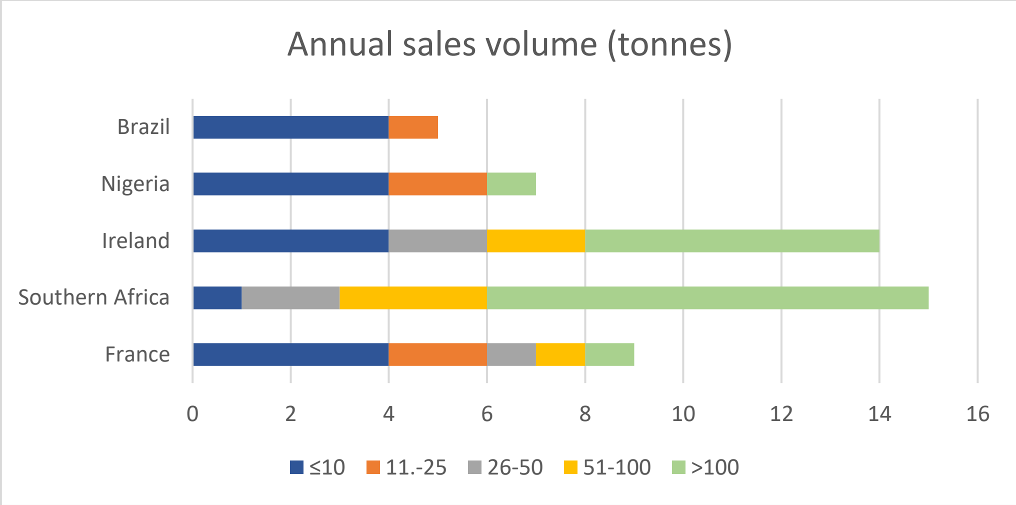


Figure 19: Annual sales volume of surveyed producers

Type of products

• Most of surveyed farmers sell fresh products (84%).

• A more mixed distribution in Brazil: 40% of respondents sell processed products (fish and crustaceans).

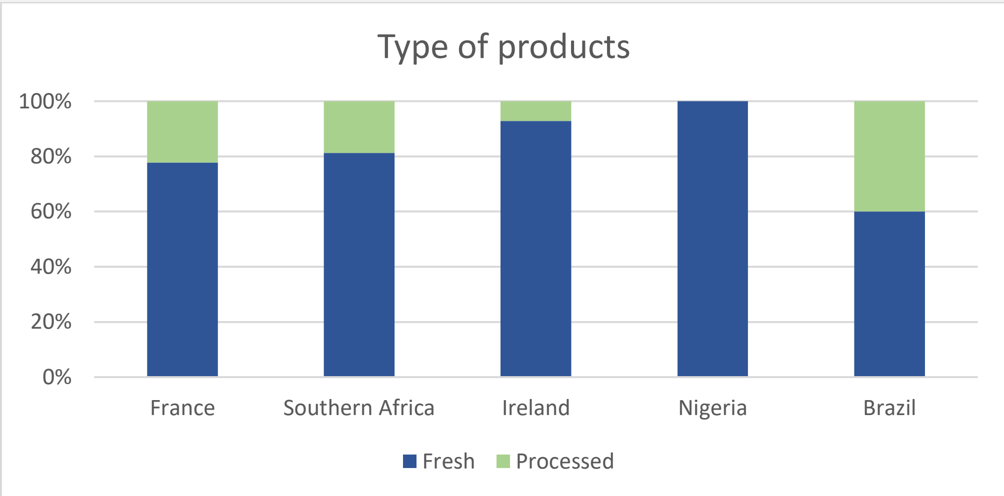


Figure 20: Type of products developed by the surveyed producers

Target markets

• In Nigeria (100%) and Brazil (60%), a majority of the respondents targets the local and regional markets.

• 44% of French farmers, 81% of South African farmers and 85% of Irish farmers (salmon producers) replied that they reach international markets.

• In Ireland, only 14% of the respondents have a local/regional market (microentreprises in polyculture).

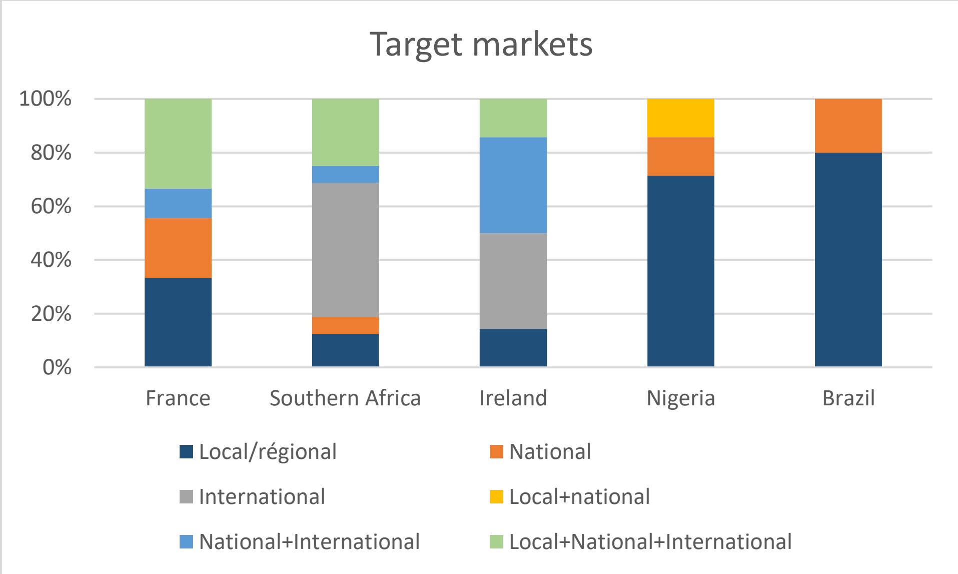


Figure 21: Target markets of surveyed producers

SWOT – Factors analysis impacting aquaculture

Strengths	Weaknesses
• Technical advancements in aquatic animal/seaweed/plant farming • An increasing capacity for production • A rising farmers' technical skills in terms of hatcheries and production system • Diversity of sites on Atlantic area to allow the production of multiple species • Contribution to local economy: direct and indirect impacts	• Environmental impacts and negative externalities (wastes, water quality, chemical wastes, sanitary impacts on wild fisheries, etc.) • Low skilled staff (marketing, digital) and low adoption of technologies in some countries • A large proportion of losses: FAO estimated that it represents 35% of the global production • Investment needed to meet competitiveness, environment standards and animal/seaweed/plant well-being • The rising structure costs (feed, energy, labour) • A poor implementation of HACCP-based procedures and other hygiene control measures
Opportunities	**Threats**
• An increasing aquatic product consumption due to rising awareness about benefits of fish/seaweed/invertebrate consumption. Aquaculture has a big part to play in transforming food systems and mitigating hunger and malnutrition. It has expanded fish/seaweed/invertebrate availability to regions / countries with limited or no access to the cultivated species • A rising demand of premium products (freshness, diversity, food safety) • Appropriate government supports • An increasing income/ livelihood across the globe	• Natural threats (predators, bloom algae, meteorological effects, etc.) reinforced by climate change and by unpredictable aquaculture production outputs • Competition for space and water resources, conflicts of use • Lack of cooperation (between stakeholders as institutions, research communities, NGOs; poor farmers organization) • Low government support • Strict regulation on environment standards, on cruelty to animals • Difficulty in recruiting: availability and qualifications of the labour force

• On-going research work on aquaculture (techniques, impacts etc)	• Asian market significance • The market gaps: some products could not match the variable consumers' expectations • Competition of imported products including production conditions (labour, environment, raw material, sanitary products and less restrictive regulations allowing the delivery at very low price). • In some countries, aquaculture is relatively inconspicuous in society and when it is, it comes up against many a priori, rather unfavourable: poor brand image of products breeding in terms of taste, environmental risks, confusion with imported products of low quality, etc. • Low information and training on aquaculture by investors and institutions

Table 4: SWOT Factors analysis impacting aquaculture

4 IMTA cost-benefit assessment

One of the main objectives of ASTRAL and work package 6 is to address IMTA value chains from the socio-economic and profitability point of view, supporting decision on best business models, best practices and best value chains.
To do so, one of our preliminary actions is to analyse the IMTA economics and cost-benefit assessment (CBA) of IMTA, which will help validating the IMTA business models and encourage transnational cooperation. This work will be complemented with the design of business models, which will be done in D6.3 “business models”, due in July 2023 (Month 35).

4.1 Cost-benefit assessment definition

In ASTRAL, the 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. A CBA is commonly used to analyse the benefits (positive consequences) to costs (negative ones) of business choices, allowing to compare scenarios and to select the best alternative for businesses.
A CBA involves measurable financial metrics such as revenue earned or costs saved, for a particular economic activity. This analysis is based on financial data that are not often available from stakeholders, and in our study the aquaculture producers, because economic data are considered sensitive for their business.
As described in Chapter 2 “Methodology”, 39 interviews with producers (IMTA, co-culture and monoculture) were conducted to collect economic data and qualitative data directly from the producers. Additional data were collected from scientific papers and grey literature on IMTA economics and business models. The full literature list is available in the Bibliography section at the end of the deliverable.

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 costs and benefits of such change/creation. The WP6 members agreed on a CBA definition that fits with ASTRAL ambition and which is adapted to the in-the-ground realities. In addition, in our current tense context (COVID-19, price volatility) and IMTA specificities, economic aspects alone can’t be considered. Developing and analysing IMTA models requires to connect economic with social, regulatory and environmental issues.

Hence, we define the CBA as a quantitative and qualitative analysis allowing to identify the impacts and effects at economic, social, environmental and regulatory levels for IMTA, to draw out major trends, shortcoming constraints and advantages.

Methodology of a classic CBA	Methodology of CBA in ASTRAL
• Step 1: Identify project scope • Step 2: Determine the costs • Step 3: Determine the benefits • Step 4: Compute analysis calculations • Step 5: Make recommendation and implement	• Step 1: Review and collect economic metrics in scientific publications • Step 2: Identify costs and constraints in economic, social, environmental and regulatory aspects • Step 3: Identify benefits and advantages in economic, social, environmental and regulatory aspects • Step 4: Draft a synthesis • Step 5: Make recommendations

Table 5: Methodology of cost-benefit assessment

This cost-benefit assessment is organized as follows:

1. **Chapter 4.2 – IMTA good practices: lessons learnt**: this section describes the scope of our analysis and the guidelines and lessons learnt from previous studies on IMTA. This gives an overview of existing economic analysis of IMTA, listing the main trends and outcomes from such studies, complemented with ASTRAL interviews' feedback and analysis;
2. **Chapter 4.3 – Analysis**: this section is the heart of the CBA as it analyses the IMTA farms regarding their economic, environmental, social and regulatory aspects, listing the costs/constraints and benefits/advantages for each entry and providing as many available economic data as possible, to help the producers with decision making;
3. **Conclusion**: to conclude this report, a SWOT analysis has been drawn, along with a CBA synthesis and a list of main recommendations for producers who are willing to shift from monoculture to IMTA production, but also for policy makers and professional organizations.

4.2 IMTA good practices: lessons learnt

In this section, we are listing the main trends and lessons learnt from previous reports, papers and studies, to capitalize on this work and see if some updates or counterarguments have to be highlighted in our analysis (section 4.3). The references for this work and analysis are listed in the Bibliography section.

It is important to mention that the publications that were used for this analysis all have different approaches regarding the model studied and analysed. The focus of each study is very different, either in terms of production systems, species used, farm size, country, etc. This makes the comparison difficult and counterarguments can be found in several papers depending on the angle chosen.

IMTA benefits and proven facts

IMTA is a different way of thinking about aquafood production that is based on the concept of circularity. The concept has not been demonstrated economically on a broad scale yet. «Only a few studies have undertaken a complete economic analysis of an IMTA production system, including taking account of external costs and benefits» (*Knowler et al., 2020*).

Knowler et al. (2020) gave an overview of IMTA's economic potential and market acceptance and consider ways to address the current gaps in our understanding. The benefits gained through IMTA production have been proven in several scientific papers and studies, as the **net present value (NPV) for IMTA is always higher** than for monocultures, for each simulation (Carras *et al*. 2019).

Scenario	Comparison NPV_{IMTA} versus NPV_{SM} (5 and 10 % discount rates)
- no price premium - no loss of salmon harvest	$NPV_{IMTA} > NPV_{SM}$ by 5.9 and 5.7 %
- 10 % price premium on IMTA salmon and mussels - no loss of salmon harvest	$NPV_{IMTA} > NPV_{SM}$ by 26.3 and 27.3 %
- no price premium - loss of salmon in Year 6	$NPV_{IMTA} > NPV_{SM}$ by 9.5 and 9.4 %
- 10 % price premium on IMTA salmon and mussels - loss of salmon in Year 6	$NPV_{IMTA} > NPV_{SM}$ by 36.5 and 38.6 %
- one-time 10 % decline in salmon market price sustained over a 10-year period	$NPV_{IMTA} > NPV_{SM}$ by 7.3 and 7.2 %
- 2 % drop/annum in salmon market price	$NPV_{IMTA} > NPV_{SM}$ by 7.4 and 7.2 %

In all scenarios, IMTA is more profitable than salmon monoculture

Figure 22: A discounted cash-flow analysis of salmon monoculture versus IMTA in Eastern Canada (Carras et al. 2019)

Nobre *et al.* (2010) gathered valuable information on IMTA and proven facts. The paper applied the Differential Drivers–Pressure–State–Impact–Response (ΔDPSIR) methodological approach to an ecological and economic comparison between mono-aquaculture and IMTA. **Profits and margins are higher in IMTA systems** than in monoculture systems. Comparing IMTA design to an abalone monoculture, the overall economic gain for the farm was valued at 1.1 million to 3.0 million USD year, depending on the scale of the seaweed facility. These values represent the outcome of the balance between the farm direct benefits expressed as increased profit, the implementation costs of the seaweed ponds and the quantifiable environmental externalities that arise due to the shift from abalone monoculture to IMTA with seaweeds in South Africa.

Nobre *et al*. (2010) showed that **abalones' growth rate is higher** in IMTA system because of the feeding process and the algal effects, along with the reduction of labour costs for seaweed ponds and the energy costs: "IMTA reduced farm costs relative to the abalone monoculture thanks to faster abalone growth to market size when fed a mixed diet of kelp and cultivated seaweed, reduced kelp consumption and energy savings due to a lower pump head in recirculation".

The effect on growth rate is also mentioned in Gomes da Silva *et al.* (2022), in which economic benefits of growth are highlighted. These authors focused on the economic viability of IMTA on the southeastern coast of Brazil (*Perna perna mussel, Nodipecten nodosus scallop and Kappaphycus alvarezii alga*, for a small-scale family production system, on 0.4 ha.

Additional costs associated with the seaweed ponds and savings that result from the shifting of monoculture (scheme 1) to the IMTA (schemes 2 and 3) in the I & J farm.

	Scheme 1 to 2	Scheme 1 to 3
Costs ($\times 10^3$ USD per annum):		
Labor for seaweed ponds	33	43
Savings ($\times 10^3$ USD per annum):		
Abalone faster growth caused by mixed diet	168	590
Energy reduction	13	9
Kelp feed costs	55	165

Figure 23: Additional costs associated with the seaweed ponds and savings from the shifting to IMTA (Gomes da Silva et al., 2022)

In addition, Gomes da Silva *et al.*, (2022) showed that in each of their simulation, located in Southeast Brazil, **IMTA models have better results than co-culture systems**, in terms of profitability and survival rates, among others.

Systems and simulations evaluated for the survival of each culture for the different cultivation systems.

	System A		System B
	Co-culture[1]		IMTA[2]
	Mussel	Scallop	Macroalgae
Simulation 1	60%	70%	
Simulation 2	60%	80%	
Simulation 3	70%	70%	
Simulation 4	70%	80%	
Simulation 5	60%	70%	90%
Simulation 6	60%	80%	90%
Simulation 7	70%	70%	90%
Simulation 8	70%	80%	90%

[1] Co-culture: Intercrop production of bivalves *Perna perna* and *N. nodosus*.
[2] IMTA (Integrated Multi-trophic Aquaculture): *P. perna*, *N. nodosus*, and *K. alvarezii*.

Figure 24: Systems and simulations evaluated for the survival of each culture for the different cultivation systems (Gomes da Silva et al., 2022)

The size of the production site and the farm is also of importance as **a smaller farm means a greater flexibility** to change and/or adapt models, but the investment costs and fixed prices will be higher and more important. Even if investment costs related to shifting to IMTA are quite important for a small farm (and in extension, for any farm), for each of the simulation, there is a **return on investment that is estimated to be 4 years**, which is significant for such a system and production site.

IMTA can improve the sustainability of seafood production, by reducing ecological impacts in proximity to intensive operations, providing financial benefits for aquaculture producers via **product diversification, faster production cycles and price premiums on IMTA products**. This also has an effect on **price volatility**, as several studies show that IMTA allows to reduce these risks (references?).

Even if economic aspects are quite important for producers, the economical sustainability of the farm is not the most important criterion for implementing IMTA production, as environmental aspects also have to be taken into account, especially with the global context that we are facing (climate change, over consumption and production, resources preservation, etc.). IMTA production systems tend to **reduce the environmental impacts of such production**, by reducing the energy demand, decreasing the feed supply and emissions, in comparison to the intensive monoculture production methods.

Regarding technical aspects and how to ensure a smooth transition towards IMTA, it has been shown that the **species chosen for the different trophic levels** are important to have an economically viable production system. According to Knowler *et al*. (2020), it would be more efficient to do IMTA experimentation with three species, instead of four, as the financial returns from investing was higher as emphasized in a discounted cash-flow analysis. In this particular case, the best choice to ensure economic sustainability and viability was to choose Atlantic salmon, blue mussel (*Mytilus edulis*) and kelp (*Saccharina latissima*) versus Atlantic salmon, blue mussel, kelp and green sea urchin (*Strongylocentrotus droebachiensis*) for the IMTA production system studied.

Reservations about IMTA

As described in the previous section, there are several aspects that producers should be made aware of to understand the impacts and benefits of developing an IMTA production system. However, some reservations have to also be listed, as IMTA is still under deployment throughout the globe and we are still dealing with some important aspects, such as public and market perceptions.

As IMTA is still not well known by the general public and the consumers, there is **not a strong demand for IMTA products**, even if consumers are more and more looking for more sustainable food, taking into account environmental impacts of the farm and the well-being of the aquatic animals. For this reason, there is an urgent need to **raise IMTA awareness in the public** and also within the aquaculture community to show the **need to adapt their methods**, shifting from a monoculture or co-culture system with negative externalities to an IMTA system with more benefits regarding environmental aspects.

Social perception is key for this success, as consumers would be ready to **pay more for a premium product**. According to *Shuve et al., 2009* and *Knowler et al., 2020,* consumers will be ready to pay 10% more for a "better" product, coming from IMTA production systems.

Price scenario posed to respondents	Yes	No	Don't know
Pay same price (*N* = 639)	61	8	31
Pay 10% premium (*N* = 595)	38	21	41
Pay 20% premium (*N* = 471)	18	35	47

Those who responded *Yes* or *Don't know* to the current price were asked whether they would pay a 10% premium. Those who responded *Yes* or *Don't know* to the 10% premium then were asked whether they would pay a 20% premium.

Figure 25: Per cent of survey respondents willing to pay varying price premiums for IMTA-produced mussels (Shuve et al., 2009)

Complementary to this, **price volatility** has a great impact on the sustainability and viability of the IMTA production system. If prices are going down, IMTA products will not be as competitive as others, as they have a production and personnel costs that are higher than the "regular" products available in the market.

Not many economic data are available to do a proper analysis of the IMTA viability and sustainability with regards to monoculture and co-culture. In previously cited simulations, NPVs are always higher for the IMTA production systems, but each country and regions have disparities and their own properties, which makes the analysis and comparisons complicated, as one model could not fit all and should be adapted for each country, production site and species. For instance, there are great differences in starting an IMTA farm in Europe in comparison to tropical regions, or between a small farm and a large farm.

Gomes da Silva *et al*. (2022) focused on a small farm in Brazil. Even if their results are valuable, it is **difficult to draw guidelines and baselines** from this study, as Brazil has very particular specificities in terms of climate, land, production systems and species. Even if the production method works in Brazil, this might not be the case in Europe, South Africa or other countries or in larger farms with different priorities and challenges.

Moreover, **biosecurity** is an important aspect to consider for the development of IMTA. It is, for instance, a major threat to abalone and IMTA systems in South Africa. Bolton *et al*. (2009) performed a SWOT analysis of *Ulva* cultivation in South African abalone farms. "Despite the fact that *Ulva* has been cultured in abalone waste and fed back to the abalone for around 6 years at Wild Coast Abalone without any increase in disease, other farmers and potential farmers express misgivings about the possibility of spreading some as yet unknown disease between abalone and seaweed tanks in integrated systems". Some farms have mitigation measure to account for good biosecurity practices, such as having independent clusters of abalone and *Ulva* that can be shut off completely independently from other clusters.

Synthesis and argumentation

In order to synthesize and put into perspective the lessons learned and analysis described in the previous section, below is a succinct synthesis of arguments and nuanced approach for each of the main items to be considered for the CBA, with regards to the interviews conducted and the recent literature:

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 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 - "*IMTA affects more the production side, rather than sales" (verbatim from an IMTA producer)*

Return on investment

- 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 higher for a larger farm, which will have more investment costs to start an IMTA farm - "*Our ROI occurred after more than 10 years of production" (verbatim from an IMTA producer - 8 employees)*

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

Table 6: Synthesis of scientific papers and lessons learned

Some of the trends highlighted above have to be nuanced as they were not all reflected in the interviews we conducted, or only a few of the interviewees mentioned them.

The following chapters will give a more in-depth picture of the current status and situation of IMTA in the ten countries that are part of the ASTRAL project, to help us draw the cost-benefit assessment of IMTA.

4.3 Analysis

At the present time, there are several ongoing IMTA projects across the globe and their common objective is to demonstrate that the process is biologically validated (except in China where it is massively and historically developed). However, some aspects remain unresolved, such as:

- the technical complexity of IMTA system (different species production requiring specific know how…);
- the level and the cost of required investment;
- the reliability and the efficiency of the system (the potential sanitary risks, the assimilation of waste according to species is not always easy...);
- the capacity and possibility for a transition from a pilot scale or pre-commercial phase to a large-scale development;
- the variability of environmental contexts and the choice to implement IMTA systems (what are the best conditions and options compared to the diversity of marine systems? ...).

In the ASTRAL project, four IMTA labs (Ireland, Scotland, South Africa and Brazil) and one prospective IMTA lab (Argentina) have been identified, in a combination of open-water, recirculating inshore and flow-through inshore IMTA systems focused on marine species. ASTRAL will assess the added value of the species combination throughout the production cycles, by developing operation welfare indices (health management), assessing risk of pathogen infection (biosecurity) and profitability. The acquired knowledge will be used to suggest new and suitable IMTA combinations for each region considering the regional challenges.

In this section, we will further analyse IMTA farms regarding their economic, environmental, social and regulatory aspects, listing the **costs/constraints** and **benefits/advantages** for each and providing as many economic data as possible, to help the producers with decision making.

First, an overview of the IMTA farms interviewed is essential to better understand the analysis and the factors influencing it.

Country	Date of creation	Number of employees	Species produced / value chain concerned	Tonnage / year	Development readiness level	Main motivation to IMTA
Argentina	2018-2019	9	Urchin / Seaweeds / Ascidians	Urchin: 40 kg Seaweeds: variable	Experimental project from a research institute	Based on a research project
Brazil	2018	21	Shrimp / Tilapia	Shrimp: 77 T Tilapia: 7 T	ASTRAL lab from a research institute	Based on a research project
France	2018	37 on the production site	Sea bass, gilthead bream and gilthead sea bream and test with mussels / oysters & lobsters	N/A	A dedicated R&D programme of the farm	Bioremediation to reduce effluents
France	2004	8	Abalone / Seaweeds	Abalone: 8 T Ulva: 20 T Kombu: 15 T Alaria: 2 T	Trying to scale up	Working in a natural environment with soft environmental impact
France	2020	7	Oysters / Periwinkles	Oysters: 200 T Periwinkles: 4 T	Start up	Bioremediation → Tackling negative externalities of classic aquaculture model
France	2015	65 on production site, 1 person dedicated to IMTA	Sea bass / Sea bream (mostly) / Meagre / Seaweeds	N/A	SME	Bioremediation → Effluent management of the farm with seaweeds
Ireland	2017	5	Lumpfish, Atlantic salmon, Atlantic wakame, Dillisk/Dulse, Sugar kelp, Sea lettuce, Cluisin, European lobster, King scallop, Native oyster/flat oyster, Purple urchin, Sea cucumber	Alaria: 2160 kg Salmon: 1681 kg Scallop: 30 kg	ASTRAL lab from a research institute	Based on a research project
Portugal	1989	2 on IMTA	Gilthead / Bream seabass / Ulva / Gracilaria	N/A	Experimental stage by the company	Linked with a research centre, use of company facilities
Portugal	2019	2	Seabass / Oysters / Salicornia / Sea lettuce	N/A	Experimental stage from a university	Based on a research project
Scotland	2020	5	Kelp / Ulva / Oysters	N/A	ASTRAL lab from a research institute	Based on a research project

South Africa	2013	210	Abalone / Ulva	Abalone: 600 T Ulva: 450 T	ASTRAL lab from a large company	Interest of trophic exchange for partial recirculation
South Africa	2011	300	Abalone / Ulva / Gracilaria	Abalone: 170 T Ulva: 720 T Gracilaria: 108 T	A large company	Interest in trophic links for feed for abalone
Norway	2014 (IMTA in 2022)	8	Salmon / Kelp	Salmon: 780 T Kelp: 100 T (research licence)	Experimental stage from a company (and temporary IMTA research license)	Bioremediation → Reducing environmental print of salmon culture
Norway	IMTA from 2016 to 2021	6	Salmon / Kelp	Salmon: 780 T Kelp: 8 T (research licence)	Experimental stage by the company (and temporary IMTA research license)	Bioremediation → Reducing environmental print of salmon culture
Ireland	IMTA from 2008 to 2016	6	Abalone / Sea urchins / Sea cucumbers	N/A	Stopped IMTA production	Trophic links for nutrients and reduction environmental print

* Grey lines = farms that operated in IMTA systems and switched to mono/co-culture since then

Table 7: Overview of IMTA interviewed farms

This overview of IMTA interviewed farms allows us to set the starting point of our CBA analysis and do a preliminary analysis on the state of the art and status of IMTA in Europe and across the Atlantic:

- Most of IMTA projects started a few years ago and are relatively new;
- Most of them are at an experimental stage and are either coming from a research institute or from a company;
- The farms are operating small production areas and have a variable production capacity;
- The value chain is different in each country, even if we can observe a common baseline in Norway (Salmon & kelp) and in South Africa (abalone);
- Producers that chose IMTA were driven by research and/or environmental aspects:
    - Willingness to address negative externalities and to solve a problem;
    - Optimization of the production cycle;
    - Desire to increase knowledge on trophic links between species.
- Those who stopped their IMTA production did it because of a change of manager and ownership (less resources to be spent on IMTA production processes) and due to a licensing burden

TO KEEP IN MIND:

- No general profile, IMTA can be implemented by any producer
- Current IMTA producers are either in an experimentation phase or a scale-up one and are producing a wide variety of products
- Our CBA will not have one single trend but various recommendations and entries, as there are many different profiles of farms and production systems (not a single model but several approaches)

4.3.1 Economic aspects

Analysis of economic "costs"

Throughout our desktop studies and the feedback received from the aquaculture producers' interviews, we were able to list and analyse several economic "costs/constraints" in IMTA implementation that need to be taken into account when producers are willing to change from monoculture / co-culture to IMTA[4].

Related costs/constraints	Country concerned	Effect on CBA and farm costs	Description
Increase of production costs	Brazil, South Africa	Increase of HR, fixed costs and production costs	Brazilian producers explained that IMTA systems had an impact on production costs, with regards to monoculture, as IMTA systems required more resources and time to be implemented
Increase of infrastructure costs and constant need of investment	Ireland, France	Increase of infrastructure and fixed costs	For Irish producers, the production of IMTA species increases the costs due to the requirements for infrastructure (IMTA requires different structure, anchoring systems for each species). Some French producers explained that they need to remain competitive and find new ways to innovate and thus to invest to have a sustainable production system and method, as some species are sensitive to changes (abalone for instance). *Opposite, Norwegian producers experience common use of infrastructure lowering total investment.*
Need time to have a viable production	France, Ireland, South Africa, Norway	Forecast increase of HR (instalment, follow-up), investment costs, fixed costs	Some producers stated that they need time to find a sustainable and profitable method, especially when starting from zero. There are risks related to investment costs, as they are higher at the beginning of the process.

[4] This only reflects the feedback of interviewed producers from the concerned countries and who are located in the ASTRAL countries and is not necessary a generality for the entire industry.

Need of new and/or additional technical skills	All	Forecast increase of costs related to HR and external services (training)	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 apprehend this new technique, to better know species and their commercialisation.
Need to know the right combination and trophic links between species	All	Forecast increase of costs related to HR (more experiments to be done) and external services (training)	Each IMTA producers need to have a clear view on species to find the right species' "combination" to reach profitability and sustainability of the farm. This essential knowledge is under development, hence the importance of R&D effort.
Lack of commercial experience in IMTA	Argentina, Brazil, Ireland, Nigeria, Norway, Portugal, Spain, Scotland	Forecast increase of costs related to HR (business/marketing department) and external services (consulting firms, marketing experts)	Most of the interviewees explained that not many IMTA producers are commercially viable and thus, no real experience in commercializing these products is available and no framework/rules are set. Moreover, producers don't know very well the markets for them. For example, some farmers have not carried out any market studies for new species cultivated.

Table 8: Analysis of IMTA economic "costs"

Analysis of economic "benefits"

Below are the main "benefits/gains" that were mentioned and effects on the CBA to be performed by the producer, the ASTRAL countries concerned and their description[5].

Related "benefits"	Country concerned	Effect on CBA and farm costs	Description
Optimisation of production costs	Argentina, South Africa, Norway	Forecast lower HR costs (less cleaning) and feed costs	Most producers, and especially Argentinean ones, explained that thanks to IMTA systems, they have spent less time on water quality control and tank cleaning, which lowered the labour and feed costs (and thus improved profitability). The condition of polyvalence of employees is highlighted. In addition,

[5] This only reflects the feedback of interviewed producers from the concerned countries and who are located in the ASTRAL countries and is not necessary a generality for the entire industry.

			seasonal staff can be employed on a longer period. Norwegian producers explained that most of the year, except during harvest season, kelp production could use available capacity from employees already in salmon production without increase labour cost.
Decrease of feeding costs	South Africa	Forecast lower feed costs and production costs	South African producers stated that implementing IMTA, and especially focusing on abalone and seaweed, allowed them to reduce the feed costs, as this species' combination has a lower feed conversion ratio than co-culture/monoculture systems
Revenue diversification	All	Forecast increase of revenue and profit	Most interviewed producers stated that IMTA production system has allowed the farm to have revenue diversification thanks to the novelty of the process (tourism through farm visits, new chain of products, etc.)
Improvement of farm efficiency	All	Forecast increase of revenue and profit, decrease production and maintenance costs	Many producers explained that IMTA was the best solution to improve the farm efficiency, as all products are being used for each production cycle: each element, even waste, are being processed and used
Improvement of species' growth rate	South Africa, France, Ireland	No direct effect on CBA but could lead to increase in revenues	Many abalone producers explained that, with IMTA, the abalone were bigger than the "regular" ones, as the growth rate was improved by to the algal feeding. This could lead to an increase in revenue as abalone of a larger size would be easier to sell with a price premium

Table 9: Analysis of IMTA economic "benefits"

Challenges & perspective

Below is a synthesis and perspective on the major trends in economic aspects for IMTA systems.

■ Access to finance

Access to finance is a key aspect for producers to develop IMTA projects. It is an upmost challenge that can constrain growth of businesses and sectors.

Farm location	Funding
Argentina	Staff funded by a research institute Private fund: 500,000 €
Brazil	Mostly private funding (bank)
France	Strong public funding for abalone & seaweeds / + 1 research project per year
France	Public funding, mostly from the European Maritime and Fisheries Fund
France	Public funding, especially at starting stage for abalone and seaweeds production
France	European Maritime and Fisheries Fund
Ireland	100% public funding (project from research institute)
Portugal	Staff financed by research institute
Portugal	100% public funding (project from university)
Scotland	100% public funding (project from research institute)
South Africa	Public fund: 465,000 € for a total of 1.5M € of investment
South Africa	Mostly private funding but obtained some public funding as well
Norway	Private fund from bank and public fund from national authority (grant & loan). Indirect, and most important so far, is financing by substantial income from selling salmon from a granted four years salmon research licence included in granted IMTA salmon/kelp license.
Norway	Private funding. But important is indirect funding financed by substantial income from selling salmon from a granted four years salmon research licence included in granted IMTA salmon/kelp license.
Ireland	Public fund: 1.7 M € (seaweeds); 1 M € (shellfish) Private fund: 2.3 M €

Grey lines = farms that operated in IMTA systems and switched to mono/co-culture since then

Table 10: Funding schemes per IMTA producers

According to the IMTA farms interviewed, public funding is very important. It is all the more important that 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).

In parallel with these tests, the aquaculture sector must think carefully about the target markets and how to reach them, so that public funding has a leverage effect on commercial profitability. This raises the question of the capacity to maintain the activity when funding stops.

Even for an established company, it is important to continue to innovate to develop its business. A French company said that they need to carry out one R&D public funded project per year to improve processes. But this questions also the skills and the time required to look for funding, to submit applications, etc.

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. Even more so, specific financing challenges (both public and private funding) faced by aquaculture businesses vary at different stages of company growth. The result of this is the aquaculture farms are not as efficient and productive as they could be and risk losing competitive advantages. If there is a critical mass of underinvestment in a sector, then a loss of market share and a loss of global competitiveness can be seen.

In addition, aquaculture comes with a unique set of risks, which are mainly stemming from its capital-intensive nature and the possibility of diseases wiping out farmed populations. As such, risk mitigation efforts are key to boosting investor trust and interest.

- **Matching to market needs: quality, traceability and freshness**

Markets, consumer preferences and concerns about food safety and sustainability are influencing economic growth and holds an increasing place forcing the implementation of quality management systems.

Market-based incentives are important drivers for producers participating in eco-certification schemes, showing the important role of the market demand for eco-certified seafood in sustainable aquaculture development, and hence the positive environmental outcomes.

Indeed, with a growing concern about food safety, more efforts have been undertaken to improve the food quality introduced in the market.

IMTA interviewed producers are convinced that the **certification of their product** is crucial for differentiation, traceability, easiest profit margins and profitability. For those who have not taken this step, they are convinced that "*green certification will become essential in the future*". "*Markets are sensitive to labels especially at international level*."

Several certifications exist, that are more or less developed and known and that are required for some products, such as organic certification for seaweeds in Europe. Nevertheless, as a result of the complex globalized supply chains and the many different species in aquaculture, certification schemes don't yet exist for some products in some regions (*i.e.* abalone in Europe).

Should we go as far as to say that an IMTA production system needs a certification label to make products visible to consumers and to make higher prices more acceptable? Views are diverging on this aspect. For some of the IMTA farmers, "*there is not a need for the moment, it is still early days and IMTA farming must guarantee product and environmental quality*". Some farmers are totally against this certification, since it would make it difficult for producers to switch to IMTA. Moreover, designing a certification system is time-consuming and costly, and certification for the producers would generate additional costs for them, which could jeopardize the economic profitability.

On the other hand, some farmers explained that the "*current certification could be adapted or expanded to include IMTA species – this could be seen as an enhancement to circularity*». «*IMTA needs to be recognised – a certification system would need a measure of circularity, i.e. a rating system.»*

Regarding **consumers' perception**, farmed fish has a more negative perception than wild fish, as some consumers mentioned that they are less healthy, less natural, less fresh and contain more antibiotics or other chemical products. That is why food safety and its communication are becoming more important and crucial globally.

One way to approach this aspect is traceability, that could contribute to the food safety and should be tackled from a technical and a policy point of view, to effectively address the whole supply chain. The adoption of standardised traceability processes can reduce the time and resources required to fulfil legal obligations, reduce operating costs and meet growing customer and consumer demands. As other aquaculture producers, most of interviewed IMTA producers have internal traceability monitoring system: most of them are manually monitoring their facility and only a few are using technology to assist them. The parameters that are monitored vary tremendously depending on the farm size and countries.

In addition, **freshness of products** is crucial for the sales value. In some countries, a deficient cold chain is a barrier to further aquaculture development. Prolonging freshness and delaying seafood spoilage are important challenges facing both the wild-caught and aquaculture industries. Product "freshness" is estimated by a combination of sensory attributes: appearance, smell, texture and taste. It is thus essential to consolidate distribution logistic channels.

Reaching and maintaining **consumer confidence** requires a tremendous effort. The need for improved marketing and distribution skills is imperative. Most aquaculture farmers think of the production aspect as an isolated matter. In most of IMTA farms interviewed, **market knowledge** is a major flaw. For example, some IMTA farmers have not carried out any market studies for new cultivated species. However, investing in a marketing strategy is seen as an intrinsic component of the business plan.
This is a crucial point for the development of IMTA. The mastery of a new culture and production in IMTA is reachable for aquaculture technicians. The very early reflection of market prospects is often neglected due to a lack of internal skills. Specific financial support for the recruitment of a salesperson, for example over a specific period, could promote IMTA and help its development and public perception.

■ The production costs

In an increasingly competitive environment, farmers must enhance **efficiency and profitability when using economic resources.**

Owning an aquaculture facility can be expensive, mostly due to the structure 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: *aquaculture in offshore conditions would solve several problems such as user conflicts, however there are also some disadvantages, as offshore practice is also a lot more reliant on high up-front investment; it is more technically challenging, riskier, and immature.*

Through the interviews conducted by the ASTRAL team, it is difficult to draw a general trend. For some producers, production costs have risen. For instance, in South Africa, "*Costs are very high, in terms of electricity, feeds and fertilizer. Costs have gone up by about 30% so being in a constant state of challenge is the new normal». "We believed we had an advantage over other abalone farms because we are growing our own seaweed, but we are paying about R11-R15 per kg produced, so it does work out quite expensive. It requires fertilizer, people to do the work, paddle-ponds and building the infrastructure."*
For others, the views are more mixed regarding the increase of costs. In general, human resources are the most important item in the production costs. Some IMTA farmers mentioned also the importance of feed in their budget.

Raw material

Fed aquaculture products rely on common input ingredients, such as soybean, corn, fishmeal, fish oil, rice and wheat, and compete in the marketplace with the animal husbandry sector, as well as with direct human consumption. Many of these ingredients traditionally used in recipes for commercial or on-farm aquaculture feeds are internationally traded commodities. Therefore, aquafeed production is subject to **any common global market shocks and volatility**. In addition, feed prices are further affected by fluctuating prices due to petroleum fuels and other transport costs.

The feed used in aquaculture accounts for 40-70% of production costs depending on the country and the company.

In South Africa and in France, several producers have decided to reduce the dependence and to **produce their own feed** through IMTA system. The challenge is twofold: creating highly nutritional aquaculture feed alternatives that works and improving the cost and nutritional performance of existing feedstock while reducing the burden on the natural environment. It is crucial that the new feed alternatives reduce, or at least mitigate the impact on the wild fish stocks and the environmental systems. It should also demonstrate energy, material and resource efficiency advantages.

According to T. Chopin: "*the IMTA principle allows one species' uneaten feed and wastes, nutrients and by-products to be recaptured and converted into fertilizer, feed and energy for the other culture, and to take advantage of synergy*". In South Africa, this makes it a trigger to develop IMTA farm, as seaweeds allow to feed abalones. This increases the growth rate of abalones significantly.

For the interviewed producer, "*the feed conversion ratio of Ulva is half that of kelp, so you end up having to produce double the amount of feed which makes it more expensive, but it also advantageous to the animal growth and animal health".* For another producer growing his own feed, it allows to save 18% of feed costs with *Ulva*. For an IMTA farm in Argentina, feed represents 5% of cost production: "*this is low because they make their own feed with fishing waste (protein extracted from shrimp heads) from the fishery company that acts as an investor, plus Ulva produced on the farm."*

Optimisation of workforce

The varied species production in IMTA system can **impact the labour force**: some are labour intensive (*i.e.* abalone) and some are seasonal (*i.e.* seaweeds). A work organisation could be found to optimise the human resources for a full year: in an Irish farm producing mussels and seaweeds, the assets (equipment and workforce) are organised taking into account the seasonality of the farm production (seaweeds cultivated in winter and mussels in summer). In Argentina, the IMTA system allows to reduce the time used to maintain the quality of the water and results in an improvement in profitability. However, this doesn't always mean a reduction in costs. A French farmer mentions that "*with the periwinkles, we have less manual work with the oyster bags. This is positive because we spend less time. But, there is an extra cost (+1 h labour per handling) during the sorting/cleaning phase. The periwinkles fall first so they have to be separated and sorted from the waste in the sorting line. During rearing, it is easier to handle because the bag is less heavy. So there is not a big difference in production costs».*

Energy and water

Aquaculture systems rely on energy for the production process, which comes with a responsibility of ensuring that it is **efficiently used, with little environmental impact**. Some farms are now investigating renewable energy harvesters to exploit the unused potential for vessels in operation in and around fish farms, such as fish carriers, fish processing and fish farm support vessels.

Some farmers are looking for **energy autonomy** because of the tense context (*i.e.* war in Ukraine) but also of the electricity infrastructure security. For instance, a wind turbine has been installed in a farm in South Africa (public funding support) and local producers have managed to save 40 % of energy costs.

■ Need for skilled staff

Aquaculture is an interdisciplinary practice by nature and requires skills in biological, technical, management, marketing and other related disciplines. Inadequate technical know-how, limited knowledge on health management in fish farming or poor training act as impediments on development in Nigeria, Brazil, Argentina and in European countries.

Over the last decades, there have been a **growing demand for technological skills** within the digital technologies' deployment. Demand for such skills will increase in the next years, as the industry develops and adopts more sophisticated systems and innovative techniques. These are lacking in the current workforce and will be increasingly important for the future sustainable development of the sector. Aquaculture-specific engineering and technology training schemes to support technology adoption are key features to investigate for training programmes.

For all interviewed IMTA producers, it is difficult to gather all the know-how required to cultivate several species within one company. The difficulty of mastering the cultivation of several species at the same time appears to be a major obstacle to the IMTA development, in addition to the complementary staff required. This shows that IMTA should not be designed vertically, but it needs to be thought in a horizontal development.

Furthermore, **attracting and maintaining an adequate labour supply**, based on encouraging young people to take up aquaculture as a career, is on-going particularly in European countries. Finding young people with an interest in outdoor work is an increasing challenge. Staffing businesses in a tight labour market is an ongoing effort, which requires creativity and the adoption of new tools to mobilise and recruit.

It is important to articulate links between schools, training programme and jobs in aquaculture (*e.g.* specific programmes in Norway or in Scotland).

■ Adequate use and offer of technology

By 2050, aquaculture production will need to grow by another 70 million tonnes to meet the world's seafood demand. The role of entrepreneurs will be key to promote innovation for a sustainable aquaculture sector. Technology developments and advancements have improved and upgraded the processes' efficiency, product quality and competitiveness in the aquaculture industry.

Aquaculture is a very unpredictable biological process, which is subject to more significant risks than most other activities. Thus, innovations must be introduced to **improve the predictability and uniformity of the production methods**. For IMTA production systems, lacking knowledge is a recurring problematic that increases the risks for farmers. All of interviewed farmers have highlighted their link with research, as a condition to develop their business and to innovate, and many projects are implemented directly by research organisations. The innovations can focus on the requirement for sustainable production (fish behaviour, safety and risk management, adaptation to climate change, etc.), the improvement of the production and resource management efficiency (monitoring, structures and vessels for exposed location, autonomous system, etc.) and the development of new products.

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 numerous data and they need to adapt their methods to avoid any problems. Most of the interviewed IMTA producers don't use these high technologies; the monitoring is still traditional, and hand made. The challenge remains the access to these technologies for local farmers, due to prohibitive costs and lack of knowledge.

4.3.2 Environmental aspects

Analysis of environmental "costs"

Throughout our desktop studies and the feedback received from the aquaculture producers' interviews, we were able to list and analyse several environmental "costs/constraints" in IMTA implementation that need to be taken into account when producers are willing to change from monoculture / co-culture to IMTA[6].

Related "costs"/constraints	Country concerned	Effect on CBA and farm costs	Description
Dependence on sea/ocean conditions	France, Ireland, Portugal, Brazil	Forecast increase of production and maintenance costs	Some producers explained that their production systems are subject to current and weather conditions, which can impact it and create damages and organic loading
Impact of climate change	All	Forecast increase of production, feed and treatment costs	Many IMTA producers explained that, with climate change, they see an increase of diseases among fishes and other species, increase of HAB and discovery of invasive species
Influence of environmental groups	Ireland	Forecast decrease of revenue and profit, increase of maintenance costs if damages occur	Irish IMTA producers stated that environmental groups were strong opponent and that they object to IMTA implementation in the country, which could lead to protests, demonstrations and damages to the farm
Lack of knowledge on environmental impacts	All	No effect on CBA but important for public perception and awareness	IMTA producers explained that their willingness to start/shift to IMTA was partly due to their environmental impact and their willingness to reduce their impact on the environment. However, they are lacking concrete data and results on this effect, that could help raise awareness among the general public and the consumers.

Table 11: Analysis of IMTA environmental "costs"

[6] This only reflects the feedback of interviewed producers from the concerned countries and who are located in the ASTRAL countries and is not necessary a generality for the entire industry.

Analysis of environmental "benefits"

Below are the main "benefits/gains" mentioned and effect on the CBA to be performed by the producer, the ASTRAL countries concerned and their description.

Related "benefits" / gains	Country concerned	Effect on CBA and farm costs	Description
Increase of oxygen by algae & CO2 absorption	All	Forecast decrease of feeding and maintenance costs	Many IMTA producers explained that they notice an increase of oxygen level in their IMTA systems, due to the algal concentration, that can lead to bioremediation and ecosystem services. For salmon production systems, it also helped to remove carbon levels.
Concealing farming negative externalities	All	Forecast decrease of feeding, production and maintenance costs	The IMTA producers stated that they shifted from monoculture/co-culture to IMTA to reduce their impact on environment and to reduce their negative externalities, caused by their production systems.
Improvement of production conditions for species	France, Ireland, South Africa	Forecast decrease of feeding, production and maintenance costs	Some IMTA producers explained that shifting to IMTA helped them to reduce the mortality rate of their species, especially for producers changing production systems to offshore grids. They highlight also that a relevant trophic combination between species can impact the growth rate (ex: *Ulva* & abalone)
Development of group dynamic to reduce environmental impacts	South Africa	Forecast decrease of shipping and feeding costs	Several South African IMTA producers explained that there is a strong group dynamic in their country, which helps farmers to produce more, get various sources of feeding and help with the shipping processes.

Table 12: Analysis of IMTA environmental "benefits"

Synthesis & perspective

■ Biosecurity

Disease of cultured organisms is one of the most serious constraints to the expansion of sustainable aquaculture. Diseases are most often caused by viruses, but also by bacteria, oomycetes or invertebrate parasites. A long-time lapse is required to manage the situation, from the moment a serious mortality is observed in the field, to the subsequent identification and confirmation of its causative agent.

Studies show that producers better understand the drivers and the factors for disease emergence and propagation, such as the trade and movement of live animals and their products, or the lack or low institutional and technical capacities limiting the application of effective biosecurity measures.

Mortalities and losses have a strong impact on farms, both economically and socially. As an example, one of the most common biosecurity problems in Norway, Scotland and Ireland is sea lice and the virus OsHV-1 for oysters in France.

Biosecurity needs to be thought 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.

Through our interviews, some monoculture and co-culture producers have mentioned the fear of the increased spread of pathogen between species with IMTA, they are *worried about feeding the animals seaweeds, such as Ulva or Gracilaria, grown in effluent water and the biosecurity concerns around that.* This is a impediment to shifting to IMTA.

Many interviewed IMTA farmers take a closer look at this biosecurity issue, especially with regard to climate change. They regularly monitor the production for pathogen management. They 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 don't really know yet **how to assess this change and its effects**. Recent studies show that it is causing rising temperature, ocean acidification, changes in rainfall/precipitation patterns, sea-level rise, changes in sea surface salinity, amongst others. Extreme events, like marine heat waves (defined as

periods of extreme warm sea surface temperatures), are identified as one of the major threats for aquaculture, causing sudden and devastating impacts as well as mass mortalities. The extent of this is still unknown but there is no doubt that there will be a significant effect for commercial aquaculture.
According to IPCC (Intergovernmental Panel on Climate Change), the effects will be persistent and likely irreversible, with severe consequences on the economy in the sector, with strong effects projected on poorer communities.

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 won't be available and on food demand.

Nowadays, researchers are aiming to find more effective mitigation and adaptation strategies, but several challenges remain**.** Grey literature showed how complex it is to adapt the aquaculture systems to environmental changes and the barriers that producers encounter to reach an adaptation, such as technological limitations, financial costs, knowledge gaps and regulations (*Sahya Maulu, et al. 2021*).

Governments and regulatory bodies should take into consideration that climate change has effects on aquaculture and depends on geographical areas, production systems, and cultured species, on regional economy, climatic zones amongst others.
According to IPCC, small-scale producers will be more impacted by climate change risks due to increased production costs and lack of support systems to recover from the effects, compared to large-scale producers.
Aquaculture producers must adapt their system to build resilience in the short term and in the long term. The IMTA systems could be a way to achieve this resilience, as it *is more environmentally friendly, sustainable, and economically rewarding as well as more resilient to changing climate compared to monoculture because it combines finfish farming with other species* (*Sahya Maulu, et al. 2021*).
However, the interviewed IMTA producers don't yet confirm this aspect. It would be necessary to assess more precisely climate change impacts and the resilience capacity of the farms. But 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.

Potential pollutants from aquafeed are phosphorylated and nitrogenous substances, as well as organic matter, chemicals such as antibiotics, fertilizers, disinfectants, antifoulants, and pathogens. These are released to the environment mainly through excretion of faecal wastes, uneaten feed or effluents with the risk of eutrophication, and production of toxic micro-organisms.

Waste management is a key factor to **sustain the production and to favour social acceptance**. It focuses on the generation, treatment, specification, controlling, prevention, handling and reuse of waste, which is one of the IMTA potential advantages. Over the past years, many directives have been initiated to address these aspects, especially in Europe under the European Commission initiatives. However, an optimal waste management system depends not only on the regulatory structures, but also on two main elements, the costs and predicted benefits in case of valorisation (biogas, biofertilizer etc).

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. Most of interviewed producers have shifted to IMTA for the negative externalities' reasons. When using commercially interesting algae near the cages at sea, algae will absorb the nutrients necessary for their growth, coming directly from fish faeces, or inorganic as seaweeds use inorganic nutrients. Circularity is a real lever for the aquaculture industry.

Some measures have been made in the ASTRAL lab in Ireland :

E.g. Seaweed harvested 2021: (Citation Reid et al 2013)
Total harvest: 1720-2160 kg (allowance for variation based on some damage to seaweed lines) of wet weight produced.
Using this, the remediation from the Salmon production this year was:

- 15-19% Nitrogen
- 21-27% Phosphorus
- 18-22% Carbon

Additional oxygen is produced by the seaweed during photosynthesis.
The total volume in kg of carbon removed from the site is 582.9-732kg. This is based on composition analysis of the seaweed.

■ Water quality

Water quality parameters are critical factors in successful aquaculture production, interviewed producers are dependent on this aspect. **Optimal water quality varies by species** and must be monitored in surface water and groundwater sources to ensure growth and survival. In addition, some farms are facing external and/or accidental pollution such as hydrocarbons in France, South Africa or Ireland.

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.

4.3.3 Social aspects

Analysis of social "costs"

Throughout our desktop studies and the feedback received from the aquaculture producers' interviews, we were able to list and analyse several social "costs/constraints" in IMTA implementation that need to be taken into account when producers are willing to change from monoculture / co-culture to IMTA[7].

Related "costs"/constraints	Country concerned	Effect on CBA and farm costs	Description
Ignorance of employees/managers regarding IMTA	All	Increase of HR costs and training costs	Many IMTA producers interviewed stated that one of the main challenges, if IMTA is not well known by the team, is to raise awareness on IMTA and help them understand the benefits and value of such production methods (especially for managers, who are the ones taking decision for the farm)
Little public and producer awareness regarding IMTA	All	No direct effect on CBA and costs	IMTA producers explained that there is a lack of knowledge within the public and producer community regarding the IMTA model benefits, thus this is an obstacle for IMTA development

Table 13: Analysis of IMTA social "costs"

Analysis of social "benefits"

Below are the main "benefits/gains", and effect on the CBA to be performed by the producer, the ASTRAL countries concerned and their description[8].

Related "benefits"/gains	Country concerned	Effect on CBA and farm costs	Description
Development of coastal areas and communities	Brazil, South Africa	No direct effect on CBA and costs	For some IMTA producers, mainly in Brazil and South Africa, IMTA was a great help to develop a sustainable aquaculture and thus develop coastal areas and communities through employment, environment preservation, etc.

[7] This only reflects the feedback of interviewed producers from the concerned countries and who are located in the ASTRAL countries and is not necessary a generality for the entire industry.
[8] This only reflects the feedback of interviewed producers from the concerned countries and who are located in the ASTRAL countries and is not necessary a generality for the entire industry.

An improved perception	Norway	No direct effect on CBA and costs	Salmon production and generally aquaculture has bad press in numerous countries. Producing and combining species (ex: seaweeds) that can absorb nutrients and reduce pollution improve the perception of the sector.
Partner dynamic	South Africa, France	Reduction of shipping costs, production costs	South African producers explained that there is a strong group dynamic in their country, which helps farmers to produce more, get various sources of feeding and help with the shipping processes. 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

Table 14: Analysis of IMTA social “benefits”

Challenges & perspective

■ Perception of aquaculture

Aquaculture has been the **fastest growing food production sector** over the past 20 years and its development has not always been done in appropriate conditions. However, the expansion of the sector has raised several concerns from the general public.

Public perception of aquaculture as a production technique – and its acceptance or rejection – depends on many factors. The implied factors do not only include objective knowledge, but also preconceived ideas such as attitudes or beliefs about the product and its processes. These factors depend on local and regional context, perceived and existing risks (environment impacts, socio-economic costs and benefits, concerns about food safety) and level of trust.

For instance, in Norway, the «*concerns about the environmental impact of the open cage production have become more salient, and media debates about the industry have turned more critical (Solås 2014). Key issues include the impacts of escapes on the wild salmon, the transmission of diseases and parasites, the impact of organic and chemical pollutants on the seabed and local ecosystems (Liu et al. 2011; Uglem et al. 2014). Other points of contention are the corporate concentration of aquaculture operations and consequent lack of local ownership, the modest local employment and economic*

benefits of this increasingly technology-intensive industry, and the spatial displacement of other users such as local fishermen and anglers (Sandersen & Kvalvik, 2015)» (Young *et al*., 2019).
The aquaculture industry needs a broader dialogue that will increase transparency in the sector and improve public awareness.

In that context, 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 don't have extended knowledge on IMTA as well as difficulties to relate to a complicated acronym.

More social science research on aquaculture is needed, especially to better understand the influence on public perception. The ASTRAL project plans to carry out three studies addressing consumer preferences, certification and social acceptability that will allow:

- to identify the characteristics of social challenges and opportunities for IMTA;
- to raise awareness among the different ASTRAL target audiences.

■ Conflicts of uses and neighbourhood dispute

Activities linked to our oceans, and widely to water, are significantly expanding within a highly competitive environment among countries and specific interest groups. Oceans provide **a valuable food supply for humanity**, both from the natural harvesting of the ocean's sea life, as well as from aquaculture.
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 opposite interests linked to the competition (spatial restrictions) or negative externalities (potential impact of aquaculture on water quality, wastes, etc.).
This aspect has been little mentioned in the interview of IMTA farmers. In Ireland, "*some conflicts can exist in the sea sites for seaweed due to space and proximity to other types of aquaculture producers & use of big boats to harvest".* A producer in Norway said that they can feel competition in sea areas (boats & lines for kelp).

4.3.4 Regulatory aspects

Analysis of regulatory "costs"

Throughout our desktop studies and the feedback received from the aquaculture producers' interviews, we were able to list and analyse several regulatory "costs/constraints" in IMTA implementation that need to be taken into account when producers are willing to change from monoculture / co-culture to IMTA[9].

Related "costs"/constraints	Country concerned	Effect on CBA and farm costs	Description
Licencing and bureaucratic red tape	All	Forecast increase of HR costs (administrative process) and licence costs	IMTA producers all agreed on the bureaucratic red tape and the burden of complying with the licensing processes, as they are very complex and authorities sometimes take time to answer every demand or obliged the production quantity (ex: rigidity of the research licencing in Norway)
Consumption and selling issues	All	Forecast decrease of profit and revenue 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 (bioremediation).
Poor support from sector representatives and associations	All	No direct impact on CBA or costs	In many interviews, IMTA producers explained that, as IMTA is not well developed throughout the Atlantic area, it was complicated to get feedback and/or support from sector representatives and associations on this topic, as monoculture is the standard model for now and species are too segmented in their systems.
Political and regulatory changes	All	Forecast increase of HR costs and production costs	IMTA being quite new and not well developed, many IMTA producers explained that having a political change in their countries or new/updated laws might slower the process and add new obstacles to their growth.

[9] This only reflects the feedback of interviewed producers from the concerned countries and who are located in the ASTRAL countries and is not necessary a generality for the entire industry.

Species' regulation	Argentina, Ireland, Portugal	Forecast increase of HR costs (administrative process) and licence costs	This aspect is often mentioned as a problem. This system makes more complex IMTA development and increase administrative effort for team members

Table 15: Analysis of IMTA regulatory "costs"

Analysis of regulatory "benefits"

Below are the main "benefits/advantages", and effect on the CBA to be performed by the producer, the ASTRAL countries concerned and their description[10].

Related "benefits"/gains	Country concerned	Effect on CBA and farm costs	Description
Support from policy makers	France, Ireland, Norway (partly)	Forecast increase of public co-funding	French and Irish producers explained that some national funding authorities expressed their will to help the aquaculture diversification and are planning to open calls for funding or direct funds to help producers in their development. In Norway, upcoming political signals have arisen, making means available for fishery-sector, that should become available for a broader part of the aquaculture sector.

Table 16: Analysis of IMTA regulatory "benefits"

Challenges & perspective

■ 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.

With the aquaculture sector moving forward, both geographically and technologically, the potential for conflicts exists based on the sites' biological suitability, technical feasibility, and cost considerations (Stelzenmüller *et al.*, 2017).

[10] This only reflects the feedback of interviewed producers from the concerned countries and who are located in the ASTRAL countries and is not necessary a generality for the entire industry.

In addition, the profitability of an aquaculture farm and the potential environmental risks and impacts are important. The statements vary substantially across regions and are influenced by the number and density of farms, in addition to i) effects of the environment on farms; ii) effects of farms on the environment; iii) the cumulative impacts and regional planning issues; iv) synergies and conflicts with other ocean management goals.

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.

With IMTA, trophic links in aquatic ecosystems can extend over a large spatial scale. It highly depends on the local hydrodynamics and the biogeochemical processes involved. Such considerations are thus relevant for developing business cases for new forms of aquaculture, even more, as aquaculture heads towards more organised spatial planning, IMTA will increasingly have to become a reality to optimize the limited space.

■ The importance of institutional support

Institutional support is crucial to develop a sustainable and profitable aquaculture. Producers often highlight the complexity of procedures: for instance, "*the Spanish political-administrative framework, with strong divisions between the state, regional and municipal levels, is lacking sufficient coordination, represents a fragmentation of the national market, carries inefficiencies in its implementation and the absence of equality of conditions between Spanish actors based on their geographical location due to divergent regulations. This situation creates heterogeneous situations and complicates the work of companies that have production facilities in several different autonomous regions of higher-ranking regulations»* (Apromar, 2020, p83). This is true also in France and Portugal. A **simplification of procedures with greater coordination** between public administration bodies is needed for producers.

Stability in policy is also critically important to consolidate the aquaculture industry. For instance, in Brazil, frequent changes in government agencies prevent achieving continuous and sufficient investment and to adopt mid-term or long-term strategies (Wagner *et al.* 2021).

While governments have an important role in developing IMTA, no single policy or managerial practice has been officially established. In terms of trends, however, the negative factors of extensive monoculture highlight IMTA's ecological and economic advantages. In Portugal, *an economic feasibility study is necessary for IMTA, because the biological studies are separate, but there is a lack of information that allows the municipalities to make investment decisions.*

Kleitou *et al.* (2018) noted **regional variations**, with IMTA projects in Southern and South Eastern Europe being less developed and facing basic production impediments, such as the lack of available seed of promising local species. On the other hand, countries in the North and Western Europe have been able to commercially exploit a few IMTA species, but with varied levels of profitability.

Governments can help industry players overcome obstacles by the provision of financial incentives, which provides 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.

To conclude, there is a real regulatory blockage of IMTA development. The regulatory framework seems to be fragmented, and often thought per species. Developing IMTA on a broad scale will require regulatory adjustments.

Overall summary and recap

To summarize the ideas and trends that have been describing in the previous sections, a synthesis table has been created, where the most common influencing factors are listed, with for each of them, their occurrence (low, medium or high) and impacts on the socio-economic model of the farm (low, medium or high).

The cells that are highlighted in green are the ones that have more impacts on the model, the higher occurrence and were the most cited throughout the interviews.

Influencing factors for IMTA development (impediment or lever)	Occurrence	Impact on farm model
Structuring factors		
Ignorance of markets for each species and distribution channels	High	High
Increase of production costs	Medium	High
Optimisation of production costs	Medium	High
New market opportunities for revenue diversification	Low	High
Complexity of production system and technical challenges	High	High
Improved species' growth rate due to IMTA	Low	High
Link with the research community	High	High
Consideration of ecosystem services for environment	Medium	Medium
Contextual factors		
Regulation	Medium	High
Societal acceptance	Medium	High
Regional development	Low	Low
Institutional support	High	High
Environmental groups objection	Low	Medium
Access to equipment, technical maintenance and high value technologies	Low	Medium
Cost variability	Low	Medium
Uncertainty of national context	Low	Medium

Table 17: Influencing factors, occurrence and impacts on the socio-economic model of the farm

5 Conclusion

During the interview process, a strong motivation from the producers for IMTA production was recorded. However, and as noted in the Methodology Chapter, a detailed economic analysis of IMTA is still premature and the trends and conclusion provided in this document are incomplete, as IMTA is still under development and in an experimental phase in many countries.

After conducting the interviews, several trends on key points of the IMTA value proposition can be identified.

In the long-term, a study of the profitability rates of IMTA operations at farm's scale could be carried out and will give a more in-depth analysis.

It is important to mention that during our interview process, 5 monoculture/co-culture producers have shown interest in IMTA and might be shifting to IMTA in the near future, which could represent great case studies in future studies.

5.1 SWOT Analysis

As a synthesis, we identified the factors influencing and impacting IMTA, as well as levers & barriers in the Atlantic area, despite the specificities of countries and regions:

- Internal factors (strengths and weaknesses): factors concerning the whole sector (the aquaculture activity, the facilities and the producers). These could affect directly and potentially an IMTA project.
- External factors (opportunities and threats) that are more or less out of control.

IMTA Strengths	IMTA Weaknesses
• Nutrient recycling • Diversification of products and, therefore, markets • Reduced demand for feed from pelagic marine fisheries and terrestrial crops • The ecosystem services could improve revenue opportunities; they remain to be better identified and quantified • Conveying a new image	• Complexity to implement and deploy (business, techniques, production methods, adaptation) • Complexity of regulations, often fragmented and per species • Lack of understanding of environmental impacts • Lack of know-how to find the right economic model(s)

	• Greater structure costs with a potential lower profitability in the short term • Multiple site criteria needed due to different species cultivation
Opportunities for IMTA	**Threats for IMTA**
• A « sustainable » image (need to reduce consumption of resources such as space, food, etc.) • An accelerated innovation potential • The potential development of collaboration between players (between farmers and between farmers and academia)	• Social acceptance and public perception • Not enough government support and public funds • Competition from other aquaculture segments (monoculture)

Table 18: SWOT Factors analysis of IMTA within the ASTRAL Atlantic area

As a perspective, we wanted to highlight that during all conducted interviews, producers (including monoculture and co-culture ones) were well aware of IMTA practices and their benefits, but were lacking the aspects highlighted in this document, such as skilled employees, technical misinformation, lack of resources, etc.

This word cloud shows the most common and positive words that were cited by these producers, to describe IMTA, which showed their willingness to switch to IMTA.

Figure 26: Word cloud representing the producers' opinions on IMTA

5.2 CBA synthesis

System	Country	Size	Species	Year Production (2021)	Number of employees	Costs: Production costs	Costs: Investment costs	Benefits: Public/private funding	Benefits: Targeted market	Benefits: Selling price	Benefits: Turnover
Offshore	Argentina	N/A	*Arbacia dufresnii (green sea urchin), Ulva lactuca (alga), Ascidians*	Sea urchin: 0.04 t Ulva: N/A Ascidians: N/A	9 FTE	Staff costs: 60 % Energy: 15 % Taxes: 15 % Maintenance: 10 % Feed: 5 %	Private investment from a local shrimp fishing company offered €0,4 M and infrastructure to adapt to production needs	Private funding (investment)	BtoB (customers, doctors and cosmetics companies)	N/A	0 (no sales have been made)
RAS, Symbiotics	Brazil	5 ha	*Shrimp, Tilapia*	Shrimp: 77 t Tilapia: 7 t	21 FTE	Production costs: N/A Raw materials: 48 % Staff costs: 18 % Maintenance:14 % Energy: 10 % Inputs:10 %	N/A	Mostly private funding (bank)	Distributors National (100 %)	N/A	N/A
Offshore	France	8.5 ha	*Oysters, Periwinkles*	Oysters: 200 t Periwinkles: 4 t	7, inc. 6 FTE	Running costs: €0.3 M (staff costs, electricity, rent)	€0.15 M (concession and second-hand barge)	€ 0.08 M of public funding Private funding (2 owners)	BtoB (Oyster farmers, customers, restaurants) National, international	Oysters (IMTA premium): 10 €/kg Regular ones: 3-4 €/kg	€ 0.36 M (2021)

Offshore	France	7 ha	*Abalone, Seaweed (Ulva, Dulse, Royal Kombu and Alaria)*	Abalone: 8 t Ulva: 20 t Kombu: 15 t Alaria: 2 t	8 FTE	Electricity: €0.3M Staff costs: €0.25 M Maintenance: €0.03 M	€0.3 M (seaweed ponds) €0.15 M (building extension, solar panels)	Highly dependent on public funding (1 research programme per year) 10 % owned by Business Angel	Restaurants and BtoC (abalone), Wholesaler (Seaweed) National (95%)	Abalone: 90 €/kg	€0.5 M (2021)
Offshore	France	N/A	*Sea bass, Gilthead bream, Meagre, Seaweeds*	N/A	65 FTE (production site), 1 FTE for IMTA	Staff costs: 50 % of turnover	€0.33 M (logistics, veterinary follow-up and impact study - public funding) €0.2 M (installation)	Public funding: EMFF	National (80 %), International (20 %)	N/A	0 (no sales have been made)
Offshore	France	2.5 ha	*Sea bream, Sea bassn Meagre*	N/A	37 FTE (production site)	N/A	N/A	Mostly public funding (national incentives and EMFF funding)	Wholesaler, independent fishmongers International (70 %)	N/A	N/A
Coastal	Ireland	21.5 ha	*Lumpfish, Atlantic salmon, Atlantic wakame, Dillisk/Dulse, Sugar kelp, Sea lettuce, Cluisin, European lobster, King scallop, Native oyster/flat oyster, Purple*	Seaweed: 2.3 t Alaria: 2.1 t Salmon: 1.6 t Scallop: 0.03 t	5 FTE	Annual costs: €0.23 M	€0.6 M over the past three years	100 % Public: Irish government, external research grants	N/A	N/A	0 (no sales have been made)

			urchin, Sea cucumber								
Offshore	Norway	16 ha	*Salmon, Kelp*	Salmon: 780 t Kelp: 100 t	8 FTE	N/A	€0.28 M: Additional investments on the construction site, mainly for the mooring system	Private (bank loans and owner equity) and income salmon sale/temporary research license	BtoB (Distributors) National and Europe	1.43 €/kg	N/A
Offshore	Portugal	N/A	*Gilthead bream, Seabass, Ulva, Gracilaria*	N/A	2 FTE	N/A	N/A	Public (R&D projects)	N/A	N/A	N/A
Offshore	Portugal	N/A	*Sea bass, Oyster, Serradela, Salicornia, Sea lettuce*	N/A	2 FTE	N/A	N/A	Public (R&D projects)	N/A	N/A	N/A
Offshore	Scotland	30 ha	*Kelp, Ulva, Oyster*	N/A	5 FTE	N/A	N/A	Public (R&D projects)	N/A	N/A	N/A
Land-based	South Africa	20 ha	*Abalone, Ulva, Gracilaria*	Abalone: 170 t Ulva: 720 t Gracilaria: 108 t	300 FTE	N/A	N/A	1/3 public funding 2/3 private funding	BtoB (Restaurants, markets) International activity (Hong Kong)	N/A	N/A
Land-based	South Africa	10 ha	*Abalone, Ulva, Gracilaria*	Ulva: 600 t Abalone: 450 t	210 FTE	N/A	N/A	Public (7 %): Beneficiary of ADEP	BtoB (Wholesalers, restaurants)	N/A	N/A

								(Aquaculture Development Enhancement Program) funding Shareholders (Major group and local farmers)	Mostly local sale ; Abalone are 70% exported to Asia		
In-land (RAS)	Ireland	N/A	*Abalone, Sea urchins, Sea cucumbers*	Abalone: 2.5 t Cucumber: 0.5 t Urchins: small number	6 FTE	€3 M: buildings, equipment, license fees, salaries and brood stock	N/A	Public: €1 M Private: €0.8 M American and Irish investors	Restaurants, distributors National	N/A	N/A
Offshore	Norway	8.5 ha	*Salmon, Kelp*	Salmon: 780 t Kelp: 8 t	6 FTE	N/A	N/A	Private (bank loans and owner equity) and income salmon sale/temporary research license	BtoB (Feed producers) National	Kelp: 1.43€/kg	N/A

Grey lines = farms that operated in IMTA systems and switched to mono/co-culture since then

Table 19: CBA analysis of interviewed IMTA producers

TO KEEP IN MIND:

This table summarizes all the economic data collected during our interviews with 15 IMTA producers.

Some of them are missing or have been removed (due to confidentiality, lack of trust, lack of information from interviewee, etc.) and are very diverse, which makes it difficult to do a proper analysis and comparison.

5.3 Recommendations

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

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

Producers	Researchers/Academia
Aquaculture professional organisations	Policy makers

1

Develop pilots and demos

Economic demonstration is still premature and experimentation farms ongoing. More work is needed for IMTA systems to become a commercial reality, despite the large amount of research and field pilot work carried out to date. There is an urgent need to develop and optimize IMTA systems and to test new production methods. This implies that producers have time to dedicate to these projects, have been technically supported and benefit from public funding.

2

Encourage an active policy to make a change

IMTA implementation and growth will only be possible with the support of policy makers. There is a need to design an IMTA development plan in each country to answer to concrete needs, to fund synergies between producers and to operate a financial support policy which is pertinent and precise, to help producers shifting to IMTA. This work should be done in close link with researchers, producers and professional organizations.

3

Increase and organise the sharing of knowledge on IMTA

Co-culture and monoculture producers are generally open to this new approach but have not embarked on it due to the lack of knowledge and demonstration of the system's effectiveness and viability. It is now necessary to find the right way of dissemination and knowledge transfer of technical, economic and environmental aspects including experience exchange. Increasing links between researchers and aquaculture professional organisations is important to share with all producers.
Innovation is a key factor of success and is a great asset for IMTA systems.

4

Improve and increase availability of trainings

It is difficult for a manager with more than 50 employees to move from a standardised mono-specific model to a multidisciplinary model. It is important that the workforce get continuous training for the work to be done within the farm, especially regarding the complexity of the system. For the young generation and students, it is crucial to disseminate the approach and seize IMTA.

5

Estimate and monetise ecosystem services

It is crucial that the values of ecosystem services* are recognised, accounted for and used as financial and regulatory incentive tools, such as in the development of nutrient trading credits. However, no real system for recognising and rewarding ecosystem services is yet in widespread and robust usage. This awareness of ecosystem services should be targeted primarily at local stakeholders to facilitate aquaculture development.

** goods and services that humans can derive from ecosystems, directly or indirectly, to ensure their well-being (Millenium Ecosystem Assessment, 2005)*

6

Stimulate a collective circular approach

The complexity of IMTA approach in terms of technical and human aspects has been highlighted several times. A solution could be to set up synergies and pooling between aquaculture producers on a specific territory. In the same way as territorial industrial ecology concept, there could be a territorial aquaculture ecology approach.

7

Change regulations and administrative processes

A key aspect for IMTA growth will be to facilitate the implementation of experiments or diversifications on the concessions of professionals. A full place must be given to IMTA and its practices must not be blocked by the superposition of various regulations.

Regulations must be made more readable, simpler and understandable by everyone.

8

Make IMTA more visible

Complementary to recommendation n°3, it is important that IMTA is recognized among policy makers, general administrations and the general public. A strong communication and promotional strategy has to be launched in order to show the benefits of IMTA for the sector and for consumers. Producers will get information and knowledge on the advantages coming from IMTA and consumers will get more insights on products' quality and environmental aspects.

9

Better address the commercialization strategy of IMTA products

The marketing of IMTA products is by definition diversified. A type of product corresponds to a specific market and marketing channel. For IMTA to be an economic advantage for producers, one can imagine the creation of an eco-label to highlight the environmental advantages of this type of production. Marketing through a local distribution channel is also to be preferred because it echoes the ecological philosophy of the IMTA. Producers need dedicated support on this aspect to reach new markets and sustainable growth/sales.

Figure 27: Recommendations on IMTA for producers, the aquaculture industry organizations, researchers/academia and policy makers

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